THE LYα LINE PROFILES OF ULTRALUMINOUS INFRARED GALAXIES: FAST WINDS AND LYMAN CONTINUUM LEAKAGE

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\textsuperscript{1}Received 2014 November 17; accepted 2015 February 6; published 2015 April 6

ABSTRACT

We present new Hubble Space Telescope Cosmic Origins Spectrograph far-ultraviolet (far-UV) spectroscopy and Keck Echellette optical spectroscopy of 11 ultraluminous infrared galaxies (ULIRGs), a rare population of local galaxies experiencing massive gas inflows, extreme starbursts, and prominent outflows. We detect Lyα emission from eight ULIRGs and the companion to IRAS09583+4714. In contrast to the P Cygni profiles often seen in galaxy spectra, the Lyα profiles exhibit prominent, blueshifted emission out to Doppler shifts exceeding \(-1000\, \text{km}\, \text{s}^{-1}\) in three H\textsc{ii}-dominated and two AGN-dominated ULIRGs. To better understand the role of resonance scattering in shaping the Lyα line profiles, we directly compare them to non-resonant emission lines in optical spectra. We find that the line wings are already present in the intrinsic nebular spectra, and scattering merely enhances the wings relative to the line core. The Lyα attenuation (as measured in the COS aperture) ranges from that of the far-UV continuum to over 100 times more. A simple radiative transfer model suggests the Lyα photons escape through cavities which have low column densities of neutral hydrogen and become optically thin to the Lyman continuum in the most advanced mergers. We show that the properties of the highly blueshifted line wings on the Lyα and optical emission-line profiles are consistent with emission from clumps of gas condensing out of a fast, hot wind. The luminosity of the Lyα emission increases nonlinearly with the ULIRG bolometric luminosity and represents about 0.1–1\% of the radiative cooling from the hot winds in the H\textsc{ii}-dominated ULIRGs.

Key words: galaxies: evolution – instabilities – line: profiles – radiative transfer

Supporting material: extended figure

1. INTRODUCTION

Hydrogen recombination in star-forming galaxies produces prodigious amounts of line radiation including eight Lyα photons for every Hα photon. The emergent Lyα and Hα line profiles typically look very different because galaxies are nearly always optically thick to the Lyα photons. Even when the neutral gas column becomes optically thin to Lyman continuum radiation, i.e., \(N(\text{H}\,\alpha) < 1/\delta_0 \approx 1.59 \times 10^{17}\, \text{cm}^{-2}\), where \(\delta_0\) represents the hydrogen photoionization cross section at the Lyman edge, the Lyα optical depth at line center remains very large,

\[
\tau_0(\text{Lyα}) = 8.02 \times 10^5 \left( \frac{15\, \text{km}\, \text{s}^{-1}}{b} \right) \left( \frac{N(\text{H}\,\alpha)}{1.59 \times 10^{17}\, \text{cm}^{-2}} \right) \tag{1}
\]

using the atomic data in Morton (2003) and a Doppler parameter \(b \equiv \sqrt{2kT/m_H}\). The Lyα photons random walk out of the galaxy and undergo diffusion in frequency space with each scattering. The increased path length makes the line photons more susceptible than the underlying continuum to absorption by dust. The luminosity and frequency of the emergent Lyα photons are therefore sensitive to the dust content, phase structure, and kinematics of interstellar gas (Dijkstra 2014).

We can better understand these properties of the interstellar medium (ISM) by studying Lyα emission from nearby galaxies for which many physical properties have been measured, and, as a result, also learn how to best derive physical properties of high-redshift galaxies from Lyα properties when few other diagnostics are possible. Given the large number of factors influencing the radiative transfer of Lyα photons (Gronke & Dijkstra 2014), empirical studies are needed for galaxies sampling the full gamut of dust properties and gas kinematics.

Prior to the \textit{GALEX} spectroscopic survey, limited access to the space ultraviolet restricted observations of Lyα 1215.67 Å to less than two dozen galaxies at low redshift (Giavalisco et al. 1996; Kunth et al. 1998). A systematic search of \textit{GALEX} data produced 66 Lyα-emitting galaxies at \(0.2 < z < 0.35\) (Deharveng et al. 2008), and a study of nine deep fields extended the redshift range of \textit{GALEX} Lyα emitters (Cowie et al. 2010). Multiwavelength follow-up demonstrated that these low-redshift, Lyα-emitters have undergone very recent star formation (Cowie et al. 2011).

These studies have introduced the concept of a Lyα escape fraction, \(f_{\text{esc}}(\text{Lyα})\), which compares the flux detected in the Lyα line to that predicted from the extinction corrected Hα flux under Case B recombination conditions at low density. Atek et al. (2009) demonstrated the systematic decline in \(f_{\text{esc}}(\text{Lyα})\) with increasing dust extinction. The attenuation of the resonance line in many galaxies exceeds the attenuation of the underlying far-UV continuum. This result suggests resonance scattering increases the pathlength of the Lyα photons and therefore the probability of absorption by dust grains (Atek et al. 2014). Resonance scattering also explains the larger angular size of the galaxies in Lyα relative to the population of massive stars (Hayes et al. 2013).
The recent addition of the Cosmic Origins Spectrograph (COS, Green et al. 2012) to the Hubble Space Telescope (HST) substantially improved ultraviolet sensitivity. This new opportunity has allowed the exploration of the Lyα properties for a wider range of galaxy types (Heckman et al. 2011; Leitherer et al. 2013; Wofford et al. 2013; Jaskot & Oey 2014). Particularly relevant COS observations for understanding Lyα emission from high-redshift galaxies include the pioneering studies of low-redshift Lyman Break Analogs (LBAs, Heckman et al. 2011) and of lower mass galaxies with extreme specific star formation rates (Green Peas, Jaskot & Oey 2014). New COS observations of the most luminous, dusty starbursts (introduced and discussed here) and a forthcoming analysis of a larger sample of Green Pea galaxies (A. Henry et al. 2015, in preparation) build on this work.

The properties of some LBAs and Green Pea galaxies make them candidates for Lyman continuum leakage. Heckman et al. (2001) showed that sightlines optically thin to the Lyman continuum would not generate completely black troughs in low-ionization state absorption lines. The discovery of significant residual intensity in the C ii λ1334.5 feature of both the LBAs with the most dominant central objects (DCOs, Heckman et al. 2011) and a few Green Pea galaxies (Jaskot & Oey 2014) therefore generated much interest, and Borthakur et al. (2014) subsequently measured an escape fraction of a few percent from the direct detection of the Lyman continuum from the DCO J0921+4509. The observations of both populations also suggested the Lyα emission properties were modified in systems with escaping Lyman continuum. In particular, Heckman et al. (2011) noted a correlation between the presence of blueshifted Lyα absorption and a high (inferred) escape for the Lyman continuum.

None of these studies have observed the most luminous sites of star formation in the local universe, deterred perhaps by their enormous infrared excess. Dusty starbursts, however, comprise an increasing fraction of the cosmic SFR with lookback time (Le Floc’h et al. 2005) and, somewhat surprisingly, submillimeter selected galaxies at high redshift actually show Lyα in emission more frequently than do Lyman-break selected galaxies (Chapman et al. 2005). Observations of the Lyα emission from local Ultraluminous Infrared Galaxies (ULIRGs) are largely missing from the literature yet would provide important insight into the physics of Lyα radiative transfer and feedback in intense star-forming regions at a much earlier time.

