PHYSICAL CONDITIONS IN THE LOW-IONIZATION COMPONENT OF STARBURST OUTFLOWS: THE SHAPE OF NEAR-ULTRAVIOLET AND OPTICAL ABSORPTION-LINE TROUGHS IN KECK SPECTRA OF ULIRGS

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ABSTRACT

We analyze the physical conditions in the low-ionization component of starburst outflows (in contrast to the high-ionization wind fluid observed in X-rays), based on new Keck/LRIS spectroscopy of partially resolved absorption troughs in near-ultraviolet and optical spectra of Ultraluminous Infrared Galaxies. The large velocity width and blueshift present in seven atomic transitions indicate a macroscopic velocity gradient within the outflowing gas. The separation of the Mg II 2796, 2803 (and Fe II 2587, 2600) doublet lines in these data constrains the gas kinematics better than previous studies of the heavily blended Na I 5892, 5898 doublet. The identical shape of the Mg II 2796 absorption trough to that of the normally weaker transition at 2803 Å (after accounting for emission filling) requires both transitions be optically thick at all outflow velocities. The fraction of the galactic continuum covered by the outflow at each velocity therefore dictates the shape of these absorption troughs. We suggest that the velocity offset of the deepest part of the troughs, where the covering factor of low-ionization gas is near unity, reflects the speed of a shell of swept-up, interstellar gas at the time of blowout. In a spherical outflow, we show that the fragments of this shell, or any clouds that expand adiabatically in rough pressure equilibrium with the hot wind, expand slowly relative to the geometrical dilution, and the covering fraction of low-ionization gas decreases with increasing radius. Our measurement of a covering factor that decreases with increasing velocity can therefore be interpreted as evidence that the low-ionization outflow is accelerating, i.e., absorption at higher velocity comes from gas at larger radii. We also present measurements of $C_f (v)$ in four species, place an upper limit of $n_e \lesssim 3000$ cm$^{-3}$ on the density of the outflowing gas, and discuss lower limits on the mass outflow rate.

Key words: galaxies: starburst – hydrodynamics – infrared: galaxies – intergalactic medium – ISM: evolution – line: profiles

Online-only material: color figures

1. INTRODUCTION

Galactic winds are a key ingredient in cosmological models of galaxy evolution. They transport the nucleosynthetic products of stars into galaxy halos and the intergalactic medium (IGM), thereby shaping enrichment and effective yields. The amount of material ejected from low-mass galaxies can significantly reduce the gas mass available for star formation, resulting in lower global efficiencies for star formation that flatten the faint end of the galaxy luminosity function, relative to that of the halo mass function (Somerville & Primack 1999). Some heating mechanism is apparently required in very massive halos in order to make the number of galaxies cutoff more steeply with luminosity than the halo mass distribution does with increasing halo mass. Simulations generally invoke some type of feedback from accreting supermassive black holes, although only the energy scale required distinguishes this feedback from supernova-driven, galactic winds. With mass-loading factors that scale inversely with galaxy mass, feedback prescriptions, starburst winds account for the metal enrichment of the intergalactic medium (IGM; e.g., Oppenheimer & Davé 2006).

The scaling relations used for feedback in cosmological simulations are largely motivated by empirical results. Nearby starburst galaxies present hot, extraplanar gas, heated by supernovae (Dahlem et al. 1998; Martin 1999; Strickland et al. 2002; Martin et al. 2002). Outflow speeds for low-ionization gas have been measured for much larger samples of nearby galaxies (Heckman et al. 2000; Rupke et al. 2002; Martin 2005, 2006; Rupke et al. 2005b; Sato et al. 2009) and composite spectra of distant galaxies (Shapley et al. 2003; Weiner et al. 2009). In the standard dynamical model for the acceleration of this gas, the kinematics of the low-ionization gas reflect properties of a hotter, energetically dominant wind. The hot wind is not a necessary component of the outflow when radiation pressure (on dust grains) accelerates the outflow. Outflow components at vastly different temperatures can only be observed from the X-ray to the infrared for relatively nearby systems. At redshifts $z \gtrsim 0.15$, observations of winds typically detect low-ionization absorption lines and, less commonly, cover strong transitions of O vi, N v, S iv, and C iv. Determining what physical information can be reliably extracted from the absorption lines is of paramount importance for understanding any evolution in galactic wind properties over cosmic time.

For nearby starbursts, the Na I 5892, 5898 lines are the most commonly detected lines from outflows owing to the aperture advantage of ground-based telescopes over satellites. The majority of luminous starburst galaxies present a strong, blueshifted Na i absorption trough (Heckman et al. 2000; Rupke et al. 2002; Martin 2005, 2006; Rupke et al. 2005b; Sato et al. 2009), but the detected fraction in Na i drops to about half for the nearby dwarf, starburst galaxies (Schwartz & Martin 2004). Although the stronger line, Na i 5892, is usually saturated based on its strength relative to the weaker line at 5898 Å, the absorption troughs are rarely black. These previous studies

3 Packard Fellow.
have concluded that the Na\textsc{i} absorbers do not completely cover the optical continuum source. The blended absorption troughs have been fitted with the minimum number of velocity components, typically from 1 to 3, required to describe the velocity asymmetry (e.g., Martin 2005, 2006; Rupke et al. 2002, 2005a), and little has been written about the variation of physical parameters with velocity in the outflow. In contrast, the very broad absorption troughs identified as outflows in active galactic nuclei (AGNs) spectra require a velocity-dependent covering factor (Arav et al. 1999, 2001; de Kool et al. 2002; Gabel et al. 2003; Scott et al. 2004). Resolving absorption troughs in starburst spectra, and comparing different transitions, can lead to new insight about the nature of the low-ionization component of outflows.

In this paper, we present Keck/LRIS spectroscopy of redshift $z \sim 0.25$ galaxies that partially resolves the Na\textsc{i} 5892, 5897, Mg\textsc{ii} 2753, Mg\textsc{ii} 2796, 2803, and Fe\textsc{ii} 2587, 2600 absorption troughs. We choose Ultraluminous Infrared Galaxies (ULIRGs) due to their high Na\textsc{i} outflow fraction and selected systems at redshifts that provided Na\textsc{i} and near-ultraviolet (near-UV) spectral coverage. The targets are among the most luminous starbursts in the local universe and are classified as ULIRGs, $\log L_{\text{IR}} > 12$. Their activity triggers by gas inflow induced by a recent, or on-going, merger (Borne et al. 2000). The wider separation of the Mg\textsc{ii} doublet lines, 768 km s$^{-1}$, relative to the Na\textsc{i} doublet, allows direct comparison of the $\lambda 2796$ and $\lambda 2803$ troughs, hereafter the blue and red troughs, respectively. At any location in the outflow, the blue transition has twice the optical depth of the red one, and the covering fraction will necessarily be identical. In contrast to the $\alpha$-element enrichment measured in the hot wind (Martin et al. 2002), the relative abundance of Fe to Mg could be as high as solar in the low-ionization gas, which may be primarily entrained interstellar gas. The optical depth in the Fe\textsc{ii} line would then be just 1.8 times lower than that in Mg\textsc{ii} 2803. However, the much weaker Fe\textsc{ii} 2587 line, $\tau_0(25800) = 3.5\tau_0(2587)$, might be optically thin when other transitions are saturated. Whether Fe\textsc{ii} 2587 or Na\textsc{i} 5898 proves to have lower optical depth, and therefore provides the better separation of the Mg\textsc{ii} transitions are saturated. Whether Fe\textsc{ii} and Na\textsc{i} have concluded that the Na\textsc{i} absorption and several emission lines in the red channel. Due to the low density of bright galaxies at these redshifts, the spectra must be obtained one at a time.

Galaxies were chosen from the IRAS 1 Jy survey of ULIRGs (Kim & Sanders 1998), which contains 118 ULIRGs with $L_0 > 1 \text{ Jy}$, based on apparent magnitude and airmass at the time of our runs. Ultraluminous Infrared Galaxies are extremely rare at the present epoch but offer the closest local analog of the IR-luminous galaxy population that dominates the cosmic star formation rate density at redshifts greater than 0.7 (Le Floc’h et al. 2005). The high dust content absorbs much of the stellar luminosity and emits this energy as thermal radiation in the infrared.

Table 1 lists some properties of the galaxies whose spectra are presented in this paper. The infrared luminosities of the galaxies observed range from $\log L_{\text{IR}} = 12.31 - 12.81$ with mean $\log L_{\text{IR}} = 12.58$, which is more luminous than the mean of the Martin (2005, 2006) sample. The AGN fraction is higher in brighter ULIRGs (Veilleux et al. 1999); and two of the five ULIRGs in the sample are spectroscopically classified as AGN (2 LINERs and 2 Sey 2’s). The more recent Kewley et al. (2006) division of these optical-emission-line ratios into excitation types classifies FSC 0039 as a composite starburst-AGN, FSC 1009+47 as a Seyfert 2, FSC 1407+05 at the Seyfert/LINER boundary, FSC 1630+15 at the LINER/Composite boundary, and FSC 2349+24 as a Seyfert 2. Among our five targets, FSC 2349+24 clearly presents the strongest AGN signatures, but AGN contribute less than half of the bolometric luminosity in the other four ULIRGs (Veilleux et al. 2009a). Among our five targets, FSC 2349+24 clearly presents the strongest AGN signatures. Rupke et al. (2005c) found little difference in Na\textsc{i} wind kinematics between H\textsc{ii}, LINER, and Sey 2 ULIRGs; only the Sey 1’s showed faster outflows. Hence, we expect these outflows are driven primarily by the starburst rather than the AGN. The far-infrared colors are all cooler than the standard demarcation, $F(25 \mu\text{m})/F(60 \mu\text{m}) > 0.2$, used to identify warm ULIRGs (Kim et al. 1998), which also suggests the total luminosity is starburst dominated. The total infrared luminosities correspond to upper limits on the star formation rates from $SFR \sim 207 - 653 M_\odot \text{ yr}^{-1}$ or $\sim 352 - 1110 M_\odot \text{ yr}^{-1}$, respectively, for the Chabrier or Salpeter initial mass functions.

2. KECK OBSERVATIONS OF OUTFLOWS IN THE NEAR-ULTRAVIOLET AND OPTICAL

We obtained (rest-frame) near-UV and optical spectroscopy of redshift $z \sim 0.25$ starburst galaxies with LRIS (Oke et al. 1995; McCarthy et al. 1998) on Keck I. The blue channel of LRIS is one of the few optical spectrographs that is efficient down to the atmospheric cut-off in the blue, allowing observations of Mg\textsc{ii} at $z \gtrsim 0.15$ (for targets directly overhead). The dual-beam design offers simultaneous coverage of Na\textsc{i} absorption and several emission lines in the red channel. Due to the low density of bright galaxies at these redshifts, the spectra must be obtained one at a time.

Longslit spectra were obtained with LRIS (Oke et al. 1995) and LRISb (McCarthy et al. 1998) on 2004 January 26, 2004 March 16-17, 2007 October 6, and 2007 November 1. Clouds and high humidity limited the exposure times on all of these nights. We present the five highest quality spectra obtained from the combined data.

2.1. Data Acquisition and Reduction

Longslit spectra were obtained with LRIS (Oke et al. 1995) and LRISb (McCarthy et al. 1998) on 2004 January 26, 2004 March 16-17, 2007 October 6, and 2007 November 1. Clouds and high humidity limited the exposure times on all of these nights. We present the five highest quality spectra obtained from the combined data.

No. 2, 2009 CONDITIONS IN LOW-IONIZATION STARBURST OUTFLOWS 1395
The position angle of the longslit was selected to cover both nuclei of FSC 1009+47 and FSC 2349+24. The atmospheric dispersion compensator, which was installed on LRIS in spring 2007, was used for the 2007 observations. Care was taken with the 2004 observations to observe the targets when the slit PA was near the parallactic angle.

The dual beam spectrophotograph was configured with the D560 dichroic, a 1200-l grism blazed at 3400 Å in the blue arm [N II] emission lines as well as the Na I absorption and He I 5876 emission line. The blue spectra cover the Mg II 2796, 2803 doublet, the Mg I 2853 line, and the Fe II 2587, 2600 doublet. The slit width was chosen based on the atmospheric seeing. The resolution (for a source filling the slit) ranged from 110 km s\(^{-1}\). The slit width was chosen based on the atmospheric seeing. The dichroic, the Mg \( \text{II} \) 2853 line, and the Fe \( \text{II} \) 2600 doublet.