In this paper, we present new COS observations of 11 galaxies selected on the basis of their high far-infrared (far-IR) luminosity, $L_{\text{IR}} > 10^{12} L_{\odot}$, but representing a range of stages in the transformation of gas-rich spiral galaxies to field ellipticals via major mergers (Genzel et al. 2001). As a class, these objects emit a tiny fraction of their luminosity in the far-UV, but their enormous luminosity makes them detectable with COS. We expect substantial variations among their absorption and emission properties in Lyα due to both the wide variation in the UV/FIR flux ratio among ULIRGs (Murray et al. 2007) and the evolution of the ISM during the merger. Because of their warm dust temperatures and high luminosities during the latest stages of mergers, a subset of ULIRGs have been recognized as quasars partly hidden by a large central concentration of dust (Sanders et al. 1988a, 1988b).

In Section 2, we describe the selection of the ULIRGs, the new HST observations, and the supporting optical spectroscopy. We characterize the Lyα radiation from ULIRGs in Section 3 emphasizing the unusual shape of the line profile. Our interpretation of the Lyα profile is enhanced by a quantitative comparison to recombination and forbidden lines in optical spectra in Section 4. We discuss the physical origin of the broad emission in starburst galaxies in Section 5 and present simple radiative transfer modeling of the Lyα line profiles in Section 6. The results point toward the highly blueshifted emission coming from a physically distinct component of the outflow related to the hot wind fluid, and we summarize the evidence for this results and its implications in Section 7.

We adopt a cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_0 = 0.3$, and $\Omega_\Lambda = 0.7$ throughout. At the median galaxy redshift of $z = 0.11$, one second of arc subtends 2.0 kpc.

2. OBSERVATIONS

We have previously used the Echellete Spectrograph and Imager (ESI, Sheinis et al. 2002) on the Keck II telescope to obtain high-resolution optical spectra of many of the 2 Jy ULIRGs (Strauss et al. 1992) imaged in K and R bands by Murphy et al. (1996). We found outflows of low-ionization-state gas via interstellar Na i and K i absorption lines that are blueshifted several 100 km s$^{-1}$ with respect to the systemic redshift (Martin 2005, 2006). We also resolved broad wings on many optical emission lines and demonstrated that shocks traveling at several 100 km s$^{-1}$ excite this component of the emission (Soto et al. 2012; Soto & Martin 2012). To gain further insight into these gas flows, we have obtained new G130M spectra of ULIRGs from the above sample with the COS on the HST (GO programs 12533 and 13407).

2.1. The COS ULIRGs Sample

2.1.1. UV Selection

We selected 11 of the UV-brightest ULIRGs at redshifts from 0.084 to 0.151 for the COS observations. Like all ULIRGs, our targets have extremely high ratios of far-IR to far-UV flux. Most of the radiation from their stars and AGNs is absorbed by dust, and the energy re-radiated as a thermal spectrum with maximum intensity between 60 and 100 $\mu$m. Their bolometric luminosities are just 0.30 dex brighter than their far-IR luminosities which we list in Table 1 for reference. Very little of their bolometric luminosity comes out in the ultraviolet. By choosing the UV-brightest ULIRGs, however, our sample is biased toward systems with lower than average (for ULIRGs) color excess, and this selection effect does weaken the average strength of interstellar Na i absorption (Martin 2005; Chen et al. 2010).

The bolometric luminosities of the COS ULIRGs span a relatively narrow range from log $(L_{\text{IR}}/L_{\odot}) = 12.07$ to 12.55 but are correlated with the merger stage. Following Veilleux et al. (2002), we estimate the merger state from the separation of the nuclei and prominence of the tidal tails as described in the notes to Column 8 of Table 1. The most luminous object, IRAS11598–0112, has progressed to stage IVb of the merger sequence. The lowest luminosity targets (IRAS09583+4714 and IRAS08030+5243) are wide binaries still in the pre-merger stage (IIa) with two distinct galaxies still recognizable. The far-IR luminosity of IRAS09583+4714 is dominated by one of
### Table 1

| Name           | $z$     | $\log L_{\text{FIR}}$ ($L_{\odot}$) | $F_\mu(25 \mu m)$/$F_\mu(60 \mu m)$ | $E_{\text{MW}}$ ($E_\nu$) | $m_{\text{NUV}}$ (AB mag) | $m_{\text{MUV}}$ (AB mag) | Merger | Separation (kpc) |
|----------------|---------|-------------------------------------|-------------------------------------|---------------------------|---------------------------|---------------------------|--------|------------------|
| IRAS00262+4251 | 0.097240| 11.90                               | 0.11                                | 0.066                     | 18.73                     | 19.22                      | IVa    | <1.4             |
| IRAS01003–2238 | 0.117701| 11.94                               | 0.25                                | 0.015                     | 18.49                     | 18.51                      | IVd    | <3.4             |
| IRAS08030+5243 | 0.085306| 11.82                               | 0.07                                | 0.037                     | 21.78                     | 21.17                      | IVb    | <1.3             |
| IRAS09583+4714 | 0.085887| 11.78                               | 0.18                                | 0.012                     | 19.46                     | 19.09                      | IIIa   | 14.5             |
| IRAS10378+1109 | 0.136238| 12.08                               | $\leq0.15$                          | 0.028                     | 21.04                     | 21.22                      | IVb    | 1.2              |
| IRAS11598–0112 | 0.150694| 12.25                               | $\leq0.22$                          | 0.023                     | 17.54                     | 17.87                      | IVb    | 1.6              |
| IRAS12071–01444 | 0.128360| 12.09                               | 0.21                                | 0.039                     | 19.46                     | 20.82                      | IVb    | 2.25             |
| IRAS16474+3340 | 0.111471| 11.96                               | 0.11                                | 0.002                     | 18.39                     | 19.83                      | IIIa   | 3.73             |
| IRAS16487+5447 | 0.103600| 11.98                               | 0.063                               | 0.013                     | 18.16                     | 18.47                      | IIIa   | 5.16             |
| IRAS17028+5817 | 0.106090| 11.99                               | 0.032                               | 0.020                     | 20.26                     | 20.82                      | IIIa   | 25.3             |
| IRAS23365+3604 | 0.064480| 11.96                               | 0.11                                | 0.097                     | 18.91                     | 19.88                      | IIIa   | <1.1             |

**Note.** Col 1: name of COS target. Col 2: redshift. Col 3: far-infrared luminosity defined as $L_{\text{FIR}} = 3.86 \times 10^4 \, d_{\text{mag}}^2 \, [2.58 \, F_\nu(60 \, \mu m) + F_\nu(100 \, \mu m)] \, L_{\odot}$. The fluxes (in Jansky) come from Murphy et al. (1996), and the luminosity distance assumes a universe with $\Omega_m = 0.7$, $\Omega_{\Lambda} = 0.3$, $h = 0.7$. In the limit that stars, rather than an AGN, heat the dust which emits the far-IR radiation, the inferred star formation rate is $SFR = L_{\text{FIR}}/5.8 \times 10^9 \, M_{\odot} \, yr^{-1}$ (Kennicutt 1998). The bolometric luminosities, $L_{\text{Bol}}$, are a factor of two larger than $L_{\text{FIR}}$. Col 4: infrared color. Ratio computed from the flux densities at 25 and 60 $\mu m$ listed in Table 1 of Murphy et al. (1996). Sanders et al. (1988b) used this ratio to identify ULIRGs with unusually high dust temperature; the warm ULIRGs have $0.2 < F_\mu(25 \mu m)/F_\mu(60 \mu m) < 2.0$. Col 5: foreground extinction (Schlafly & Finkbeiner 2011) recalibrated from the infrared-based dust map of Schlegel et al. (1998). The recalibration assumes a Fitzpatrick (1999) reddening law with $R_V = 3.1$. Col 6: near-UV magnitude from GALEX (not corrected for foreground extinction). Col 7: far-UV magnitude from GALEX (not corrected for foreground extinction). Col 8: interaction classification as described in Section 3.4 of Veilleux et al. (2002): I—First approach, II—First contact, IIIa/IIIb—Pre-merger (Wide binary/Close binary), IVa/IVb—Merger (Diffuse/Compact), V—Old Merger. "d" indicates object classified by Soto & Martin (2012). Col 9: separation of nuclei. Upper limits from Murphy et al. (1996); all others made from the observations presented here.

a Redshift from CO in Solomon et al. (1997).

b Redshift from optical emission lines.

c Redshift from infrared Paschen line.