**Table 1**

| Object          | f25/f60 | f60/f100 | log(\(L_\text{IR}/L_\odot\)) | (70.0,3.0,0.7) | SFR-S (M\(\odot\) yr\(^{-1}\)) | SFR-C (M\(\odot\) yr\(^{-1}\)) |
|-----------------|---------|----------|---------------------|----------------|-----------------------------|-----------------------------|
| FSC00397−1312   | 0.180   | 0.963    | H\(\alpha\) (V99)    | 12.81          | 1110                        | 653                         |
| FSC10091+4704   | 0.068   | 0.761    | LINER (V99,K98b)    | 12.57          | 641                         | 377                         |
| FSC14070+0525   | 0.131   | 0.797    | Sey2 (K98b)        | 12.66          | 789                         | 464                         |
| FSC16300+1558   | 0.047   | 0.744    | LINER (K98b)      | 12.53          | 585                         | 344                         |
| FSC23498+2423   | 0.118   | 0.703    | Sey2 (V99)        | 12.31          | 352                         | 207                         |

**Notes.** (1) ULIRG name. (2) f25/f60 color computed from far-infrared fluxes in KS98. (3) f60/f100 color computed from far-infrared fluxes in [KS98]. (4) Spectral type from Kim et al. (1998) – FSC1009+47, FSC1407+05, FSC1630+15, – and Veilleux et al. (1999) – FSC0039–13, FSC1009+47, FSC2349+24. (5) \(L_\text{IR}\), calculated using the prescription of Sanders & Mirabel (1996). For FSC objects, the luminosities from Kim et al. (2002) and Veilleux et al. (1999), which assume luminosity distances based on \(H_0 = 75\text{ km s}^{-1}\text{ Mpc}^{-1}\) and \(q_0 = 0\), were converted to the cosmology used throughout this paper. (6) For Salpeter IMF from 0.1 to 100M\(\odot\), the star formation rate is \(SFR = L_\text{IR}/5.8 \times 10^9L_\odot\), where \(L_\text{IR}\) is the bolometric luminosity (Kennicutt 1989). (7) SFR for Chabrier IMF, i.e., K89 SFR by 1.7.

**Table 2**

| Object          | Redshift | PA (deg) | Res. (km s\(^{-1}\)) | SNR | Date Observed | Notes                  |
|-----------------|----------|----------|----------------------|-----|---------------|------------------------|
| FSC00397−1312   | 0.26171  | −54.0    | 160                  | 9.4 | 2007 Nov 1    | Advanced Merger         |
| FSC10091+4704   | 0.24508  | 109.0    | 130                  | 5.0 | 2004 Jan 26, 16-17 | Diffuse Merger         |
| FSC14070+0525   | 0.26602  | −25.0    | 110                  | 8.2 | 2004 Jan 26, 16-17 | Advanced Merger         |
| FSC16300+1558   | 0.24200  | −45.0    | 155                  | 6.2 | 2004 Mar 16-17, 2007 Oct 6 | Pre-Merger, Separation 4.4 kpc |
| FSC23498+2423   | 0.21249  | −45.9    | 160                  | 6.4 | 2007 Nov 1    | Pre-Merger, Separation 14 kpc |

**Notes.** (1) Target. (2) Redshift measured from emission lines including H\(\alpha\), [N II] 6584.48, [S II] 6717.31, and [O I] 6300.64. The absolute velocities have not been corrected to the Local Standard of Rest. (3) Position angle of the longslit measured east of north. (4) Spectral resolution defined by the measured full width at half maximum intensity of the arc lamp lines. If frames from different runs are combined, then the poorer of the two resolutions is listed. (5) SNR per pixel is measured in a 100 Å bandpass immediately blueward of Mg \(\text{II}\). (6) Date(s) observed. (7) The Veilleux et al. (2002) merger classification is compared to the structure observed along the longslit.

The dispersion solution for the blue (red) spectra was 0.05 (0.07) Å. Application of a small, additive shift, up to a couple tenths of an angstrom, registered the wavelengths of night sky emission lines with their values in a telluric-line spectrum (Hanuschik 2003) smoothed to our spectral resolution and transformed to vacuum wavelengths (using the Edlen formula). We attribute these corrections to shifts in the dispersion solution with airmass and rotator angle. The correction to the Local Standard of Rest (LSR) was computed for each observation using the IRAF task RVCORRECT. All the offsets were less than 30 km s\(^{-1}\). Since we are only concerned with relative velocities, the corrections to LSR were not applied to the data.

We rectified the two-dimensional spectral images, using the dispersion solution and traces of a standard star stepped along the longslit, and then extracted an integrated galaxy spectrum for each target. These spectra have SNR ~ 5 – 10 per pixel as shown in Table 2. Additional, lower quality spectra were extracted for the distinct continuum sources within FSC 1009+47, FSC 1407+05, and FSC 2349+24. After substraction of the median sky intensity at each wavelength, significant residuals from strong night-sky emission lines remained in the red spectra near the Na I line in FSC 1009+47, 1407+05, and 1630+15. Variance spectra were extracted for each target prior to sky subtraction and flux calibration. The variance vectors were later scaled by a multiplicative factor that made the uncertainties in the intensity consistent with the measured standard deviation in the extracted, target spectra.

Observations of multiple, standard stars determined the relative sensitivity with wavelength. The data were flux calibrated...
using this sensitivity function and then normalized by a fitted continuum. The error in continuum placement is negligible around Na i, Mg i, and Mg ii; but the blending of stellar absorption lines washes out the true continuum level at shorter wavelengths. To identify bandpasses near Fe ii 2587, 2600 that likely reach the true continuum level, we compared high-resolution, synthesized spectra models of stellar populations to copies smoothed to 100 km s\(^{-1}\) resolution. We fitted a first or second order cubic-spline through these bandpasses as well as the broad bandpasses near the Mg i and Mg ii lines. The resulting error in the continuum level near Fe ii depends on the star formation history. The severe blanketing in older bursts requires actual fitting of reddened, model spectra. This level of sophistication was unnecessary, however, because these near-UV spectra are bluer than the \( t > 100 \) Myr burst models; and we confidently rule out old, burst models for the continuum. The population synthesis models indicate either continuous star formation or a burst within the past 100 Myr. Repeated fitting trials indicate the uncertainty in the continuum level around Fe ii was 1 to 5\%.

For a typical line width of 470 km s\(^{-1}\) FWHM, we detect a rest-frame equivalent width \( W_r(\sigma) \approx 1.52 \, \text{Å} \left( 5/\text{SNR}_{\text{pix}} \right) (\Delta v/470 \, \text{km s}^{-1})^{0.5} \) in the red spectra at the 5\% significance level. A typical 5\% sensitivity limit for the blue spectra is \( W_r(\sigma) \approx 0.92 \, \text{Å} \left( 5/\text{SNR}_{\text{pix}} \right) (\Delta v/470 \, \text{km s}^{-1})^{0.5} \).

2.2. Sensitivity of Spectra to Physical Properties

We measured redshifts from recombination lines of H and He and forbidden lines of singly ionized N and S. These lines all fall in our red spectra. The dispersion solution ties both the blue and the red spectra to the vacuum wavelengths of night sky emission lines. These redshifts agree with the previous measurements of Kim & Sanders (1998). Our independent check is important because that work used the Na i absorption line in the redshift estimate; and we will show that the Na i kinematics differ significantly from that of the recombination lines.

The sensitivity of the seven metal lines to outflowing gas depends on the relative abundances of the elements, the oscillator strengths of the transitions, the dust depletion, and the ionization corrections. In the limit of comparable ionization corrections for all species, the optical depth in the Mg i 2853 line would be the largest for solar-abundance ratios. The Mg ii lines have lower oscillator strengths, and the cosmic abundances of Fe and Na are lower. Our typical detection limit for Mg i corresponds to a minimum hydrogen column density,

\[
N(H I) = 1.62 \times 10^{17} \, \text{cm}^{-2} \frac{(N(Mg)/N(Mg I)) (5/\text{SNR})}{1 + 1.25 \left( \Delta v/470 \, \text{km s}^{-1} \right)^{0.5}}.
\]

Under the same conditions, the Na i 5898 line optical depth would be slightly lower than the weakest Fe ii line, but whether either transition is optically thin depends on the relative ionization correction, where

\[
\frac{\tau_0(\text{Fe ii} 2587)}{\tau_0(\text{Na i} 5898)} = 1.41 \frac{\chi(\text{Fe ii})}{\chi(\text{Na i})}. \tag{2}
\]

The Na i 5898 line can, in principle, provide the best measurements of an ionic column density in the outflow, but interpretation is complicated by the blending with the Na i 5892 transition, the ionization correction, and depletion of Na by dust grains. The Fe ii transitions with the lowest oscillator strengths lie blueward of the atmospheric cut-off for nearby galaxies, and their measurement will likely lead to the best estimates of mass column density.

3. MEASURED PROPERTIES OF LOW-IONIZATION OUTFLOWS

Figure 1 shows the absorption troughs on a velocity scale. The high spectral resolution, relative to the broad troughs, allows us to compare the shape of the absorption troughs among seven transitions. The centroids of the H\( \alpha \) and [N ii] emission lines lie at the systemic velocity by construction. The spectra of all five galaxies present broad absorption troughs in the Na i and Mg ii doublets. The spectrum of FSC 0039–13 has the best SNR near the Mg i 2853, Fe ii 2600, and Fe ii 2587 lines; but these transitions are detected in all the spectra except for FSC 2349+24. The Fe ii 2587, 2600 lines lie shortward of \( \lambda 3200 \) for FSC 2349+24, and the SNR is severely compromised by atmospheric attenuation. In Figure 1, the two Seyfert 2 galaxies in the sample, FSC 1407+05 and FSC 2349+24, present Mg ii in emission. Some He i emission is present near the Na i doublet in all the spectra and is most prominent in FSC 0039–13.

Spectra of A, F, and G stars present low-ionization metal lines; but any photospheric contribution to the total equivalent width in our spectra is small. The velocity offset of the absorption troughs require a non-stellar absorption component; and the Mg ii troughs for four of the galaxies show little or no absorption at the systemic velocity. Only the FSC 0039–13 spectrum presents absorption at \( v = 0 \). We attribute it to the interstellar medium in the host galaxy, likely a result of high inclination relative to our sightline.

A dominant stellar origin for the resonance absorption appears unlikely in these ULIRGs for several reasons. First, Figure 2 shows Mg ii and Mg i equivalent widths measured from synthetic spectra, computed with the STARS2002 stellar population synthesis code (Sternberg 1998; Thorløy et al. 2000; Sternberg et al. 2003; Davies et al. 2007) and the UVBLUE library of high-resolution stellar spectra (Rodríguez-Merino et al. 2005), for a broad range of star formation histories.\(^5\) Only post-starburst populations, with continua dominated by A, F, or G stars, show Mg ii 2796 equivalent widths of more than a couple Angstroms. The large Mg ii equivalent widths of FSC 0039–13, FSC 1407+05, and FSC 1630+15 are inconsistent with continuous star formation; and the other two ULIRGS do not lie near the stellar locus. Second, the ULIRG spectra lack detectable absorption from excited, electronic states of Fe ii, lines that are prominent in the spectra of older stellar populations in Figure 3. In addition, the synthesized spectrum of the stellar population shows Mg ii lines much broader than those from Mg i, although smearing by the motions of stars in the galaxy could hide this difference. Previous ULIRG outflow studies estimated the stellar contamination in the Na i absorption trough from the equivalent width of the excited Mg i triplet at \( \sim 5200 \) Å (not covered by our spectra) and typically found a negligible stellar contribution (Martin 2005).

Extracting quantitative information about the absorbing material in the outflow from the absorption troughs requires a physical model. The spectra presented in this paper resolve components with intrinsic velocity widths of 100 km s\(^{-1}\) or more; and neither thermal nor turbulent motion easily explains the extremely broad, \( \sim 800 \) km s\(^{-1}\), velocity width of the absorption troughs. Macroscopic variations in velocity are required and

\(^5\) All models assumed a Kroupa initial mass function from 1 to 120 \( M_\odot \), solar metallicity, and an exponentially declining star-formation rate.
could be associated with discrete supershells and their fragments (Fujita et al. 2009), interstellar clouds overrun by the superbubble shock (Cooper et al. 2008), eddies formed at the wind–disk interface (Heckman et al. 2000), or the velocity gradient in a smoothly accelerating wind (Murray et al. 2005). These ideas motivate descriptions with discrete velocity components, where components correspond to individual clouds or shell fragments.

In Section 3.3, we formally fit all the absorption troughs with such velocity components. For unblended, doublets, a parametric description of the absorption troughs requires fewer physical priors, however; and we apply this approach in Section 3.2 to build intuition. The key constraint throughout this modeling is the observation that many of the transitions must be optically thick, not only at the deepest part of the absorption

Figure 1. Normalized intensity vs. velocity, where the velocity is relative to the systemic velocity determined from emission lines. (a) LRIS spectra of FSC0039−13, (b) LRIS spectra of FSC1009+47, (c) LRIS spectra of FSC1407+05, (d) LRIS spectra of FSC1630+15, (e) LRIS spectra of FSC2349+24.

(A color version of this figure is available in the online journal.)
trough but at high outflow speed. To illustrate the robustness of this model-independent statement, we directly compare the absorption trough shapes among the different transitions in Section 3.1.

3.1. Direct Comparison of Absorption Trough Shape in Seven Transitions

When intervening absorption is studied in quasar spectra, or the Galactic halo studied in absorption against stellar spectra, the angular size of the absorbing gas clouds exceeds that of the continuum source. Gas between the observer and the light source attenuates the continuum by an amount proportional to the logarithm of the optical depth in any transition. For a doublet, we have

$$I_B(v) = I_0 e^{-\tau_B(v)}$$  \hspace{1cm} (3)
$$I_R(v) = I_0 e^{-\tau_R(v)}.$$  \hspace{1cm} (4)

For interstellar conditions, the relative optical depth between electronic transitions in a single ion from the ground state,
of the transitions are very similar. Substitution in Equation (3) indicates that the relative depth of the continuum-normalized absorption troughs must be \( I_B(v) = I_R(v) \). These relations hold provided the clouds completely cover the continuum source over a velocity range comparable to (or greater than) the spectral resolution. In practice, when transitions with different \( f \) values saturate, both troughs appear black in noisy spectra.

Observations of Na\textsc{i} absorption troughs in ULIRGs cannot directly measure the relative intensities \( I_B(v) \) to \( I_R(v) \) due to the blending of the two absorption troughs. Previous modeling of the combined trough strongly suggests, however, that the assumption of complete continuum coverage is not met (Martin 2005, 2006; Rupke et al. 2005a, 2005b).

3.1.1. Description of Mg\textsc{ii} Absorption Troughs

The Mg\textsc{ii} absorption troughs delineate the outflow kinematics most cleanly. In FSC0039−13, the majority of the trough equivalent width is blueshifted, but the minimum intensity of the trough lies near the systemic velocity. The intensity minima are blueshifted several hundred km s\(^{-1}\) in the other Mg\textsc{ii} spectra with little or no absorption at the systemic velocity. In FSC1630+15 and FSC2349+24, the minima in the absorption troughs lie at \( v \sim -400 \) km s\(^{-1}\). The FSC1407+05 spectrum presents a broad trough from \(-200\) to \(-500\) km s\(^{-1}\). The Mg\textsc{ii} 2796 and 2803 absorption troughs blend together in the FSC1009+47 spectrum, possibly due solely to the lower SNR of this spectrum. The Mg\textsc{ii} absorption troughs have residual intensities < 10% in FSC0039−12 and FSC1630+15 at minimum intensity. The residual intensity at line center is low but not zero in the other three spectra. The Mg\textsc{ii} absorption troughs are noticeably deeper than the Mg\textsc{i} or Na\textsc{i} absorption troughs.

We can test the condition represented by Equations (3) and (4) by comparing the Mg\textsc{ii} \( \lambda 2796 \) and \( \lambda 2803 \) troughs in our spectra of FSC0039−13, FSC1407+05, FSC1630+15, and
The scaled Mg $\text{ii}$ 2796 and 2803 troughs are essentially indistinguishable after this scaling. The assumption of unity covering factor implicit to the apparent optical depth method clearly fails. As seen in projection on the sky against the spatially extended galactic continuum, the low-ionization outflow does not uniformly cover the source.

### 3.1.2. Relative Shape of Mg $\text{i}$ and Mg $\text{ii}$ Absorption Troughs

In Figure 4, we scale the depth of each Mg $\text{i}$ absorption trough to facilitate comparison to the shape of the Mg $\text{i}$ absorption trough. Based on our inspection of the data, we argue that the Mg $\text{i}$ and Mg $\text{ii}$ absorption troughs trace gas with the same kinematics.

**FSC2349+24:** The FSC2349+24 spectrum shows strong Mg $\text{ii}$ and Mg $\text{i}$ emission. The 2796 emission fills in part of the Mg $\text{ii}$ 2796, 2803 and Mg $\text{i}$ profiles at low velocity. The Mg $\text{ii}$ trough is cleanly detected to $750 \text{ km s}^{-1}$, but the Mg $\text{i}$ profile is reduced by a factor of 2.5, the Mg $\text{i}$ profile is indistinguishable from the 2796 profile at high velocity and the 2803 profile at low velocity.

**FSC1407+05:** The Mg $\text{i}$ and Mg $\text{ii}$ 2796 lines in FSC1407+05 are both detected to velocities reaching $-750 \text{ km s}^{-1}$. The Mg $\text{i}$ 2803 profile presents emission from 0 to $+250 \text{ km s}^{-1}$. The Mg $\text{ii}$ 2796 emission is diluted by the Mg $\text{ii}$ 2803 absorption at the same wavelength. The addition of the 2796 emission to the Mg $\text{ii}$ 2803 absorption trough elevates the latter between velocities $-750$ and $-500 \text{ km s}^{-1}$. At intermediate velocities less affected by blending, $-500$ to $0 \text{ km s}^{-1}$, the Mg $\text{ii}$ and Mg $\text{i}$ profiles lie right on top of each other after reducing the depth of the Mg $\text{ii}$ troughs by a factor of 2.0.

**FSC1630+15:** In FSC1630+15, the shape of the Mg $\text{ii}$ and Mg $\text{i}$ profiles are the same from 0 to $-620 \text{ km s}^{-1}$ after scaling Mg $\text{ii}$ by a factor of 2.0. Maximum absorption is offset to $-400 \text{ km s}^{-1}$. The Mg $\text{ii}$ 2796 absorption trough is detected to $-825 \text{ km s}^{-1}$. The SNR in Mg $\text{i}$ near these velocities is not adequate to detect the scaled Mg $\text{ii}$ profile, so the velocity ranges of absorption Mg $\text{i}$ and Mg $\text{ii}$ are consistent with being the same.

**FSC2349+24:** The FSC2349+24 spectrum shows strong Mg $\text{ii}$ emission. The 2796 emission fills in the bluest portion of the 2803 line profile. The 2796 trough reaches $-650 \text{ km s}^{-1}$. We...
magnesium, Mg II, is the dominant ion of Mg over a large range of density and temperature. In contrast, the Murray et al. (2007) ionization models predict a larger variation in $\chi$(Na i) from object to object, allowing a wide range of possibilities for the relative optical depth of Mg i and Na i. For comparable Mg and Na ionization fractions, i.e., $\chi$(Na i) $\approx$ $\chi$(Mg ii) where $\chi$(X$^{+}$) $\equiv$ N(X$^{+}$)/N(X), the Na i 5892 optical depth and that of the weaker Na i 5898 line will be lower than the Mg i 2853 optical depth.

The blending of the Na i 5892, 98 lines complicates the direct, model-independent comparison. In Figure 5, we use the Mg i profile as a template for both the Na i 5892 (left column) and 5898 (right column) absorption troughs. In three of the ULIRGs, the depth of the Na i and Mg i absorption troughs are similar at minimum intensity. The two ULIRG spectra with strong He i 5877 emission present shallower troughs in Na i relative to Mg i, which we explain in part by emission filling of the Na i troughs. We take account of the He i 5877 emission filling in Section 3.3 and estimate comparable maximum outflow speeds in Na i, Mg i, and Mg ii. Surprisingly, the modeling in Section 3.3 demonstrates that the kinematics of the Na i absorbing gas are not distinguishable from that in the low-ionization UV transitions.

**FSC0039−13:** In the FSC 0039−13 spectrum, we detect Na i absorption up to $\sim$320 km s$^{-1}$. Emission filling from He i plausibly explains why the Mg i and Mg ii absorption troughs extend to higher velocity. The Mg i trough is nearly twice as deep as the bluer portion of the Na i trough (left panel) and three times deeper than the redder portion of the Na i trough (right panel). The He i emission contributes to the shallowness of the blue half of the Na i trough (relative to Mg i), but emission filling fails to explain the low intensity of the red half of the Na i trough over 1000 km s$^{-1}$ from the He i line. The deepest part of the Mg i profile at $+90$ km s$^{-1}$ matches the minimum in the Na i trough. At the wavelength corresponding to the same Doppler shift in the Na i 5892 transition, we find another local minimum in the blended, absorption trough. We postpone discussion of the relative intensities of the Na i 5892 and 5898 absorption troughs to Section 3.3 because both transitions contribute to the absorption at minimum intensity.

**FSC1009+47:** In the FSC1009+47 spectrum, the Na i absorption trough extends from roughly the systemic velocity to about $\sim$450 km s$^{-1}$. At the coarse level of comparison allowed by the poor spectral SNR, the shapes of Na i 5892 and Mg i profiles match without any scaling. Better SNR at Mg ii shows the outflow reaches $\sim$800 km s$^{-1}$.

**FSC1407+05:** The Na i absorption is detected to $\sim$650 km s$^{-1}$, close to (within one resolution element of) the maximum absorption velocity detected in Mg i and Mg ii. The Na i and Mg i absorption trough shapes are very similar, with the latter being slightly deeper.

**FSC1630+15:** In FSC1630+15, the Mg i profile provides a good description of the Na i absorption trough with no scaling of the Na i 5892 or 5898 lines. Absorption is detected in both troughs to $\sim$600 km s$^{-1}$. The SNR’s of the Na i and Mg i spectra do not allow detection up to the maximum velocity detected in Mg ii.

**FSC2349+24:** In FSC2349+24, He i emission fills part the blue-end, $v < -250$ km s$^{-1}$, of the Na i absorption trough.

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Footnote 6: Depletion quoted for cool interstellar medium of the Galaxy (Savage & Sembach 1996).
The Mg\textsc{i} and Na\textsc{i} troughs have similar intensity at other velocities.

### 3.1.4. Relative Strength of the Fe\textsc{ii} and Mg\textsc{ii} Absorption Troughs

The oscillator strength of Fe\textsc{ii} 2600 is about 3.5 times higher than that of Fe\textsc{ii} 2587. The similar shape of the two blueshifted Fe\textsc{ii} troughs requires even the Fe\textsc{ii} 2587 transition to be optically thick at the highest velocities measured in the outflow. Iron has only a slightly lower cosmic abundance than Mg. Using cosmic abundance ratios, the optical depth of Fe\textsc{ii} 2600 will be 57% that of Mg\textsc{ii} 2803 for comparable depletion and ionization corrections. We directly compared the shape of the Fe\textsc{ii} 2600, Fe\textsc{ii} 2587, Mg\textsc{ii} 2796, and Mg\textsc{ii} 2803 absorption troughs below, omitting the two objects with low SNR near Fe\textsc{ii}. We find similar intensity in all four troughs at comparable velocity. Section 3.3 presents quantitative, but model dependent, fits.

**FSC0039−13:** From $-600$ km s\(^{-1}\) to $+200$ km s\(^{-1}\), $I_B \approx I_R$ for the Fe\textsc{ii} 2587, 2600 troughs. The Fe\textsc{ii} 2587 trough does not present the dip seen in Fe\textsc{ii} 2600 from $-800$ to $-600$ km s\(^{-1}\). We do not detect the Mn\textsc{ii} 2576 line, so absorption from the weaker Mn\textsc{ii} 2594 transition does not produce the blue dip in Fe\textsc{ii} 2600. We also exclude blending with excited, photospheric lines based on the location of such lines in the stellar spectra shown in Figure 3. We attribute the discrepancies in the Fe\textsc{ii} profile shape over a small velocity range to a combination of statistical and systematic errors in the data, where continuum fitting uncertainties dominate the systematic error in this spectral region. The Fe\textsc{ii} 2600 trough is identical to the Mg\textsc{ii} trough (to within the error bars) over the velocity range from $-600$ km s\(^{-1}\) to $+400$ km s\(^{-1}\). The Fe\textsc{ii} 2587 trough varies in lock step with the Mg\textsc{ii} trough from $-900$ km s\(^{-1}\) to $+200$ km s\(^{-1}\). We conclude that the Fe\textsc{ii} and Mg\textsc{ii} absorption troughs sample gas with similar kinematics.

**FSC1009+47:** The Mg\textsc{ii} profile for FSC1009+47 provides a good description of the blue wing of the Fe\textsc{ii} 2600 trough with no scaling. The Fe\textsc{ii} 2587 trough is slightly shallower.