### the two galaxies, which we call IRAS09583+4714, but it is the companion 14.5 kpc away which emits most of the far-UV flux. We pointed COS at this companion which we will refer to as IRAS09583+4714-B.

The properties of the COS ULIRG sample are also consistent with the emergence of an AGN at late times. Most of the COS ULIRGs have the cool far-IR color typical of starburst dominated ULIRGs. However, the relative flux densities at 25 and 60 $\mu m$, which are listed in column 4 of Table 1, identify two objects—IRAS01003–2238 and IRAS12071–0444—with the higher dust temperatures indicative of a more compact source. The upper limit on the color for IRAS11598–0112, $F_\mu(25 \mu m)/F_\mu(60 \mu m) \leq 0.22$, also allows a classification as a warm ULIRG. These warm ULIRGs are less common than cool ULIRGs and mark the transition from cool ULIRGs to optically selected quasars (Sanders et al. 1988b). The three warm ULIRGs in our sample show compact morphologies indicative of a late stage merger. For example, IRAS01003–2238, is the most compact merger in the sample (stage V). Both IRAS12071–0444 and IRAS11598–0112 are classified morphologically as (stage IVb) compact mergers.

#### 2.1.2. The AGN Contribution to $L_{\text{bol}}$

In recent years, much progress has been made toward understanding the AGN contribution to the bolometric luminosity of ULIRGs. In particular, the ULIRG evolution study of Veilleux et al. (2009), used six independent methods to estimate the AGN fraction and found consistent luminosity fractions to within 10–15%. We can use these results to estimate the AGN contribution to the bolometric luminosity of each COS ULIRG.

For example, Figure 1 shows the optical spectrum of IRAS11598–0112. The narrow forbidden lines and the broad Balmer emission lines identify this ULIRG as a Seyfert 1 galaxy (Osterbrock & Ferland 2006). The presence of strong Fe II emission in the optical spectrum defines this object as a Narrow Line Seyfert 1 (NLS1; Leighly & Moore 2004). The ULIRG evolution study showed that AGNs provide roughly 75% of $L_{\text{IR}}$ in Seyfert 1 ULIRGs, so the luminosity of IRAS11598–0112 is likely dominated by the AGN.

The emission-line ratios measured from the optical spectra of IRAS01003–2238 and IRAS12071–0444 place them in the Seyfert 2 region of the excitation diagrams (Soto & Martin 2012). The Seyfert 2, IRAS01003–2238, is the most advanced merger (stage V) in the sample and, since this is consistent with the scenario where the AGN emerges toward the end of the merger, we consider this object AGN dominated. The emission-line nebula in IRAS12071–0444 is larger than the typical narrow-line region of an AGN, however, and (Soto & Martin 2012) previously attributed the excitation to shocks related to a galactic wind rather than an AGN. Still, the high far-IR luminosity of IRAS12071–0444, its warm color, and late (stage IV) merger class are all consistent with a significant AGN contribution. The Veilleux et al. (2009) results find that AGN power as much as 50% of the total luminosity from Seyfert 2 ULIRGs, and we infer that the AGN luminosity could be as large as the starburst luminosity in both IRAS01003–2238 and IRAS12071–0444. For most of the COS ULIRGs, their H $\alpha$-dominated optical spectra and cool far-IR color strongly suggest the starburst dominates the bolometric luminosity. For this class of ULIRG, Veilleux et al. (2009) estimate that AGNs contribute no more than 15% to 35% of the bolometric luminosity.
2.2. HST Imaging and COS Target Acquisition

For ULIRGs with single-nuclei, we centered the brightest UV knot in the 2′.5 diameter primary science aperture (PSA) using the dispersed-light acquisition procedure recommended by the COS Instrument Handbook for Cycle 19. In those ULIRGs that have double nuclei, however, the UV emission may be dominated by star formation in either galaxy or even compact knots in the tidal tails (Surace & Sanders 2000). For all but the compact ULIRGs associated with the later merger stages, we obtained short exposures with HST through far-UV,

![Figure 1. Optical spectra of the Seyfert 1 ULIRG IRAS11598–0112 zoomed in on features that identify this object as a narrow-line Seyfert 1 galaxy. In addition to broad Balmer lines and more narrow forbidden lines, the optical spectrum shows strong Fe II emission complexes.](image)

| Program | Visit | HST ID | Config | Filter | Target | Date | τ (s) |
|---------|-------|--------|--------|--------|--------|------|-------|
| 13407   | 1     | JC8T01010 | ACS/SBC | F125LP | IRAS00262+4251 | 2013 Dec 28 | 892   |
| 13407   | 1     | IC8TA1010 | WFC3/UVIS | F225W | IRAS00262+4251 | 2013 Dec 28 | 892   |
| 13407   | 1     | IC8TA1YMQ | WFC3/UVIS | F625W | IRAS00262+4251 | 2013 Dec 28 | 71    |
| 5982    | n/a   | U20206T | WFC3/UVIS | F439W | IRAS01003-2238 | 1995 Oct 21 | 800   |
| 12533   | 21    | JBRM21010 | ACS/SBC | F439W | IRAS09583+4714 | 2012 Jun 08 | 934   |
| 12533   | 21    | IBRM1A10Q | WFC3/UVIS | F225W | IRAS09583+4714 | 2012 Jun 08 | 704   |
| 12533   | 9     | JBRM09010 | ACS/SBC | F625W | IRAS12071-0444 | 2012 May 17 | 75    |
| 12533   | 9     | JBRM09010 | ACS/SBC | F125LP | IRAS12071-0444 | 2012 May 17 | 934   |
| 12533   | 9     | IBRM09F2Q | WFC3/UVIS | F625W | IRAS12071-0444 | 2012 May 17 | 75    |
| 12533   | 9     | IBRM09F2Q | WFC3/UVIS | F439W | IRAS12071-0444 | 2012 May 17 | 75    |
| 12533   | 22    | JBRM22010 | ACS/SBC | F125LP | IRAS16474+3430 | 2012 Dec 14 | 934   |
| 12533   | 22    | IBRM22010 | ACS/SBC | F225W | IRAS16474+3430 | 2012 Dec 14 | 710   |
| 12533   | 22    | IBRM22010 | ACS/SBC | F625W | IRAS16474+3430 | 2012 Dec 14 | 75    |
| 13407   | 2     | JC8T02010 | ACS/SBC | F125LP | IRAS16474+3430 | 2014 Jan 12 | 932   |
| 13407   | 2     | JC8T02010 | ACS/SBC | F225W | IRAS16474+3430 | 2014 Jan 12 | 932   |
| 13407   | 2     | JC8T02010 | ACS/SBC | F625W | IRAS16474+3430 | 2014 Jan 12 | 91    |
| 12533   | 23    | JBRM23010 | ACS/SBC | F125LP | IRAS23365+3604 | 2012 Sep 23 | 934   |
| 12533   | 23    | IBRM23010 | ACS/SBC | F225W | IRAS23365+3604 | 2012 Sep 23 | 704   |
| 12533   | 23    | IBRM23010 | ACS/SBC | F625W | IRAS23365+3604 | 2012 Sep 23 | 76    |

Note. Col 1: HST guest observer program number. Col 2: visit number. Col 3: program identifier. Col 4: instrument configuration. Col 5: imaging filter. Col 6: target name. Col 7: date Col 8: exposure time.
near-UV, and optical filters and found the coordinates for the UV-brightest knots prior to acquiring each target with COS. Table 2 lists the parameters of these imaging observations. The standard pipeline processing for each imaging configuration proved sufficient for target acquisition purposes. To construct images suitable for photometry, however, we applied a zero-level bias correction to the raw images and ran LACosmic to remove cosmic rays before combining frames with AstroDrizzle. After these steps, significant trails can still be seen on the detector from the incomplete transfer of charge toward the amplifier.