**FSC1407+05:** The blueshifted wing of the FSC1407+05 Fe\textsc{ii} spectra at $v < -200$ km s\(^{-1}\) shares the shape of the Mg\textsc{ii} profile, but the Fe\textsc{ii} troughs are slightly shallower (amplitude reduced by 1.3 in 2600 and 1.6 in 2587). Both Fe\textsc{ii} troughs lie well below the Mg\textsc{ii} troughs from $-100$ km s\(^{-1}\) to $+100$ km s\(^{-1}\). The Mg\textsc{ii} 2803 profile presents a weak, but significant, emission
bump from 0 to +200 km s\(^{-1}\). No Fe\(^{II}\) emission is detected, so the Fe\(^{II}\) absorption troughs will look broader than the Mg\(^{II}\) troughs. The Mg\(^{II}\) absorption trough may share the kinematics of the low-velocity Fe\(^{II}\) trough but be filled in by emission.

3.2. Parametric Descriptions of the Absorption Troughs

In the spectral regions where the Mg\(^{II}\) \(\lambda 2796, 2803\) absorption troughs can be directly compared, their intensities are nearly equal, \(I_R \approx I_B\). Since the galaxy (continuum) likely subtends a large angle relative to that of an individual shell fragment or cloud, we might expect variation in the properties of the absorbing material as a function of the spatial and/or velocity coordinates in the outflow. A number of methods have been developed to parameterize the relative geometry of the outflow and continuum source. We apply the most common method to the absorption troughs from FSC0039–13 and FSC1630+15, which show no sign of emission filling and little blending of the \(\lambda 2796\) and \(\lambda 2803\) lines. We then explain why two other parameterizations fail to describe the distribution of outflowing gas.

3.2.1. Pure Partial-covering Model

An approach used extensively for quasar winds (Arav et al. 2001; Arav et al. 2005; Arav et al. 2008) is to assume that a fraction \(1 - C_f(v)\) of the area of the continuum source is free of absorption at velocity \(v\); and the optical depth distribution in front of the covered part of the source is constant. For this parameterization, the line intensities are given by

\[
I_R(v)/I_0 = 1 - C_f(v) + C_f e^{-\tau(v)}
\]

\[
I_B(v)/I_0 = 1 - C_f(v) + C_f e^{-2\tau(v)},
\]

where \(\tau(v)\) is the optical depth at velocity \(v\) in the weaker line, here Mg\(^{II}\) \(\lambda 2803\). The coefficient in the argument of the exponential in Equation (6) depends on the relative oscillator strengths and wavelengths of the doublet transitions. We binned the blue and red profiles to the spectral resolution; and then computed the covering fraction

\[
C(v) = \frac{I_R^2 - 2I_R + 1}{I_B - 2I_R + 1},
\]

where the continuum has been normalized to unity, \(I_0 = 1\). At velocities where measurement errors produced unphysical line intensities, \(I_R < I_B\) or \(I_R^2 > I_B\), we set the covering fraction to \(C(v) = 1 - I_R/v\) or \(C(v) = 1.0\), respectively. By substitution, the optical depth is

\[
\tau(v) = \ln \left( \frac{C(v)}{I_R(v)/I_B + C(v) - 1} \right).
\]

Where statistical fluctuations result in \(I_R < I_B\), measurement of the optical depth is not constrained. At velocities where \(I_R \approx I_B\), both transitions must be optically thick; and this method cannot discriminate an optical depth of 3 from 30 in galaxy spectra of typical quality. The limited spectral resolution and low SNR of these data leave open the possibility of substantial systematic errors in our best estimate \(\tau(v)\). We will refer to this method as the pure partial covering scenario with velocity-dependent covering fraction.

Figure 6 shows the covering fraction of low-ionization absorption derived this way varies significantly across the trough. Our analysis necessarily neglects components narrower than 100 km s\(^{-1}\), which may contribute to the total gas column but are unconstrained by our spectra. The covering fraction is near unity only where the trough is black. In the FSC0039–13 spectrum, this maximum coverage is near the systemic velocity regardless of whether we remove a symmetric, zero-velocity absorption component before computing \(C(v)\). In FSC1630+15, the velocity of the low-ionization gas with the highest covering fraction is between 300 and 400 km s\(^{-1}\). The covering fraction falls steadily with increasing outflow speed in FSC0039–13, reaching 35% at 500 km s\(^{-1}\). Similarly, away from the velocity where the absorption trough presents minimum intensity, \(C_f(v)\) declines in FSC1630+15. The residual intensity correlates with the derived covering fraction. We conclude that the shape of the absorption trough, \(I(v)\), is strongly influenced by the velocity dependence of the covering fraction of low-ionization gas in the outflow.

Figure 7 compares the Mg\(^{II}\) \(\lambda 2803\) optical depth, \(\tau(v)\), to \(C_f(v)\). The low-ionization gas at velocity \(v \sim -600\) km s\(^{-1}\) is apparently optically thick in the Mg\(^{II}\) transitions. At higher speeds, the blending of the blue wing of the Mg\(^{II}\) \(\lambda 2803\) trough with the Mg\(^{II}\) \(\lambda 2796\) line prevents a unique comparison of \(I_R(v)\) to \(I_B(v)\). The solution to Equation (8) for FSC0039–13 and FSC1630+15 indicates that \(\tau(v)\) increases by a factor of \(2\) and \(1.5\), respectively, as the covering fraction grows by a similar factor. Such a trend is physically plausible, even probable, but is not required by the data. The method only returns a lower limit on optical depth, \(\tau \gtrsim 3\). In our spectra, optical depths of 3, 30, and 300 yield essentially identical line profiles; in contrast, damping wings (not seen) would distinguish \(\tau \gtrsim 10^4\). The lower limits on the optical depth, \(\tau(v)\), determines the lower limit on the ionic column density in the outflow at a given velocity. Applying Equation (1) from Arav et al. (2001) to the optical depth in the Mg\(^{II}\) \(\lambda 2803\) transition,

\[
\mathcal{N} [\text{cm}^{-2}] = \frac{3.7679 \times 10^{14}}{\lambda_0 [\text{Å}] f} \int \tau(v) dv,
\]
unphysical intensity ratios, \( IB > I_R \), we binned the Mg \( \text{ii} \) absorption troughs to the outflow near the systemic velocity; but the fit to the outflow portion of Figure 7. optical depth of the Mg \( \text{ii} \) \( \lambda 2803 \) line vs. Mg \( \text{ii} \) covering fraction. We binned the Mg \( \text{ii} \) absorption troughs to the spectral resolution and then computed \( C_i(v) \) and \( \tau(v) \) from Equations (7) and (8). Triangles and pentagons represent FSC0039–13 and FSC1630+15, respectively. Where statistical errors led to unphysical intensity ratios, \( IB > I_R \), no upper bound on the optical depth could be obtained; and no results are shown. Removal of a symmetric, zero-velocity component in FSC0039–13 assigns zero covering fraction and optical depth to the outflow near the systemic velocity; but the fit to the outflow portion of the trough barely changes (open symbols). The data allow, but do not require, regions of the absorption trough with higher covering fraction to have higher optical depth.

we estimate total ionic column densities of \( N(\text{Mg \text{ii}}) > 6.4 \times 10^{14} \) cm\(^{-2} \) and \( > 4.28 \times 10^{14} \) cm\(^{-2} \) toward FSC0039–13 and FSC1630+15, respectively.

3.2.2. Inhomogeneous Absorption

The pure partial covering scenario with velocity-dependent covering fraction is just one particular two-parameter \( (C_I, \tau) \) description of the relative intensities of the doublet troughs. With just two absorption troughs to fit, other two-parameter models would also exactly fit the data. A real test of the model requires spectra covering additional transitions from the same ion, which is not possible with our data. We can, however, calculate parameter values for other models and examine how they change our view of the distribution of low-ionization gas in the outflow.

One such model is inhomogeneous absorption across the source. This is appealing for AGN outflows because sharp edges in the spatial distribution of absorbing gas appear unrealistic because the gas lies at distances thousands of times greater than the size of the AGN emission source (de Kool et al. 2002). Arav et al. (2005) present a simple model, where the optical depth distribution across a uniform surface brightness source varies as \( \tau(v, x) = \tau_0(v)x^a \), where \( x \) describes the location (in the plane of the sky) across the projected area of the source; and \( x \) is confined to the range \([0, 1]\). To produce similar intensities in the Mg \( \text{ii} \) \( \lambda 2796 \) and \( \lambda 2803 \) lines, they require the function \( \tau(x) \) be steep, e.g., \( a \gtrsim 8 \). A high value of the exponent works because it yields a factor of two change in the optical depth over a relatively small number of spatial elements, \( x \), resulting in \( I(2x) \approx I(x) \). For even moderately large values of \( \tau_0 \), the optical depth will be low over at least a few tenths of the source area, and the absorption troughs will not be black.

In the ULIRG outflows, \( I_R \approx I_B \) over a wide velocity range; but the Mg \( \text{ii} \) troughs are nearly black over a smaller velocity range. The inhomogeneous absorber model requires unphysically large optical depths to reproduce these Mg \( \text{ii} \) absorption troughs. Starburst outflows also do not present the problem with pure-partial covering as do AGN outflows. The rotation observed across some low-ionization outflows suggest the outflowing gas lies within a few kpc of the galaxy (Martin 2006). Hence, we find no reason to adopt an inhomogeneous-absorption model for ULIRG outflows.

3.3. Fitting Velocity Components to the Absorption Troughs

The direct method of the previous section cannot be applied to the absorption troughs in which the doublet transitions blend together and/or the absorption trough blends with one or more emission lines. A quantitative description of these absorption troughs requires fitting the parameters of functions describing each spectral component. A covering fraction, Doppler parameter, optical depth at line center, and Doppler shift describe the attenuation of the continuum by one component, or cloud, at every wavelength, \( I_j(\lambda)/I_0 = 1 - C_j e^{-\tau_j(\lambda)} \). When the absorption trough is a blended doublet, the optical depth at a given wavelength may include significant contributions from each transition, and we add the doublet optical depths at that wavelength. At any particular velocity, the two transitions of the doublet must have the same \( C_I, b, \) and Doppler shift; and atomic physics fixes the ratio of their optical depths. At the systemic velocity of the He \( \text{i} \) \( 5877 \) and Mg \( \text{ii} \) emission lines, we fitted the amplitude of Gaussian intensity profile with velocity width matched to that measured for H\( \alpha \).

The relative intensities of the Mg \( \text{ii} \) and Fe \( \text{ii} \) doublet troughs constrain these transitions to be optically thick, setting a firm lower limit on the optical depth, \( \tau_0 \gtrsim 3 \), at line center. The blue skew of the absorption troughs requires at least two velocity components. When we fitted such models, however, we found a number of parameter degeneracies. We could describe the velocity width of each trough by adding additional velocity components, increasing the Doppler parameter, or further increasing the optical depth of individual components. For example, \( \tau_0 \) can be made arbitrarily large by simply allowing the Doppler parameter \( b \) to shrink; and the product \( b\tau_0 \) of a component can be made smaller (or larger) by adding (or removing) additional velocity components. Previous studies (Rupke et al. 2005a; Martin 2005, 2006) chose the minimum number of velocity components required to describe the Na \( \text{i} \) absorption troughs.

Simulations of winds show that a single sightline intersects multiple shell fragments (Fujita et al. 2009). And high resolution spectra of starburst galaxies resolve some broad absorption troughs into components (Schwartz & Martin 2004). With this picture in mind, we assume a sightline intersects a number of velocity components, where these structures partially overlap spatially. To allow for the possibility that some of the sightlines within the beam intersect different structures, we adopt the partial overlap model introduced by Rupke et al. (2005a). Each of the \( n \) successive velocity components attenuates the continuum (and the preceeding components) such that \( I(v) = \prod_{j=1}^{n} I_j(v) \). A Maxwellian distribution provides a reasonable description of the atomic velocities within each velocity component, so a Gaussian function models the optical depth distribution, \( \tau(\lambda) = \frac{\tau_0 e^{-(\lambda-\lambda_0)^2/\Delta\lambda^2}}{(\lambda_0 b/c)^2} \), of each component. The covering fraction is constant across a given component but varies from one component to the next. The Doppler parameter, \( b \), describes the turbulent motion along the line-of-sight.
in a given gas cloud. For purposes of illustration, we fix the Doppler parameter at $b \equiv 50 \text{ km s}^{-1}$ for all velocity components. For a typical minimum value of $\tau_0 \sim 3$, this choice yields a line width at half the trough depth around 100 km s$^{-1}$, consistent with the spectral resolution. We add velocity components until the fit statistic stops improving or a component becomes weaker than the detection limit. With this Doppler parameter, we need 6 velocity components to fit the Mg ii absorption trough in FSC 0039–13 and 5 velocity components for the other 4 galaxies.

Allowing $\tau_0$ to vary among velocity components revealed no obvious trends with outflow velocity. The optical depth at the center of each component must be greater than three for the doublet transitions, but the probability distribution is very asymmetric with a significant tail reaching values $\sim 50$ times higher than the minimum value. (See the Monte Carlo approach described by Sato et al. 2009 for describing uncertainties in optical depth.) We obtained an equally good fit statistic when we required a single value of $\tau_0$ describe all the velocity components. This assumption of a velocity-independent optical depth is our most dubious prior, and we discuss how to improve upon it in Section 3.3.3. We adopt this approach for the purposes of comparing the velocity dependence of the gas covering fraction among objects and among transitions. For optically thick velocity components, the exact value of $\tau_0(v)$ has little effect on $C_f(v)$. Our approach assumes the velocity dependence of the covering fraction determines the trough shape.

We first fit $C_f(v)$ and the minimum value of the optical depth to the Mg ii absorption troughs. We found that the same kinematic components described the Fe ii and Mg i absorption troughs well. In Section 3.3.1, we show that the minimum optical depth in the weak lines raises our best estimate of the minimum optical depth in Mg ii. We test the hypothesis these velocity components also describe the blended, Na i absorption troughs and compare covering fractions among species. Table 3 summarizes the fitted parameters. Figure 8 shows the resulting fits for Mg ii, Mg i, and Na i. We plot Fe ii separately in Figure 9.

### 3.3.1. Fitted Optical Depth

For Mg ii, we can compare the ionic column inferred from the fitted partial-overlap model to those estimated in Section 3.2.1. With $b \equiv 50 \text{ km s}^{-1}$, we construct the same ionic columns by setting $\tau_0(\text{Mg ii} 2803) = 2.75$, which implies an integrated optical depth across each velocity component of

| FSC (1) | V(km/s) (2) | $C_f$(Mg ii) (3) | $\tau_0$(2803) (4) | $\chi^2$(Mg ii) (5) | $C_f$(Mg i) (6) | $\tau_0$(2853) (7) | $\chi^2$(Mg i) (8) | $C_f$(Na i) (9) | $\tau_0$(Na i) (10) | $\chi^2$(Na i) (11) | $C_f$(Fe ii) (12) | $\tau_0$(Fe ii) (13) | $\chi^2$(Fe ii) (14) |
|---------|------------|-----------------|-------------------|---------------------|----------------|-------------------|-------------------|-----------------|-------------------|-----------------|-----------------|-------------------|-----------------|
| 0039–13 | 83         | 0.74 ± 0.03     | 17.7              | 1.136 ± 0.22        | 4.147 ± 0.17      | 0.02 ± 0.04       | 4.235 ± 0.99       | 0.04 ± 0.04      | 2.335 ± 0.72       | 0.05 ± 0.02      | 2.335 ± 0.50       | 0.06 ± 0.04       | 2.342 ± 0.28      |
| 0039–13 | 13         | 0.47 ± 0.06     | 17.7              | 1.136 ± 0.20        | 4.147 ± 0.11      | 0.02 ± 0.04       | 4.235 ± 0.72       | 0.05 ± 0.02      | 2.335 ± 0.72       | 0.05 ± 0.02      | 2.342 ± 0.50       | 0.06 ± 0.04       | 2.342 ± 0.28      |
| 0039–13 | 13         | 0.45 ± 0.05     | 17.7              | 1.136 ± 0.24        | 4.147 ± 0.05      | 0.02 ± 0.04       | 4.235 ± 0.72       | 0.05 ± 0.02      | 2.335 ± 0.72       | 0.05 ± 0.02      | 2.342 ± 0.50       | 0.06 ± 0.04       | 2.342 ± 0.28      |
| 0039–13 | 13         | 0.33 ± 0.02     | 17.7              | 1.136 ± 0.19        | 4.147 ± 0.09      | 0.02 ± 0.04       | 4.235 ± 0.72       | 0.05 ± 0.02      | 2.335 ± 0.72       | 0.05 ± 0.02      | 2.342 ± 0.50       | 0.06 ± 0.04       | 2.342 ± 0.28      |
| 0039–13 | 13         | 0.27 ± 0.02     | 17.7              | 1.136 ± 0.21        | 4.147 ± 0.07      | 0.02 ± 0.04       | 4.235 ± 0.72       | 0.05 ± 0.02      | 2.335 ± 0.72       | 0.05 ± 0.02      | 2.342 ± 0.50       | 0.06 ± 0.04       | 2.342 ± 0.28      |

Notes. (1) Galaxy. (2) Doppler shift of component in km s$^{-1}$. All components have a Doppler parameter $b \equiv 50 \text{ km s}^{-1}$, or $b_{90} \equiv 1$. (3) Fitted covering fraction for Mg ii (4) Minimum optical depth at line center for Mg ii 2803. The lower limit on the ionic column density is $N(\text{Mg ii}) > 3.90 \times 10^{13} \text{ cm}^{-2} b_{90}$. (5) Fit statistic for the Mg ii doublet. (6) Fitted covering fraction for Mg i (7) Minimum optical depth at line center for Mg i 2853. The lower limit on the ionic column density is $N(\text{Mg i}) > 6.39 \times 10^{12} \text{ cm}^{-2} b_{90}$. (8) Fit statistic for the Mg i line. (9) Fitted covering fraction for Na i (10) Minimum optical depth at line center for Na i 5898. The lower limit on the ionic column density is $N(\text{Na i}) > 1.78 \times 10^{13} \text{ cm}^{-2} b_{90}$. (11) Fit statistic for the Na i doublet. (12) Fitted covering fraction for Fe ii. (13) Minimum optical depth at line center for Fe ii 2600. The lower limit on the ionic column density is $N(\text{Fe ii}) > 1.87 \times 10^{14} \text{ cm}^{-2} b_{90}$. (14) Fit statistic for the Fe ii doublet.
Figure 8. Fitted covering fraction of absorbing gas in each velocity component (red) and, when required, emission lines (green). Left column: fitted Mg ii absorption troughs. All velocity components have the Doppler parameter fixed at $b = 50$ km s$^{-1}$ and an optical depth at line center of $\tau_0$. Middle column: velocity components fitted to the Mg ii absorption troughs. The Doppler shift and $b$ of each component matches the corresponding Mg ii component, and we fitted the velocity-dependent covering fraction $C_f(v)$ and minimum $\tau_0$. Right column: velocity components fitted to blended Na i doublet trough. The Doppler shift and $b$ value of each component matches the corresponding Mg ii component; we fit a velocity-dependent covering fraction $C_f(v)$ and the minimum $\tau_0$. Dotted line shows the relative intensity of sky emission; an additive constant of 0.4 has been applied to the normalized sky intensity for display purposes. Although the fitted models are not unique; they demonstrate that all three line profiles can be described with the same kinematic components.

The implied column densities, $N[\text{cm}^{-2}] = \frac{1.13 \times 10^{20} \tau_0 \lambda_0 [\text{Å}]}{\lambda_0 [\text{Å}]^2 f}$, add up to $N(\text{Mg} \, \text{ii}) = 6.4 \times 10^{14}$ cm$^{-2}$ for the 6 components describing FSC 0039−13. This model has the minimum $\tau_0$ that comes close to describing the Mg ii absorption trough given our prior on $b$. The reduced chi-squared statistic improves significantly, from 1.425 to 1.143, when $\tau_0$ is increased to 5. The fit statistic does not get much better as $\tau_0$ is increased up to $\sim 50$, so we consider $\tau_0 \approx 5$ to be our lower limit when the Mg ii absorption is considered independently. The pure partial-covering method also provided only a lower bound on $\tau_0(\text{Mg} \, \text{ii})$ due to saturation and low spectral SNR.

Based on inspection of the Fe ii absorption troughs, we argue that the actual Mg ii 2803 optical depths are 2 to 3 times larger than the minimum required to fit the doublet. For a cosmic abundance ratio of gas-phase iron to magnesium, the optical depth in the stronger iron line is $\tau_0(\text{Fe} \, \text{ii} 2600) \sim 0.57 \tau_0(\text{Mg} \, \text{ii} 2803) \chi(\text{Fe} \, \text{ii})/\chi(\text{Mg} \, \text{ii})$. For the weaker Fe ii line, $\tau_0(\text{Fe} \, \text{ii} 2587)$ will always be 3.5 times lower than $\tau_0(\text{Fe} \, \text{ii} 2600)$. It follows that $\tau_0(\text{Fe} \, \text{ii} 2587)$ will be slightly less than unity if $\tau_0(\text{Mg} \, \text{ii} 2803) = 5$ and if our estimate for the relative ionization correction, $\chi(\text{Fe} \, \text{ii}) \approx \chi(\text{Mg} \, \text{ii})$, is correct. This model predicts the Fe ii (2587) absorption trough is much shallower than the Fe ii (2600) trough as illustrated for FSC 0039−13 and FSC 1630+15 in panels a and e, respectively, of Figure 9.

For FSC 0039−13, this model spectrum is inconsistent with the shallow Fe ii (2587) trough, which requires $\tau_0(\text{Fe} \, \text{ii} 2587) \sim 3$ or larger. As addressed further in Section 3.4, a difference this large in ionization fraction is unlikely given predictions from photoionization modeling. We conclude that the actual central optical depth in Mg ii 2803 is closer to 18 (than 5). Figure 9(d) shows that the resulting Mg ii fit is really indistinguishable from

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7 Although Fe and Mg have similar 1st and 2nd ionization potentials, the ionization equilibrium is complicated by the larger role of dielectronic recombinations for Fe (Shull & Van Steenberg 1982). The Murray et al. (2007) photoionization calculation for outflows indicates that the largest difference in the Mg ii and Fe ii ionization fractions occurs at high gas density, $6 \times 10^5$ cm$^{-3}$, for the softest SEDs, when $\chi(\text{Fe} \, \text{ii})$ can be twice as large as $\chi(\text{Mg} \, \text{ii})$. 
We argued that $\tau$ deeper than the prediction from the minimum $\tau$ likely to us that Mg fraction must be less than 1 to 2 percent to determine if other lines might be blended with the Fe in the UVBLUE spectra of synthesized stellar populations to constrain the Mg line. We identified resonance transitions from Mn and it is preferable to that in panel a. The Mn line is not detected. The SNR around the Fe $\tau$ absorption trough, the models shown in Figure 8 have $\tau_0$($\tau_1$) = 3 for 4 galaxies and 5 for FSC 2349+24. The ratio of these lower limits to those for $\tau_0$($\tau_1$) = 3, the Fe $\tau$ absorption trough requires $\tau_0$($\tau_1$) = 3, the Fe $\tau$ lines are not nearly strong enough. (f) FSC 1407+05. Assumes the minimum Mg optical depth that fits Mg $\tau$ = 5. With $\tau_0$($\tau_1$) = 3, the Fe $\tau$ lines are not strong enough. The green line shows the fitted emission component. (g,h) FSC 1407+05. Fitting the Fe $\tau$ trough requires $\tau_0$($\tau_1$) = 5.7, even when a 7th velocity component is included. Increasing $\tau_0$($\tau_1$) = 10 is not inconsistent with the Mg $\tau$ troughs. These results suggest the Mg optical depth is likely a factor of 2 to 3 larger than the minimum required by the data.

Figure 9. Constraints on optical depth from comparison of Fe $\tau$ and Mg $\tau$ absorption troughs. The Fe $\tau$ model in the left panel has $\tau_0$($\tau_1$) = 0.56$\tau_0$($\tau_1$) = 2803. The top and bottom two panels show FSC 0039–13 and FSC 1407+05, respectively. (a,b) FSC 0039–13. Assumes the minimum Mg optical depth that fits Mg $\tau$ = 2795 and 2803, i.e., $\tau_0$($\tau_1$) = 5. With $\tau_0$($\tau_1$) = 3, the Fe $\tau$ lines are not nearly strong enough. (c,d) FSC 0039–13. Fitting the Fe $\tau$ trough requires $\tau_0$($\tau_1$) = 17.6 is not inconsistent with the Mg $\tau$ troughs. (e,f) FSC 1407+05. Assumes the minimum Mg optical depth that fits Mg $\tau$ = 2795 and 2803, i.e., $\tau_0$($\tau_1$) = 5. With $\tau_0$($\tau_1$) = 3, the Fe $\tau$ lines are not quite strong enough. The green line shows the fitted emission component. (g,h) FSC 1407+05. Fitting the Fe $\tau$ trough requires $\tau_0$($\tau_1$) = 5.7, even when a 7th velocity component is included. Increasing $\tau_0$($\tau_1$) = 10 is not inconsistent with the Mg $\tau$ troughs. These results suggest the Mg optical depth is likely a factor of 2 to 3 larger than the minimum required by the data.