Figure 2 shows these optical, near-UV, and far-UV images. The ACS SBC/F125LP and WFC3 UVIS/F225W images generally detect the same knots, but many of the morphological features present in the optical F625W images remain completely undetected in the ultraviolet. Even the optical images can be blind to the most active regions which are veiled by thick layers of dust, e.g., $A_V \sim 50$ (Genzel et al. 1998).

The far-UV images illustrate the distribution of light in the COS Primary Science Aperture (PSA) for our spectroscopic observation. The sizes of the ULIRGs range from 0″7 to 1″07 FWHM, smaller than the full diameter of the PSA but similar to the unvignetted portion. For example, the COS PSA subtends 5.03 kpc at the median target redshift, but the diameter of the unvignetted region is just 1.61 kpc. It is unknown whether a low surface-brightness halo of scattered Lyα emission extends beyond the PSA for some targets.

Our strategy for computing blind offsets used all three images. The F125LP bandpass provides the best match to our spectroscopic bandpass, so we used it to identify the brightest knot, but the field of view is typically too small to include a bright point-source. The WFC3/UVIS F225W images provide a larger field of view which typically includes a star or quasar bright enough for a near-UV imaging acquisition, and the blind offsets were computed from these images. The short WFC3/F625W exposures provide easy registration with optical images and were used to verify absolute pointing and estimate the red leaks in the UV filters. In one case, IRAS09583+4714, the stars in the F225W image were not bright enough for a blind offset. Following the same procedure adopted for ULIRGs without pre-imaging, we centered the PSA on a bright knot significantly offset from the position of the maximum far-IR intensity, hereafter IRAS09583+4714-B.

2.3. COS Far-UV Spectroscopy

We obtained COS spectra in TIME-TAG mode through the PSA using the medium resolution far-UV grating, G130M. We observed at four focal plane offset positions in order to reduce the impact of fixed-pattern noise associated with the micro-channel plate. The spectra covered much of the bandpass from...
1137 to 1468 Å. The Lyα line fell on Detector B in the observation of the lowest redshift target, IRAS23365+3604, but was redshifted onto Detector A for all other observations. In each case, the redshift of the galaxy cleanly separated the Lyα profile from geocoronal emission. Table 3 lists the central wavelengths (CWLS) of each pointing and additional details about the observations.

Individual frames were processed with version 2.13.6 of the CalCOS pipeline. Calcos corrects the data for instrumental effects, assigns a vacuum wavelength scale, and extracts flux-calibrated spectra. It applies a heliocentric correction to the final x1d files for each exposure. We combined the x1d files using software developed by the COS GTO team (Danforth et al. 2010). A simple mean pixel combination gave better results than the default variance weighting for these low S/N data.

2.3.1. Wavelength Calibration

Emission from geocoronal airglow fills the COS aperture, so the observed wavelengths of these lines are independent of target position in the PSA. We measured the wavelengths of Lyα 1215.67, O1 1302.1685, O1 1304.8576, O1 1306.0286, O1 1335.71 line in some spectra, and this blend systematically increases the Lyα profile from geocoronal emission. We measured the wavelengths of the unblended Milky Way absorption lines in the spectra with continuum S/N. The Stark broadening of the Lyα line fell on Detector B in the observations.

In the spectra IRAS01003−2238, IRAS11598−0112, IRAS16487+5447, IRAS00262+4251, and IRAS09583+4714, we measured five lines—Si II 1190.42, Si II 1193.29, Si II 1260.42, Si II 1260.50, and C II 1334.53, and we measured a subset of these in the IRAS23365+3604 and IRAS12071−0444 spectra. The continuum S/N is not adequate to measure any of these lines in the IRAS10378+1109, IRAS17028+5817, and IRAS08030+5243 spectra. Blends with other transitions are the main source of error in the velocity offsets. After rejection of the obvious blends, the average velocity offset of the Milky Way absorption lines was consistent within the uncertainties of the wavelength calibration for most targets.

We identified three spectra, however, with Galactic absorption lines that were Doppler shifted by amounts greater than the uncertainty in the wavelength calibration. We compared these Doppler shifts to the Wakker (2004) map of Galactic high velocity clouds. Since the only significant velocity offsets we found have the same sign as the Doppler shifts of high-velocity clouds in their direction, we concluded that the UV knots were well centered in the COS PSA and did not apply any corrections to the pipeline wavelength scale. Hence when

For completeness, we also note that our sightline toward IRAS00262+4251 passes 3.2 northwest of M 31, a projected distance of just 44 kpc. In the IRAS00262+4251 spectrum, we detect Si ii, Si ii, and S ii at approximately −300 km s\(^{-1}\), an offset consistent CGM (see, for example, Lehner et al. 2014).

2.3.2. Spectral Resolution

The G130M resolution is excellent when observing point sources, \( R \approx 18,000 \), but degrades to \( R \approx 1450 \) (about 207 km s\(^{-1}\)) when the angular size of the target exceeds the diameter of the COS PSA. The effective resolution of each COS ULIRG spectrum depends on the angular size of the UV knots but must lie between these limits.

We estimated the actual resolution of our spectra two ways. We first measured the widths of the unblended Milky Way absorption lines in the five spectra with good continuum S/N. Then we estimated the resolution from the size of each source in the near-UV image. These measurements had four objects in common, and we found the Galactic absorption lines always indicated lower resolution by a factor of two to three relative to the images. We attribute this to the extended nature of the UV emission which is not captured by the FWHM. Using the Galactic lines, the COS G130M resolution for the most compact ULIRG, IRAS01003−2238, is 69 km s\(^{-1}\) when the stage IIIa merger IRAS16487+5447 fills the COS aperture and degrades the resolution to approximately 200 km s\(^{-1}\). For IRAS16474+3430, IRAS00262+4251, and IRAS11598−0112, we measure a spectral resolution of 150 km s\(^{-1}\), 154 km s\(^{-1}\), and 159 km s\(^{-1}\), respectively. Based on the size of IRAS09583+4714 B in the near-UV image, we would estimate the resolution \( R < 1830 \) or, equivalently, FWHM > 164 km s\(^{-1}\).

2.3.3. The Ultraviolet Continuum

When the ultraviolet continuum was detected, we typically found spectral signatures of young stars. Broad, shallow O vi and N v absorption troughs accompanied by redshifted emission, for example, indicated the presence of stellar winds from very massive stars. The ultraviolet continuum is solidly detected in six of the COS spectra, and only the spectrum of IRAS11598−0112 fails to directly indicate a population of ionizing stars.