For FSC 1630+15, the Fe $\tau$ absorption trough is slightly deeper than the prediction from the minimum $\tau_0$($\tau_1$) = 2803 model. Increasing $\tau_0$($\tau_1$) = 2803) to 10 and 1.6 provides an acceptable fit; larger optical depths make the Fe $\tau$ trough deeper than observed in this case. We examined the UVBLUE spectra of synthesized stellar populations to determine if other lines might be blended with the Fe $\tau$ line. We identified resonance transitions from Mn, marked in Figure 3. The Mn $\tau$ transition does not cause the depression seen at slightly shorter wavelengths because the stronger Mn $\tau$ line is not detected. The SNR around the Fe $\tau$ 2587, 2600 lines is not adequate for further comparison in the other objects.

Our observation of a single Mg transition does not directly constrain the Mg $\tau$ optical depth. The optical depth in Mg is

$$\tau_0(\text{Mg } 2853) = 6.1 \tau_0(\text{Mg } 2803) \chi(\text{Mg } 1)/\chi(\text{Mg } 2). \tag{11}$$

We argued that $\tau_0(\text{Mg } 2)$ reaches at least $\sim$ 10–18, so the neutral Mg fraction must be less than 1 to 2 percent to produce an optically thin Mg $\tau$ trough. It seems more likely to us that Mg $\tau$ is optically thick. The covering fraction then determines the shape of the Mg $\tau$ absorption trough, $I(\nu) \approx 1 - C_\nu(\nu)$. Since covering fraction dictates both the Mg $\tau$ and Mg $\tau$ absorption trough shape, they have a similar appearance, as shown quantitatively in the middle column of Figure 8. That the Mg $\tau$ troughs are deeper indicates that only a fraction of the cloud volume contains much neutral Mg.

The fitted models in Figure 8 assume equivalent kinematic components for Na and Mg. For a cosmic abundance ratio, $N(\text{Mg})/N(\text{Na}) = 19.07$, the Na optical depth, $\tau_0(\text{Na } 15898) = 0.115 \tau_0(\text{Mg } 2803) \chi(\text{Na } 1)/\chi(\text{Mg } 2)$, will be lower than that of Mg $\tau$ for similar ionization fraction. In Section 3.4, we argue that $\chi(\text{Na } 1)/\chi(\text{Mg } 2)$ may be of order unity for soft spectral energy distributions (SED) with $L_{5100}^\nu/L_{5100}^\nu \sim 10^{-5}$ but will vary among outflows, dropping to $\chi(\text{Na } 1) = 0.001$ for hard starburst SEDs.

When the weaker Na line is optically thin, the fitted Na models fall well short of the observed intensity in the redder half of the absorption trough. The models shown in Figure 8 have $\tau_0(5898)$ = 3 for 4 galaxies and 5 for FSC 2349+24. The ratio of these lower limits to those for $\tau_0(\text{Mg } 2803)$ in the same objects is 0.3 or more. Since the photoionization models, and consideration of depletion factors, disfavor a situation with $\chi(\text{Na } 1)/\chi(\text{Mg } 2) > 1$, the moderate optical thickness required for Na suggests $\tau_0(\text{Mg } 2803)$ could easily be a factor $\sim$ 2 higher than that required by $\tau_0(\text{Fe } 2587)$. As discussed in
Section 3.1.1, however, the Na i and Mg ii absorption troughs could probe physically distinct regions of the outflow.

3.3.2. Constraints on Covering Fraction

The attraction of forcing the same kinematic components is that we can directly compare covering fraction of different species as a function of velocity, as summarized in Table 3. The fitted $C_f$ values for the Fe ii velocity components come out similar to the values for Mg ii. The maximum covering fraction in low-ionization gas occurs at minimum intensity by construction, and we again associate the velocity of maximum covering fraction with the speed of swept-up shells at breakout. The covering fraction decreases towards higher outflow velocity.

Independent of any particular model, the shallow troughs of Mg i relative to Mg ii require a lower covering factor for the former at every velocity. The $\chi^2$-fitting approach demonstrates that the shape of the Mg i absorption trough can be well described by the same velocity components as the Mg ii troughs and further quantifies the change in covering fraction. Figure 10 compares the fitted covering fractions for Mg ii and Mg i. The covering fraction for neutral gas remains roughly half that of the Mg ii at all velocities. Given the similar kinematics but constant offset in projected area, we suggest that the Mg i absorption originates in denser regions of larger structures traced by Mg ii.

The fitted Na i covering fraction is similar to that fitted to Mg i for each velocity component. Sodium and magnesium have similar first ionization potentials, 5.1 eV for Na, and 7.6 eV for Mg. In the FSC0039–13 spectrum, emission filling could explain shallow Na i 5892 trough, relative to Mg i; but the emission is not broad enough to account for the shallow Na i 5898 trough. We suggested that the FSC 0039 spectrum, emission filling could explain shallow Na i 5892 trough, relative to Mg i; but the emission is not broad enough to account for the shallow Na i 5898 trough. We suggested that the FSC 0039–13 sightline intersects more of the galactic gas disk than our other observations; and the high inclination of this disk means we probe the swept-up shell where it has stalled in the disk.

The extra attenuation at high inclination would likely produce larger than average differences between near-UV and optical continuum morphology. High-resolution imaging in these bands may yield further insight into why the covering fraction of neutral, alkali metals differs by almost a factor of two between lower velocities to the same outflow rate, i.e., $\dot{M}(v)$ equal to a constant. We obtain the equivalent answer by estimating the mass flux from the highest velocity component.

For FSC 0039–13, the velocity component at 571 km s$^{-1}$ carries a mass flux of $M \approx 6 M_\odot$ yr$^{-1}$ (Mg ii) $^{-1}/R/\Delta R(R/10$ kpc) ($\Omega/4\pi$), where the lower limit comes directly from the requirement that $\tau_\odot(2587) \gtrsim 2.7$. The velocity component at 615 km s$^{-1}$ in the Fe ii absorption troughs of FSC 1407+05 requires $M \approx 5 M_\odot$ yr$^{-1}$ (Fe ii) $^{-1}/R/\Delta R(R/10$ kpc) ($\Omega/4\pi$). In Section 3.4, we will argue that the ionization corrections for Mg ii and Fe ii are of order unity. The unknown distance to the absorbing gas and radial thickness of the component leave order-of-magnitude uncertainty in the lower limit.

Comparison of cosmic abundances and atomic data indicates $r_\odot = 3$ will yield the highest mass-loss rate for Na i 5898, with Fe ii 2587 about 66% as large. To make the implied mass columns agree, the minimum optical depth in Fe ii 2587 would need to be 4.5$C_f$(Na i)/$C_f$(Fe ii)$/\chi$(Na i), or roughly 2.25$\chi$(Fe ii)/$\chi$(Na i). In Section 3.4, we find the upper bound on the correction to the minimum optical depth, 1/5$\chi$(Na i) could reach 10$^3$ for those ULIRGs with relatively hard SEDs. The lower limits on the mass fluxes likely yield an accurate picture for some systems but underestimate the true mass-flux in low-ionization gas by orders of magnitude in others.

3.4. Gas Volume Density

The volume density of the low-ionization gas varies widely among outflow models. Figures 4 and 5 of Murray et al. (2007) illustrate the sensitivity of the Mg ii and Na i ionization fractions to the gas density. Since the saturated lines provide only lower limits on the column densities of Mg i and Mg ii, we cannot directly estimate the ionization fraction, thereby constraining the volume density. The null-detection of absorption from collisionally excited levels above the ground state provides a useful upper limit on the electron density, however. The most relevant excited transitions of Fe ii$^*$ are marked in Figure 3; see Korista et al. (2008) for a summary. We compute this upper limit and then discuss how it constrains ionization fraction in the outflow.

Above the critical density, the level populations approach their Boltzmann ratio, and we can easily calculate the relative strengths of absorption lines from different energy levels. The lowest energy level above the ground state, $E = 385$ cm$^{-1}$, has the lowest critical density. Our spectra cover the second strongest line from the multiplet with this lower energy level, Fe ii$^*$ 2612.6542.

In the FSC0039–13 spectrum, we expect Fe ii$^*$ 2612.6542 to be the strongest excited line. We place an upper limit on the observed equivalent width using the continuum SNR and assuming a line-width comparable to a spectral resolution element. The 5σ upper limit on the corresponding rest-frame equivalent width is 0.40 Å. For comparison, we also fitted a single-absorption-line model with $b \approx 50$ km s$^{-1}$ and $C_f \approx 1$ to the spectrum. At the systemic velocity, we find $\tau_\odot(\text{Fe ii}$ 2612) $< 0.30$, a value typical of this spectral bandpass. We obtain a more conservative limit if we repeat this procedure where the largest continuum deviation occurs at $-850$ km s$^{-1}$; and we find $\tau_\odot(\text{Fe ii}$ 2612) $< 0.62$. This more conservative limit corresponds to a column density, $N(\text{Fe ii}$ 2$^*$) $< 6.26 \times 10^{13}$ cm$^{-2}$ per component.

The optical depth in the individual velocity components of the weakest, detected resonance line is $\tau_\odot(\text{Fe ii}$ 2587) $< 3$. Each of the 6 velocity components had $b \approx 50$ km s$^{-1}$, so
the lower limit on the column density in the ground state is \( N(\text{Fe}^{\text{II}}) > 5.61 \times 10^{14} \text{ cm}^{-2} \). Our measurements place a solid upper limit on the relative column densities in the first-excited and ground states, \( N(\text{Fe}^{\text{II}}^*/N(\text{Fe}^{\text{II}}) < 0.11 \), and likely less than 0.05. For densities well above the critical density this ratio would be \( \sim 0.75 \) with a slight dependence on temperature. Using the level population calculations from Figure 3 of Korista et al. (2008), we conservatively limit the electron density to \( \log n_e < 3.5 \) (or 3.4) for a temperature of \( (1-1.5) \times 10^4 \text{ K} \) (or \( 5 \times 10^3 \text{ K} \)), respectively. The stronger limit of \( N(\text{Fe}^{\text{II}}^*)/N(\text{Fe}^{\text{II}}) < 0.05 \), which applies if the highest density gas is at low velocity, lowers log \( n_e \) to 3.1 (or 3.0), respectively, at \( T = (1-1.5) \times 10^4 \text{ K} \) (or \( T = 500 \text{ K} \)).

The gas density is important for understanding the relationship between the hot wind and the outflow observed in UV-optical absorption lines. Photoionization equilibrium likely sets the temperature of the low-ionization gas at about \( 10^4 \text{ K} \). The density of the cool, low-ionization gas must be \( > 50 \text{ cm}^{-3} \) to be in pressure equilibrium with the hot wind, where \( P_h \gtrsim (10^7 \text{K})(0.05 \text{ cm}^{-3}) \sim 5 \times 10^5 \text{ K} \text{ cm}^{-3} \). Outflows accelerated by radiation pressure on dust grains do not require a hot wind at all (Murray et al. 2005), allowing the low-ionization gas to have much lower density. Our upper limit on the gas density does not challenge the multi-phase models.

Our result does eliminate the Murray et al. (2007) ionization models with \( n \sim 6 \times 10^4 \text{ cm}^{-3} \) or larger (see their Figures 4 and 5). We can confidently claim that Mg II is the dominant ionization state of Mg. For any reasonable starburst spectral energy distribution (SED), \( \chi(\text{Mg}^{\text{II}}) \geq 0.7 \); and the neutral fraction is less than 30%. The correction from the ionic columns of \( N(\text{Mg}^{\text{II}}) \) (and \( N(\text{Fe}^{\text{II}}) \)) to the elemental columns will be relatively minor. This knowledge of the Mg ionization balance suggests the Mg II 2853 optical depth significantly exceeds its minimum value of 3. Obtaining the same total column of Mg from the Mg II 2853 and Mg II 2803 components requires

\[
\tau_0(2853) = 6.1 \frac{\chi(\text{Mg}^{\text{II}})}{\chi(\text{Mg}^{\text{II}})} \frac{C_f(\text{Mg}^{\text{II}})}{C_f(\text{Mg}^{\text{II}})} \tau_0(2803), \tag{12}
\]

or \( \tau_0(2853) \) up to \( 5.2 \tau_0(2803) \) when \( \chi(\text{Mg}^{\text{II}}) = 0.3 \) and \( C_f(\text{Mg}^{\text{II}}) = 0.5C_f(\text{Mg}^{\text{II}}) \).

Eliminating very high density rules out a high neutral fraction of Na. Interpolating between the curves in Figure 4 of Murray et al. (2007) to a density of 1000 \( \text{ cm}^{-3} \), the Na I ionization fraction plummets from unity, when \( L_{\text{UV}}/L_{\text{IR}} \lesssim 10^{-9} \), to \( \chi(\text{Na}^{\text{I}}) \sim 10^{-3} \) when the SED hardens to \( L_{\text{UV}}/L_{\text{IR}} \sim 10^{-4} \). In contrast, only at very high gas density does the neutral Mg fraction change rapidly with spectral hardness. The ionization potential of Mg is 2.5 eV higher than that of Na.

### 3.5. Emission

Our spectrum of FSC2349+24 very clearly shows Mg II emission. The emission line appears to be a bit redshifted, but we argue that the Mg II absorption attenuates the blue side of the emission profile. The only other spectrum that definitely presents Mg II is FSC1407+05. The Mg II 2803 profile shows the emission from 0 to +250 km s\(^{-1} \). The corresponding Mg II 2796 line is less obvious because of Mg II 2803 absorption at the same wavelength. We suggested that emission filling of the Mg II trough explains the deeper absorption in the Fe II trough relative to the Mg II trough near systemic velocity.
Weiner et al. (2009) discovered Mg II emission in a subset of $z \sim 1.4$ galaxies with outflows and argued that the composite spectrum of the non-emission galaxies presented weak emission. They demonstrated the presence of the emission by fitting the red-shifted portion of the Mg II 2803 absorption trough with a symmetric absorption component at the systemic velocity. Removal of this component yielded a redshifted emission component in Mg II 2796. This technique cannot be applied to four of five galaxies in our sample because their Mg II absorption troughs present no absorption at $v > 0 \text{ km s}^{-1}$. Removing a symmetric, zero-velocity component fitted to the redshifted absorption trough in FSC0039−13 reveals no significant emission excess in Mg II 2796.

The origin of the Mg II emission is not completely clear, but we adopt the hypothesis that the Mg II lines are excited by recombination. The two objects presenting emission are classified as Sey 2 on the basis of their optical emission-line ratios, suggesting the ionizing spectrum is harder. The absence of extended Mg II emission in the 2D spectra of FSC1407+05 and FSC2349+24 rules out a scattering origin from a galaxy-scale nebula.

The fitted profiles are shown in Figure 8. In FSC1009+47, the red side of the Fe II troughs are marginally lower than those of Mg II, hinting at a hidden emission component in the latter. However, inclusion of an emission component in the model for any of the other three galaxies does not improve the fit to the Mg II absorption trough. In fact, any emission component at the systemic velocity significantly degrades the fit if the maximum intensity is more than 10% of the continuum level. We conclude that only two of the five ULIRGS present significant Mg II emission. In contrast, an He I 5876 emission improves the model for the Na I absorption trough in all five galaxies. The line is strongest in FSC0039−13, which is the only object classified as an H II galaxy in our sample.

3.6. Dynamical Ages of Targets

In the popular “cool ULIRGs $\rightarrow$ warm ULIRGs $\rightarrow$ quasars” evolutionary scenario, as suggested by Sanders et al. (1988), one expects the AGN to provide the increase in bolometric luminosity. Advanced mergers in the 1 Jy sample tend to have higher luminosity (Veilleux et al. 2002). While our sample does contain rather luminous ULIRGs, their 25-60 μm colors, see Table 1, are red enough to be classified as cool ULIRGS, i.e., $f_{25}/f_{60} < 0.2$.

Following the morphological classification scheme outlined in Veilleux et al. (2002), the most advanced mergers we observed are FSC0039−13 and FSC1407+05. These are single nuclei systems with a compact morphology and little tidal structure. The dynamically younger merger, FSC1009+47, presents tidal tails but the nuclei have coalesced. The tails extend to 29 kpc in FSC1009+47 (Veilleux et al. 2002). Our second spectrum for FSC1009+47 is extracted 44 kpc south (along the slit) of the nucleus. Veilleux et al. (2002) classify this feature as a prominent knot in a tidal arm rather than a second nucleus because it is not detected in their K’ image. Pre-merger sources with separated nuclei are rare in the 1 Jy sample, but we observed at least two such objects. FSC1630+15 is a close binary, separation 4.4 kpc (Veilleux et al. 2006); and FSC2349+24 is a wide binary, separation 14.5 kpc.

Among this small sample we found no evolutionary trends in low-ionization outflow properties. We compared the outflow properties along the sightlines to each nucleus in the double systems. The outflow was always seen in each spectrum.

4. DISCUSSION

We detected outflows in 5 ULIRGs in ground-state absorption from Na I, Mg I, Mg II, and Fe II and illustrated the remarkably similar shapes of the absorption troughs in all these transitions. We then demonstrated that the velocity dependence of the gas covering fraction determines the trough shape. Similarities in trough shape suggest these species reside in the same, low-ionization gas structures. Because Mg II and (Fe II) absorption covers a higher fraction of the continuum source, at a given outflow velocity, than do neutral Mg and Na, we argue that the absorbing clouds or filaments are not homogeneous.

The Doppler shift of the absorbing gas does not identify its position along the line-of-sight. In particular, no consensus had been reached previously as to whether the highest velocity material detected resides close to the starburst region or at much larger radii. A close connection likely exists between this neutral-atomic gas, outflowing dust, and large-scale molecular outflows. Images revealing the presence of dust and molecular gas in M82 out to a few kpc (Walter et al. 2002; Hoopes et al. 2005; Veilleux et al. 2009b) provide strong evidence for the survival (or continuous creation) of dense clouds despite ablation by the hot wind and evaporation, as described (for example) by Marcolini et al. (2005).

Along the outflow axis of M82, it remains unclear whether the denser material shares the same kinematics as the Hβ emission. The Hβ Doppler shift does increase with increasing distance along the minor axis (Heckman et al. 1990; Shopbell & Bland-Hawthorne 1998; Martin 1998), consistent with acceleration. However, we lack such well resolved, position-velocity information for most nearby (and all high-redshift) galactic outflows. In this section, we describe what the velocity dependence of the gas covering fraction may imply about the location of the low-ionization absorbing gas along the line-of-sight. We begin by considering some pedantic dynamical models, starting with the blowout of a superbubble as described by DeYoung & Heckman (1994).

4.1. Development of a Galactic Wind

The thermalized energy from supernova explosions drives a shock front through a galaxy, sweeping interstellar gas into a thin, radiating supershell (Tenorio-Tagle & Bodenheimer 1988; Shull 1993). While the growing shell remains smaller than the pressure scale height of the interstellar medium, it plows through an ambient medium of essentially uniform density; and the shell decelerates with velocity falling as $v \propto r^{-2/3}$, or equivalently $v \propto R^{-2/3}$, for a continuous injection of mechanical energy (Weaver et al. 1977). The shell mass grows linearly with the bubble volume at this stage, and the mass column through the shell grows linearly with radius

$$\dot{m}N(r) = \frac{1}{3}r \rho_0,$$

where $\rho_0$ is the average density of the ISM. During the supershell phase, the covering factor of the low-ionization gas will be unity provided the shell traps the ionization front.

Emission-line images of nearby, starburst galaxies show that supershells outgrow their host galaxies. We expect the shell to accelerate when the density gradient becomes steeper than $\rho(r) \propto r^{-2}$ (McKee & Ostriker 1988), a highly unstable situation in which a dense shell pushes on more rarefied gas. Numerical simulations show that the shell breaks up due to hydrodynamic instabilities at a few pressure scale heights (Mac Low et al. 1989). The evolution of the shell fragments
has received relatively little attention, but they are clearly one source of low-ionization gas that will absorb continuum emission. Additional sources of low-ionization gas include hydrodynamic instabilities induced by shear at the disk–wind interface (Heckman et al. 2000) and pre-existing, interstellar clouds over run by the supershell (Cooper et al. 2008).

A primary origin for the low-ionization outflows in shell fragments is appealing because it naturally explains the velocity offset of the Mg ii absorption troughs from the systemic velocity. Due to the high central concentration of gas in ULIRGs, the pressure scale-height is several times smaller than the value $h_z \sim 100$ pc typical of normal galaxies; and the blowout radius $R_0 \sim 3h_z \sim 200$ pc. By the time of blowout, the mean speed of a shell has dropped to

$$v(R) = 164 \text{ km s}^{-1} \left( \frac{L_w}{7.08 \times 10^{43} \text{ erg s}^{-1}} \right)^{1/3} \left( \frac{10^3 \text{ cm}^{-3}}{n_H} \right)^{1/3} \times \left( \frac{200 \text{ pc}}{R} \right)^{2/3},$$

(14)

where the mass per H atom is $\bar{m} = 1.4m_H$ in the ambient medium and $L_w$, the rate of mechanical energy injection, has been scaled to a SFR representative of ULIRGs, i.e., $100 M_\odot \text{ yr}^{-1}$. A shell velocity $\sim 200$ km s$^{-1}$ can describe the Doppler shift of the deepest part of the Mg ii absorption troughs in Figure 1 b-1e. A sightline at high inclination (i.e., close to the plane of the gas disk) would intersect a lower velocity shell due to the higher average gas density in the plane. We appeal to this scenario as a plausible explanation for the kinematics of the gas disk) would intersect a lower velocity shell due to the higher average gas density in the plane. We appeal to this scenario as a plausible explanation for the kinematics of the gas disk.

Numerical simulations of ULIRGs (e.g., Fujita et al. 2009) confirm that shell velocities decline to 200-300 km s$^{-1}$ by the time of blowout and suggest that, following blowout, the hot interior of the bubble accelerates outward creating a hot wind with terminal velocity $v_h \approx \sqrt{3}c_s \approx 940T_{7/2}^{1/2}$ km s$^{-1}$. Fujita et al. did not follow the shell fragments very far into the halo; they simply assumed the clouds coast outwards on ballistic trajectories. Whether or not cosmic rays (Breitschwerdt 2008; Everett et al. 2008; Socrates et al. 2008), radiation pressure, and/or the ram pressure of the hot wind further accelerates the low-ionization gas remains an important question.

Murray et al. (2005) analytically modeled low-ionization outflows accelerated by the ram pressure of a hot wind and outflows accelerated by radiation pressure. It remains challenging to observationally distinguish not only these two types of momentum-driven outflows but also the energy-conserving, ballistic trajectories. The former accelerate quickly and then coast. The latter coast for a large distance before gradually decelerating. Factors favoring radiative-driving include an empirical correlation between outflow speed and escape velocity (Martin 2005), the high dust content of ULIRGs, and the high luminosity of ULIRGs. Reasonable objections include the small number of dwarf galaxies used in the outflow speed correlation, the difficulty of coupling radiative momentum to the gas in dust-poor, lower luminosity dwarf galaxies, and evidence for the presence of hot winds in ULIRGs (V. Scintino & C. L. Martin 2010, in preparation).

For purposes of illustration, we consider acceleration by the ram pressure of a hot wind following blowout. The shell radius, $R_0$, and velocity, $v_0$, at blowout set the initial conditions at the start of the wind phase. In a spherical outflow geometry, the ram pressure drops as the inverse-square of the radial distance, so clouds accelerate over a relatively short spatial scale. The terminal velocity of any shell fragment depends on its column density, with the low columns reaching, at most, the hot wind velocity, $v_h \approx v_0$ (Martin 2005). The absorption troughs presented in this paper require the covering fraction of shell fragments to decrease with increasing velocity. This situation can be achieved by tuning the distribution of cloud column densities. The lowest column density fragments, which reach the highest terminal velocities, would need to be relatively rare, covering less area than higher column density clouds. Alternatively, the geometrical dilution of clouds offers a simpler way to achieve the desired result. We demonstrate this largely geometrical effect in Section 4.2. Further numerical work, beyond the scope of this paper, will be required to address the broader problem.

### 4.2. Geometrical Interpretation of the Velocity-Dependent Covering Fraction

To illustrate the importance of geometrical dilution, let the locus of fractures in a shell define individual clouds. Suppose, for simplicity, these clouds all have the same column density and initial velocity, equal to that of the shell just before blowout. If the area of a cloud does not change as it is moved outwards (think of a brick-like cloud), then the covering fraction of clouds decreases as $C_f(R) = C_f(R_0)(R/R_0)^γ$.

Most shell fragments are unlikely self-gravitating structures, however; and we expect them to expand as they fly outwards due to the drop in ambient pressure. The sound crossing time in a cloud is likely short enough for the cloud to maintain pressure equilibrium with the hot wind, $P_r \approx P_h$. The clouds expand adiabatically, so we can calculate their size at any outflow radius, $R$, and compare the cloud area to the that of a solid shell, thereby estimating the covering fraction, $C_f(R)$.