Since the UV spectral slope of a young stellar population is more sensitive to reddening than to age, we could estimate the stellar reddening \( E_{B−V} \) from the observed shape of the UV continuum. We first corrected each spectrum for Galactic reddening using the Fitzpatrick (1999) extinction curve. Next, we assumed an intrinsic UV spectral slope appropriate to a young stellar population, i.e., \( \beta \approx −2.3 \) where \( F_\lambda \propto \lambda^\beta \) (Leitherer et al. 1999), and reddened this template using a Calzetti extinction law (Calzetti et al. 2000). Using custom software which allowed spectral binning and interactive adjustments to the fitting window, we fit the stellar reddening \( E_{B−V} \) and the UV continuum simultaneously.

The uncertainty in our estimate of the stellar reddening was taken to be the larger of (1) the range resulting from placement

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6. The Si ii 1260.42 can blend with Si ii 1259.52. In the IRAS00262+4251 spectrum, for example, the other two lines in the Si ii 1250.58, 1253.81, 1259.52 triplet are detected and unblended making the S ii 1259 blend with Si ii 1260.42 very obvious. The blend gives the Si ii 1260 absorption trough an anomalous blueshift. The C ii 1334.53 trough is blended with the weaker C ii* 1335.71 line in some spectra, and this blend systematically increases (redshifts) the velocity offset. This C ii blend lies on top of the IRAS00262+4251 Lyα line in that spectrum.

7. We have measured the profile of the near-UV surface brightness and then used the scaling given by Heckman et al. (2011) for COS observations of the DCOs, i.e., FWHM of 0.1 to 0.5 yields a resolution \( R \approx 13,000 \) to 3000 with the medium resolution gratings.
| Program | Visit | HST ID | Target | Date       | Acquisition | R.A.     | Decl.     | CWL (Å) | Band (A/B) | Duration (s) |
|---------|-------|--------|--------|------------|-------------|----------|-----------|---------|-------------|--------------|
| 12533   | 1     | LBRM01010 | IRAS00262+4251 | 2011 Nov 11 | peak         | 00 28 54.1526 | +43 08 15.82 | 1291 | 1137-1274/1292-1432 | 592          |
| 12533   | 1     | LBRM01020 | IRAS00262+4251 | 2011 Nov 11 | peak         | 00 28 54.1526 | +43 08 15.82 | 1309 | 1154-1293/1310-1448 | 592          |
| 12533   | 2     | LBRM02010 | IRAS01003−2238  | 2011 Dec 03  | peak         | 01 02 49.9631  | −22 21 57.02 | 1291 | 1137-1274/1292-1432 | 1716         |
| 12533   | 4     | LBRM04010 | IRAS08030+5243  | 2011 Oct 30  | peak         | 08 06 50.8856  | +52 55 7.70  | 1291 | 1137-1274/1292-1432 | 932          |
| 12533   | 18    | LBRM18010 | IRAS09583+4714-B | 2012 Nov 08  | peak         | 10 01 30.4490  | +46 59 51.74 | 1291 | 1137-1274/1292-1432 | 1832         |
| 12533   | 6     | LBRM06010 | IRAS10378+1109  | 2011 Nov 11  | peak         | 10 40 29.1743  | +10 53 18.17 | 1291 | 1137-1274/1292-1432 | 420          |
| 12533   | 6     | LBRM06020 | IRAS10378+1109  | 2011 Nov 11  | peak         | 10 40 29.1743  | +10 53 18.17 | 1309 | 1154-1293/1310-1448 | 420          |
| 12533   | 8     | LBRM08010 | IRAS11598−0112  | 2011 Nov 18  | peak         | 12 02 26.7505  | −01 29 15.49 | 1309 | 1154-1293/1310-1448 | 652          |
| 12533   | 8     | LBRM08020 | IRAS11598−0112  | 2011 Nov 18  | peak         | 12 02 26.7505  | −01 29 15.49 | 1327 | 1173-1312/1328-1468 | 652          |
| 12533   | 17    | LBRM17010 | IRAS12071−0444  | 2013 Jan 24  | offset       | 12 09 45.1000  | −05 01 13.20 | 1291 | 1137-1274/1292-1432 | 588          |
| 12533   | 17    | LBRM17020 | IRAS12071−0444  | 2013 Jan 24  | offset       | 12 09 45.1000  | −05 01 13.20 | 1309 | 1154-1293/1310-1448 | 588          |
| 12533   | 24    | LBRM24010 | IRAS16474+3430  | 2013 Apr 14  | offset       | 16 49 14.2380  | +34 25 8.68  | 1291 | 1137-1274/1292-1432 | 2204         |
| 12533   | 13    | LBRM13010 | IRAS16487+5447  | 2011 Nov 06  | peak         | 16 49 47.0306  | +54 42 35.41 | 1291 | 1137-1274/1292-1432 | 1888         |
| 12533   | 14    | LBRM14010 | IRAS17028+5817  | 2011 Oct 26  | peak         | 17 03 42.0084  | +58 13 44.39 | 1291 | 1137-1274/1292-1432 | 1456         |
| 12533   | 16    | LBRM16010 | IRAS182365+3604  | 2011 Nov 07  | peak         | 23 39 1.2726   | +36 21 8.45  | 1327 | 1173-1312/1328-1468 | 1340         |
| 12533   | 20    | LBRM20010 | IRAS23365+3604  | 2012 Nov 24  | offset       | 23 39 1.2290   | +36 21 8.03  | 1327 | 1173-1312/1328-1468 | 1876         |

Note. Col 1: HST Program ID. Col 2: visit number. Col 3: HST ID. Col 4: target name. Col 5: date of observation. Col 6: type of acquisition: blind offset or peak up. Col 7,8: coordinates. For blind offset acquisitions, these coordinates are the exact position of the PSA. For peak ups, the telescope was pointed near these coordinates and then moved in a spiral pattern to cover a square grid (ACQ/SEARCH with SCAN-SIZE = 2 and STEP-SIZE = 1") recording a spectrum at each stop. The telescope was then moved to the flux-weighted mean position of the target. We then improved the centering in the cross-dispersion direction by taking a spectrum, collapsing it in the dispersion direction, finding the offset in the cross-dispersion direction to the mean of the collapsed spectrum, and finally slewing the telescope by this offset. After this ACQ/PEAKXD, we moved the telescope along the dispersion direction to obtain several ACQ/PEAKD exposures (STEP-SIZE = 1.118; CENTER FLUX WEIGHTING) and found the center of the knot along the dispersion direction. The science spectra were then obtained through the PSA. Col 9: central wavelength. Col 10: wavelength coverage. Each spectrum has a gap between detector Segments B and A. For some targets, we simply chose a CWL that avoid loosing important lines to this gap, but for others we needed continuous coverage and requested exposures at two CWL’s as indicated. Col 11: exposure time.
of the continuum or (2) the range obtained by repeating the exercise with \( \beta = -2.1 \) and \( \beta = -2.5 \). The resulting values of the stellar reddening in Table 4 range from 0.02 to 0.32. These values are not large compared to normal galaxies and demonstrate that the UV light emerges through holes in the overall dust distribution.

The global continuum fits generally seemed reasonable around individual spectral lines. Where the pseudo-continuum formed by the blending of lines in the underlying galaxy/AGN spectrum was significant, however, we fit a linear continuum to bandpasses on either side of the spectral line and normalized the spectrum by the fitted continuum. We illustrate the allowed range for the continuum placement near \( \text{Ly} \alpha \) in Figure 3. We used these limits to estimate the uncertainties in our measurements of the \( \text{Ly} \alpha \) emission.

### 2.4. Echelle Optical Spectroscopy

We previously obtained optical spectra with ESI in echelle configuration on the Keck II telescope as described previously (Martin 2005). The resolution through the 180 by 200 ESI slit, \( R \approx 5000 \) or 60 km s\(^{-1}\) FWHM, is comparable to that obtained for the most compact ULIRGs with COS G130M. These slits intersect the locations of the COS pointings and are shown in Soto & Martin (2012). We extracted an ESI spectrum along a 2′/5 length of each slit centered at the position of the COS aperture. The rows of the spectrum were weighted by their distance from the center of this aperture using the vignetting function for the G130M grating.\(^8\)

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8 COS ISR-2010-09 provides throughput measurements in only the XD (cross dispersion) direction for G130M. The Instrument Science Report compares the vignetting function for G160M in the XD and spectral directions and shows that they are nearly identical; hence, we have tacitly assumed the G160M vignetting is also quite similar to the XD and spectral directions.

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### 2.4.1. Emission-line Diagnostics

All the ULIRGs show strong Balmer and forbidden line emission in these ESI spectra. We fit these emission lines simultaneously using the procedure described in Soto et al. (2012) which includes a stellar Balmer absorption component. Table 5 gives the reddening estimated from the Balmer decrement. This nebular color excess is similar to normal galaxies because it does not probe the dust in the regions completely opaque to optical light. The reddening toward these \( \text{H} \beta \) regions is generally, but not exclusively, larger than our rough estimates of the stellar reddening from the UV spectral slope in Section 2.3.3 as would be expected considering that the younger ages of the stars emitting the Lyman continuum limit the distances the stars have traveled from their birth clouds.

Soto & Martin (2012) previously measured well-known, emission-line diagnostics from the ESI spectra and placed pairs of emission-line ratios in diagrams that distinguish excitation by photoionization from massive stars from radiative shocks (Allen et al. 2008). Soto et al. (2012) found the broad component of the line profile is excited exclusively by shocks moving at speeds of 200–400 km s\(^{-1}\). In Table 5, we list the shock velocity estimated from the line ratios \([\text{O} \text{III}] / \text{H} \beta\) and \([\text{O} \text{I}] / \text{H} \alpha\) at the position of the COS aperture.

### 2.4.2. Doppler-shifted Resonance Absorption

Measurements of the \( \text{Na} \) resonance absorption for IRAS00262+4251, IRAS08030+5243, IRAS16487+5447, and IRAS23365+3604 were collected from Martin (2005). Table 5 shows these equivalent widths and new measurements made in a similar manner for the other COS ULIRGs and IRAS09583+4714-B. The ESI spectra of IRAS10378+1109 and IRAS08030+5243 show the strongest \( \text{Na} \) absorption at 6.7 and 7.4 Å, respectively. The \( \text{Na} \) doublet in IRAS09583+4714-B and
shift of the blue wing, spectrum of the mini-BAL respectively; note the strong pseudo-continuum from metal lines in the uncertainty range are shown by the horizontal solid and dashed lines, IRAS detection of a non-stellar component. The interstellar Airglow lines are denoted by Rest-frame Ly\(\alpha\) (denoted as a logarithm in ergs s\(^{-1}\)) and the rest wavelength of Ly\(\alpha\) is indicated by

\(V_{\text{kin}} = 700 \text{ km s}^{-1}\)

as it

\(V_{\text{kin}} = 700 \text{ km s}^{-1}\)

The Doppler correction because the scale lengths of galactic disks in the R band and in H\(\alpha\) are very similar (Kennicutt 1989). Specifically, we vignetted the R image using the COS function described above, and then measured the R band flux in the 2'/5 diameter COS aperture relative to that in a 1'/0 by 2'/5 rectangular ESI aperture. To estimate the H\(\alpha\) flux that would be measured through a 2'/5 diameter aperture, we multiplied the extinction-corrected H\(\alpha\) fluxes by these aperture corrections which we also list in column4 of Table 5.

The spatial extent of Ly\(\alpha\) halos can also introduce systematic errors in estimates of \(f_{\text{esc}}(\text{Ly} \alpha)\). For example, as demonstrated in Hayes et al. (2013), resonance scattering enlarges galaxies in Ly\(\alpha\) by a factor of 1 to 3.6 over their size in H\(\alpha\); hence, our aperture may include a larger fraction of the total H\(\alpha\) emission than of the total Ly\(\alpha\) emission. This type of bias is unlikely for the COS ULIRG sample, however, because the LARS data empirically show that a low dust content is a necessary requirement for Ly\(\alpha\) halos to extend well beyond the region of H\(\alpha\) emission (Hayes et al. 2013).

3. COS SPECTROSCOPY OF LY\(\alpha\)

Figure 3 shows the COS G130M spectra around Ly\(\alpha\). We detect emission from eight of the ten ULIRGs. Considering the large optical depth of the Ly\(\alpha\) transition, see Equation 1, and extreme concentration of dust in ULIRGs, it is remarkable that any Ly\(\alpha\) photons escape from ULIRGs. It is perhaps easier to understand the absence of Ly\(\alpha\) emission from IRAS08030+5234 and IRAS17028+5817; the upper limits on their Ly\(\alpha\) fluxes are far below those detected.

To better appreciate the surprising shape of the ULIRG Ly\(\alpha\) profiles, we show the spectrum of the non-ULIRG, IRAS09583+4714-B, in Figure 4. The Ly\(\alpha\) emission is redshifted roughly 250 km s\(^{-1}\) relative to the optical emission lines, and the resonance absorption in several Si \textit{ii} transitions and Si \textit{iii} is blueshifted 100 km s\(^{-1}\) or more. Blueshifted Ly\(\alpha\) absorption is visible after smoothing the spectrum. P Cygni line profiles with redshifted emission and blueshifted absorption as seen in this spectrum arise from resonance scattering in an expanding, neutral medium (Verhamme et al. 2008). Six of the 13 Ly\(\alpha\) emitters from the H\(\alpha\)-selected galaxy sample of Wofford et al. (2013) and all 4 of the infrared luminous galaxies \((10^{11} < L_{\text{IR}}/L_{\odot} < 10^{11.7})\) observed by Leitherer et al. (2013) show these P Cygni Ly\(\alpha\) profiles; they have been modeled with outflowing shells of neutral gas expanding at velocities \(<200 \text{ km s}^{-1}\).

The dominance of blueshifted emission among the ULIRG Ly\(\alpha\) profiles indicates different physical conditions than those
which produce the P Cygni profiles. The profiles are unlike the local Hα-selected galaxies without P Cygni profiles; they display Lyα absorption troughs with damping wings fit by Hβ column densities in the range of $1.0 \times 10^{20} - 2.3 \times 10^{21} \text{cm}^{-2}$ (Wofford et al. 2013). Even among UV-selected galaxies at $z = 2-3$ where 30% show multiple emission peaks, Kulas et al. (2012) find the redshifted peaks are normally stronger than the blueshifted emission component. Only the line profiles of IRAS16474+3430 and IRAS16487+5447 show most of the net emission redward of the systemic velocity, and only IRAS16474+3430 may (depending on the continuum placement) have a weak, blueshifted absorption component.

We have ordered the ULIRG spectra by decreasing Lyα luminosity in Figure 3. The most luminous ULIRG, IRAS11598−0112, is a quasar on account of its dominant AGN and bolometric luminosity; blending of its broad Lyα profile with emission lines from N5, Si ii, and C iv produces line wings much broader than on any other COS ULIRG. If a G160M spectrum of this object is obtained in the future, the C iv emission could be used as a template profile to deblend this complex as shown, for example, in Leighly et al. (2007). For now, the line flux we measure from integrating this broad emission complex provides an upper limit on the Lyα luminosity due to the contamination from other lines.