Mass conservation in a steady-state, constant velocity hot wind requires the density to fall as $ρ_h \propto r^{−2}$. For an isothermal hot wind, the resulting increase in the volume of low-ionization clouds is

$$V_c(R) = \left( \frac{R}{R_0} \right)^{2/γ_c} V_c(R_0),$$

(15)

where $γ_c = 5/3$ for a monatomic, ideal gas. For roughly spherical clouds, the increase in cloud volume is accompanied by an increase in cloud area, $A_c \propto V_c^{2/3}$. Defining the covering fraction as

$$\frac{C_f(R)}{C_f(R_0)} = \frac{A_c(R)}{A_c(R_0)} \left( \frac{4π R_0^2}{4π R^2} \right) \frac{1}{A_c(R_0)},$$

(16)

these relations yield a covering fraction,

$$\frac{C_f(R)}{C_f(R_0)} = \left( \frac{R}{R_0} \right)^{4/3γ_c−2},$$

(17)

that falls as $R^{−1.2}$. If the hot wind cools adiabatically, then $T_h \propto R^{−4/3}$; and the pressure falls off faster with radius. The lower pressure allows the clouds to expand faster than in the isothermal case. Repeating the steps in the previous paragraph, we find

$$\frac{C_f(R)}{C_f(R_0)} = \left( \frac{R}{R_0} \right)^{4γ_c/3−2}. \tag{18}$$

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8 Value of $L_w$ from SB99 continuous star formation model (Leitherer et al. 1999) for $1 M_\odot \text{ yr}^{-1}$ in 1 to 100 $M_\odot$ stars.
Assuming $\gamma = 5/3$ for both the hot wind and the clouds, we find

$$\frac{C_f(R)}{C_f(R_0)} = \left( \frac{R}{R_0} \right)^{-2/3}. \quad (19)$$

The low-ionization clouds cannot expand quickly enough to keep up with the geometrical dilution inherent to spherical, outflow geometry. Their covering fraction must decrease with increasing outflow radius.

4.3. Is Acceleration of the Low-Ionization Gas Required?

The absorption trough measurements require lower $C_f$ at higher velocity. Geometrical dilution produces lower covering fractions at larger outflow radii. Combining these two results implies that the gas producing the highest velocity absorption resides at the largest distance from the starburst. While we find this argument illuminating, some of the underlying assumptions should be examined.

First, the outflow geometry is uncertain. It should be roughly spherical on spatial scales larger than the galaxy, but the outflow geometry may be better described as cylindrical at blowout. We know the absorbing gas lies close to the gaseous disk in some ULIRG outflows because the outflows present rotation in Na\textsc{i} (Martin 2006). In a version of the above model with cylindrical geometry, both the covering fraction and column density of “brick-like” clouds become independent of height above the disk. The decrease in covering fraction would require other physical effects such as cloud ionization, evaporation, or ablation to become important at the higher outflow velocities.

Second, blowout may yield a distribution of cloud column densities and velocities, something three-dimensional numerical simulations may soon be able to address. The fastest fragments—whether determined by blowout, acceleration by the hot wind, or acceleration by the starburst radiation—will reach the largest distances. Our models indicate the low-ionization cloud reach their maximum distance long after the starburst activity has ceased. It follows that if we observe such outflows during the starburst phase, the highest velocity absorption will come from material at the largest radii. Our underlying explanation for the shape of the absorption troughs would remain geometrical dilution; however, acceleration of the low-ionization outflow would not be required beyond blowout.

4.4. Measurement of Terminal Velocities and Estimates of Spatial Extent

Comparison of the Mg\textsc{ii}, Mg\textsc{i}, and Na\textsc{i} absorption troughs indicates the highest velocity gas sometimes escapes detection in Na\textsc{i} and Mg\textsc{i}. For example, in FSC0039–13, we detect Mg\textsc{i} and Na\textsc{i} absorption to 300 km s$^{-1}$; but the Mg\textsc{ii} absorption demonstrates that the outflow persists to 500 km s$^{-1}$. In FSC1407+05, we measure terminal velocities of 350, 600, and 750 km s$^{-1}$ from Na\textsc{i}, Mg\textsc{i}, and Mg\textsc{ii}, respectively. We find our spectral signal-to-noise ratio insufficient to detect the higher velocity components of these outflows in Na\textsc{i} and Mg\textsc{i}.

The Mg\textsc{ii} lines allow more robust terminal velocity measurements for a number of reasons. First, the Mg\textsc{ii} 2796, 2832 transitions have a higher value of $N(X)/N_H f$ than does Na\textsc{i} 5892, 5898. Second, expected ionization corrections favor singly ionized Mg, Fe, and Na over their neutral species. Third, we find a larger cloud covering fraction for the singly ionized lines than for neutral lines.

We emphasize that the highest velocity absorption detected in Mg\textsc{ii} appears to be limited by covering fraction. At continuum $SNR \sim 10$, the absorption trough blends with the continuum where $C_f(v) \lesssim 0.1$, regardless of column density. The gas at the largest radii may well go undetected by typical absorption-line measurements. For example, if we assume unity covering fraction at $R_0$, then gas beyond $R \sim 3.2 R_0$ cannot be detected if $C_f$ falls as $R^{-2}$. In the more realistic case, $C_f \propto R^{-2/3}$, the covering fraction drops to 0.1 at $32 R_0$. For a launch radius $R_0 \approx 200$ pc, our measurement would detect gas out to 6.4 kpc. This distance exceeds the extent of the H\textsc{ii} filaments in many nearby starburst galaxies but remains considerably smaller than the recently detected soft, X-ray halos in ULIRGs (V. ScIortino & C. L. Martin 2010, in preparation). Spectroscopy of background light sources at projected separations of just a few tens of kpc from starburst and post-starburst galaxies should be more effective than line-of-sight studies for determining the spatial extent of the low-ionization outflow, but such studies need to account for the geometrical dilution of the clouds.

5. SUMMARY AND CONCLUSIONS

We presented the first comparison of optical and near-ultraviolet absorption troughs in ULIRG spectra. We detected outflows in 5 ULIRGs in ground-state absorption from Na\textsc{i}, Mg\textsc{i}, Mg\textsc{ii}, and Fe\textsc{ii}. Previous observations of ULIRG outflows have been limited to the Na\textsc{i} doublet, and blending of the Na\textsc{i} 5890, 5896 lines complicated measurement of the absorption trough shape. We summarize the primary, empirical results.

1. Comparison of the unblended, doublet components of Mg\textsc{ii} and Fe\textsc{ii} distinguish the effects of optical depth and covering fraction in determining the shape of the absorption troughs. The high optical depth in these transitions at all outflow velocities places a lower limit on the column density. The nonzero intensity requires partial coverage of the continuum source by the low-ionization gas over a broad velocity range.

2. The covering fraction in all four ions decreases as the outflow velocity increases beyond the velocity of minimum intensity, or equivalently the velocity of maximum covering fraction. At a given velocity, the Mg\textsc{i} covering fraction is roughly half that measured in Mg\textsc{ii} and Fe\textsc{ii}, and the covering fraction in Na\textsc{i} is less than or equal to that measured in Mg\textsc{i}.

3. Accounting for these differences in ionic covering fraction, and taking spectral SNR into consideration, we detect Mg\textsc{ii}, Fe\textsc{ii}, Mg\textsc{i}, and Na\textsc{i} absorption over the same velocity range. The decrease in covering fraction with increasing velocity suppresses the absorption signature of the highest velocity gas. The higher covering fraction of Mg\textsc{ii} and (Fe\textsc{ii}) yields detection to higher velocity than indicated by Mg\textsc{i} (or Na\textsc{i}). Any comparison of terminal velocities measured from Na\textsc{i} and Mg\textsc{ii} must take the bias introduced by the velocity-dependent covering fraction into consideration. Many measurements exist for Na\textsc{i} at $z \sim 0.6$, whereas ground-based, optical spectrographs can measure outflows with the Mg\textsc{ii} doublet over the broad redshift range from $0.25$ to $z \sim 2.5$. Caution should be exercised when examining evolution in outflow properties between these samples. For completeness, we point out that our spectra do not cover high-ionization transitions like O\textsc{viii} 1032, 1038, which reveal higher-velocity gas in some starburst outflows (Grimes et al. 2009).
4. The absence of Fe II lines, principally the λ2612 transition, place an upper limit on the volume density of n_e < 10^{3.5} cm^{-3}, and likely < 10^{3.1} cm^{-3}. When present in quasar outflows, low-ionization absorption troughs from excited or metastable states indicate much higher volume density n_e = 10^{4.4} cm^{-3} with less than 20% scatter (Korista et al. 2008; Arav et al. 2008). In the lower density ULIRG outflows, Mg II will be the dominant ionization state in the low-ionization outflow over a broad range of spectral hardness. In contrast, at these densities the Na I ionization fraction remains very sensitive to spectral hardness. We suggest that the harder radiation field in dwarf galaxies likely explains the lower fraction of dwarf starburst outflows detected in Na I relative to ULIRGs, which are almost always detected in Na I (Martin 2005; Rupke et al. 2005b).  
5. We found Mg II emission in two Sey 2 ULIRGs and He I emission in all spectra. These results provide new insight into the relationship of the low-ionization outflow and the hot wind. We defer physically motivated models of the absorption trough shape to another paper (C. L. Martin 2009, in preparation)) but summarize key aspects of the emerging, physical picture here.

1. We associate the velocity of maximum covering fraction with that of a swept-up shell of interstellar gas at the time of blowout. Factors motivating this interpretation include the Doppler shift of the trough minimum (0 to −400 km s^{-1}), the large width of the absorption troughs (up to 800 km s^{-1}), the column density lower limits, and results from recent numerical simulations (Fujita et al. 2009). Regardless of their physical origin, however, the large velocity width of the absorption troughs require contributions from multiple structures along the sightline. The relative shapes of the doublet troughs require these clouds or filaments to transition sharply (spatially) from opaque to optically thin gas. The neutral alkali metals reside in the same kinematic structures as the singly ionized metals but fill a smaller fraction of that volume.

2. The most significant result of our study may be the discovery of a velocity-dependent covering fraction in low-ionization outflows. The simplest interpretation is geometrical. The dilution associated with the spherical expansion of a population of absorbers causes their covering fraction to decrease with increasing radius. We showed that the adiabatic expansion of clouds in pressure equilibrium with the hot wind is not fast enough to offset this dilution. In the context of this physical scenario, our result implies that the high-velocity gas detected in the absorption trough is at larger radii than the lower velocity (and higher covering fraction) gas. This mapping between velocity and relative radius indicates allows requires acceleration of the low-ionization gas. Either shell blowout or subsequent momentum-driving by a hot wind and/or radiation pressure could cause this acceleration.

3. In an alternative scenario, the shell fragments into clouds with a wide range of column densities. Due to momentum conservation, the ram pressure of the hot wind (or radiation pressure) would accelerate the lowest column density fragments to the highest terminal velocities. This relationship might even arise from blowout alone without requiring a momentum-driven wind phase. Either way, the new empirical constraint, requiring lower covering fraction at higher velocity, would imply the covering fraction of low-ionization gas increases with increasing column density.

We find the first, geometrical explanation more appealing due to its simplicity.

4. The lower limits on Na I and Fe II column density provide the highest (i.e., strongest) lower limits on the mass outflow rate in low-ionization gas. Better limits can be obtained by either determining the Na I ionization fraction or observing bluer, Fe II transitions with lower oscillator strengths.

5. Assuming that photoionization equilibrium likely sets the temperature of the low-ionization outflow, T_e ∼ 10^4 K, the upper limit on the volume density allows the pressure of the cold outflow to be as high as P_e/k ≤ 10^7 K cm^{-3}. Tighter constraints on the volume density would be valuable, as very low density would be incompatible with pressure equilibrium with a hot wind, P_e ≈ P_h, and favor a purely radiatively driven outflow.

Our conclusion about the acceleration of the low-ionization outflow, while illustrative, is subject to an assumption about outflow geometry and a bias towards a shell origin for the low-ionization gas. Our empirical results, however, clearly challenge plausible dynamical models. Acceptable models need to reproduce the velocity dependence of the low-ionization covering fraction, explain the lower covering fraction of neutral, alkali metals relative to low-ionization species, and be consistent with the observed constants on both column density and volume density. With sufficient spectral sensitivity, all of these outflow properties can be measured over a very broad redshift range, so we expect any evolutionary effects with galaxy mass and/or cosmic time to eventually be measured.

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