Blueshifted emission wings are prominent on the Lyα profiles of IRAS01003−2238, IRAS12071−0444, IRAS10378+1109, and IRAS23365+3604. These wings extend roughly $-1000 \text{ km s}^{-1}$ from the systemic velocity. The process that generates these line wings does not appear to be uniquely associated with an active nucleus. Although we argued in Section 2.1.1 that the starburst and AGN may make roughly equal contributions to the bolometric luminosities of IRAS01003−2238 and IRAS12071−0444, starbursts power IRAS10378+1109 and IRAS23365+3604. Radiative transfer modeling has previously linked blueshifted Lyα emission to either radial infall (Dijkstra et al. 2006a, 2006b) or low columns of neutral gas (Behrens et al. 2014; Verhamme et al. 2014).

### 3.1. Escape Fraction of Lyα Photons

To gain insight into the role of radiative transfer effects in shaping the Lyα emission, we compare the strengths of the Lyα and Hα emission. Scattering off neutral hydrogen atoms increases the pathlength of Lyα photons through the ISM. The Lyα photons will be more attenuated than the Hα radiation due to a combination of the longer distance traveled due to scattering and the frequency dependence of interstellar reddening. We will distinguish between these processes using the attenuation of the far-UV continuum.

The intrinsic ratio $F(\text{Lyα})/F(\text{Hα})$ depends only on the electron density and temperature for Case B conditions, i.e., the ionized region is optically thick to photons just above the hydrogen edge (IP = 13.60 eV). In the low density limit, we have $n_e < n_{\text{crit}} = 1.55 \times 10^4 \text{cm}^{-3}$ and collisions can be neglected. The intrinsic Lyα flux is then 8.1 times the intrinsic Hα flux (Draine 2011).

Galaxies typically have Lyα to Hα flux ratios much less than the Case B ratio. It is therefore common to describe the suppression of Lyα photons relative to the intrinsic Lyα flux indicated by the Hα emission. We define the escape fraction of Lyα photons as

$$f_{\text{esc}}(\text{Lyα}) = \frac{F(\text{Lyα})}{8.1 \times F(\text{Hα})_{\text{corr}}}.$$

We calculate the intrinsic Hα flux from the observed Hα flux and the nebular reddening using the relation appropriate for a
reddening curve, namely

$$E_{B-V} = \frac{1}{0.9692} \log \left[ \frac{F(H\alpha)}{F(H\beta)} \right]$$

(4)

and was computed from the same reddening curve. We take the intrinsic Balmer decrement from Osterbrock & Ferland (2006) for Case B conditions, an electron density of $n_e = 100$ cm$^{-3}$, and a temperature of $T_e = 10^4$ K.

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Figure 5. Escape fraction of Ly$\alpha$ photons vs. (nebular) color excess. The inverted triangles are upper limits. The dashed line illustrates the suppression of the continuum near Ly$\alpha$ from dust as given by a Cardelli et al. (1989) reddening curve and the color excess (measured from the Balmer decrement). When the Ly$\alpha$ escape fraction of a galaxy lies far below this curve, we attribute the extra Ly$\alpha$ attenuation to the longer path length caused by resonance scattering. The ULIRGs do not stand out from other samples of Ly$\alpha$ emitting galaxies shown here for comparison. See Section 3.1.1 for further discussion of the Seyfert I galaxy, IRAS15918−0112.

The Ly$\alpha$ escape fraction computed this way ranges from 1–3% among the starburst-dominated spectra with Ly$\alpha$ emission. For our two non-detections, we find $f_{esc, Ly\alpha} < 0.5\%$. Figure 5 shows that these escape fractions decline with increasing color excess. Among the nine Ly$\alpha$ detections, the Spearman rank order correlation coefficient is $r_S = 0.42$, and the correlation deviates from the null hypothesis of no correlation by just 1.2σ. These escape fractions fall within the range measured for local galaxies (Atek et al. 2014) as indicated in Figure 5.

To assess the importance of resonance scattering, we compare the attenuation of Ly$\alpha$ to that of the continuum emission near Ly$\alpha$. The continuum attenuation is shown as a function of the color excess by the dashed line in Figure 5. From this comparison we see that the Ly$\alpha$ escape fractions of the ULIRGs—IRAS1207−0444, IRAS10378+1109, and IRAS23365+3604—is similar to the continuum attenuation. In spectra of the other non-AGN ULIRGs and IRAS09583+4715-B, the Ly$\alpha$ escape fractions is greatly suppressed relative to the continuum due to scattering. The upper limits on the Ly$\alpha$ flux for the two undetected ULIRGs imply the resonance line is attenuated over a factor of 100 more than the far-UV continuum. We conclude that the Ly$\alpha$ optical depth varies widely among the COS ULIRGs, scattering has the least affect on the Ly$\alpha$ emission emerging from IRAS1207−0444, IRAS23365+3604, and IRAS10378+1109.

3.1.1. High $f_{esc}$ (Ly$\alpha$) from a Mini-BAL Quasar

Our measurements allow unusually high values of $f_{esc}$ (Ly$\alpha$) for IRAS11598−0112, but the accuracy of this estimate merits additional discussion because a quasar powers this object. The uniqueness of this object’s far-UV spectrum among the COS ULIRGs might have been anticipated from the strong optical Fe II emission lines shown in Figure 1 which Lipari et al. (1993), Lipari (1994) have previously associated with the emergence of nascent broad absorption line quasars in
ULIRGs. Our detection of broad, high-ionization-state lines in Figure 6 solidly identifies this object as a mini-BAL quasar.

The assumptions underlying the intrinsic strength of Lyα in Equation (2) may not hold for IRAS11598−0112. For example, the intrinsic Case B ratio of \( \frac{F(\text{Ly} \alpha)}{F(\text{H} \alpha)} \) will be larger than 8.1 as \( n_e \) approaches the critical density; collisions promote electrons from the 2s state to 2p where they can decay by emission of a Lyα photon. In some quasar spectra, the intrinsic ratio is driven in the opposite direction (i.e., toward enhanced Balmer emission relative to Lyα) by thermalization of the energy levels (Kwan & Krolik 1979). Thermalization only becomes important at very high densities however.

The far-UV spectrum illustrated in Figure 6 helps us place constraints on the electron density. The IRAS11598−0112 outflow is only detected in lines from high-ionization-state gas. We detect blueshifted absorption in the O vi 1032, 1038, N v 1239, 1243, and possibly the S iv λ1062 transitions; the widths of these lines place IRAS11598−0112 in the mini-BAL (broad absorption line) quasar category. To directly measure \( n_e \), we need to measure the absorption from a collisionally excited level of one of the ions (Dunn et al. 2012; Borguet al. 2013).

Our spectrum covers S iv λ1073 at comparable S/N to the resonance transition at Al062 Å. No absorption is detected from the excited line, so the electron density lies well below the critical density of \( 3.16 \times 10^4 \text{ cm}^{-3} \). To summarize, the density is too low for thermalization to determine the level populations of hydrogen but is likely high enough for the intrinsic Case B ratio to be significantly larger than 8.1.

By assuming the low density limit, we have underestimated the value of the denominator in Equation (2). As explained above, however, we have overestimated the Lyα flux in the spectrum (i.e., the numerator in Equation (2)) by including blended metal lines in our Lyα flux. It follows that we obtain no quantitative limit on \( f_{\text{esc}}(\text{Ly} \alpha) \) for IRAS11598−0112. Our point is that the fiducial value stands out compared to the other ULIRGs, and we attribute this to the dominant AGN in IRAS11598−0112. We speculate that this object is viewed through an ionized cone (with neutral walls) pointed in our direction. In radiative transfer calculations, the escape fraction of Lyα photons from a compact source in an anisotropic gas distributions can be boosted by factors of 2–4 relative to the isotropic case when viewed through low-N(H i) holes (Behrens et al. 2014).

### 3.1.2. Correlation of \( f_{\text{esc}}(\text{Ly} \alpha) \) with the Width of the Lyα Profiles

To facilitate direct comparison of the linewidth with \( f_{\text{esc}}(\text{Ly} \alpha) \), we need a quantitative characterization of broad wings and/or line asymmetries. Describing the broad wings and asymmetries of the Lyα profiles robustly, however, provides a challenge. The full width of the profile at half maximum intensity, for example, is not uniquely defined for the double peaked profiles, nor does it flag line profiles with broad wings or significant asymmetry. In Appendix, we define velocity markers \( V_{20} \) and \( V_{50} \) as a continuous function of the fractional profile area. For any percentile of the profile area, the full width of the interpercentile velocity (IPV) is well defined. The widths at the 0.20, 0.50, and 0.80 percentiles are marked on each Lyα profile in Appendix Figure A1(a)–(i) to illustrate this concept.

The escape fraction increases as the width of the Lyα emission line increases. This correlation is both more significant and stronger than that for \( f_{\text{esc}}(\text{Ly} \alpha) \) and color excess. The correlation with line width reflects an underlying correlation of \( f_{\text{esc}}(\text{Ly} \alpha) \) with the Doppler shift of the blue wing. This correlation is stronger than the one with total linewidth, and \( f_{\text{esc}}(\text{Ly} \alpha) \) does not show a correlation with the velocity of the red wing. Figure 7 compares \( f_{\text{esc}}(\text{Ly} \alpha) \) to the Doppler shift of the blue wing.

This measured correlation is in the opposite direction to that expected for a static slab. For a static slab, the width of the resonance line would increase with the number of scatterings. Since the longer pathlengths would decrease \( f_{\text{esc}}(\text{Ly} \alpha) \), we would expect the Lyα escape fraction to decline as the line width increased.

Perhaps the simplest intrepretation of this correlation is that \( f_{\text{esc}}(\text{Ly} \alpha) \) depends strongly on the gas kinematics, not just the column density of gas and dust. However, previous empirical evidence for this effect has been limited to studies of a few galaxies (Kunth et al. 1998; Atek et al. 2008; Wofford et al. 2013). Among the H ii-dominated ULIRGs, we find \( f_{\text{esc}}(\text{Ly} \alpha) \) is correlated more strongly with emission-line width than with color excess.

### 3.1.3. The Lyα Equivalent Width

Often the H α spectrum is not accessible for Lyα emitters. In this situation, the Lyα equivalent width may be a useful indicator of the attenuation of Lyα photons. The equivalent width measures the strength of the emission line relative to the continuum. The ULIRGs as a class show moderate equivalent widths similar to the values measured previously for the local IUE-selected galaxies plotted Figure 5. The median \( W(\text{Ly} \alpha) \) is 11 Å among the COS ULIRGs, and the strongest equivalent width ULIRGs include the AGNs.

For continuous star formation, the UV continuum (like the Hα emission) scales linearly with the SFR. In contrast to the \( F(\text{Ly} \alpha)/F(\text{H} \alpha) \) ratio, however, the strength of Lyα relative to the UV continuum is quite sensitive to the age of the stellar population because the UV continuum can be produced by stars of insufficient mass to generate a substantial ionizing continuum. Considering the sensitivity of \( W(\text{Ly} \alpha) \) to stellar age (Cowie et al. 2011) then, the expected strength of the correlation between these Lyα measurements is not clear a priori.

Figure 8 illustrates how \( W(\text{Ly} \alpha) \) grows with \( f_{\text{esc}}(\text{Ly} \alpha) \). Even among the starburst-dominated ULIRGs, there is a nearly one-to-one correspondence, and we conclude that \( f_{\text{esc}}(\text{Ly} \alpha) \) and \( W(\text{Ly} \alpha) \) indicate a consistent picture of moderate Lyα escape fractions from starburst dominated ULIRGs. In the opposite picture where stellar age dictates \( W(\text{Ly} \alpha) \), the ULIRGs farthest along the merger sequence would in fact be expected to have the oldest stellar populations and therefore the weakest \( W(\text{Ly} \alpha) \). In contrast, we find the opposite. The most advanced mergers tend to be AGN-dominated ULIRGs, and these objects show the highest Lyα equivalent widths.

### 3.2. Caveats

In this section, we have shown that Lyα escape fractions from ULIRGs are comparable to those in more typical star-forming galaxies. We explain this surprising result by the fact that the COS spectroscopy is blind to the most active and

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9 We define the Lyα equivalent width by an integral over the line such that

\[ W(\text{Ly} \alpha) \equiv \int (F_{\lambda}(\lambda) - F_{\lambda,\text{cont}})/F_{\lambda,\text{cont}} \lambda \mathrm{d}\lambda, \] where \( F_{\lambda,\text{cont}} \) is the fitted continuum. It represents the continuum bandpass (measured in A) with the same flux as the emission line.
heavily obscured regions in ULIRGs. Unlike normal star clusters and starburst galaxies which show a strong correlation between the far-IR excess and the UV spectral slope (Meurer et al. 1995), the ULIRGs have a very blue UV spectral slope for their infrared excess. No UV radiation would be detected from ULIRGs if the dust distribution could be approximated by the foreground screen model which works so well for local galaxies. To illustrate this point, we used the GALEX magnitudes and far-IR luminosities from Table 1 and estimated the infrared excess following Meurer et al. (1995). We find the typical infrared excess value in the COS ULIRGs is $F_{\text{IR}} \approx 220$. We have only measured the escape fraction relative to the regions transparent to optical light. To estimate the escape fraction in an absolute sense, we compare the SFR from unobscured regions, as measured from the H$\alpha$ luminosity (not corrected for internal extinction), to the SFR indicated by the far-IR luminosity. We estimate that unobscured regions account for only 0.3–2% of the total SFR among the COS ULIRGs, and the measured escape fractions refer only to these unobscured regions. The absolute escape fraction increases with the blueshift of the Ly$\alpha$ emission wing, defined here as the velocity beyond which 10% of the Ly$\alpha$ emission line flux is measured. The Spearman rank order correlation coefficient is $r_s = 0.83$, and the null hypothesis is rejected at 2.4$\sigma$. The correlation strength is driven by the large $f_{\text{esc}}$(Ly$\alpha$) values inferred for the ULIRGs with the highest AGN fraction.

Figure 6. COS G130M and optical H$\beta$ spectra of the narrow-line, Seyfert 1 ULIRG IRAS15598–0112. (a) The Ly$\alpha$ and Ly$\beta$ profiles show strong absorption near the systemic velocity. The hydrogen Balmer lines have broad wings reaching nearly 2000 km s$^{-1}$. While we expect such wings on the Ly$\alpha$ profile, the even broader wings visible in the top panel are believed to be heavily blended with broad emission from metal lines including Si ii. See also the [O iii] profile in the Appendix. (b) The COS G130M spectrum shows strong absorption from high-ionization gas. No absorption is detected from low-ionization-state gas or Si iii. The absorption from high-ionization state gas is blueshifted up to 500 km s$^{-1}$. The equivalent widths of O vi $\lambda$1032 and N v $\lambda$1239 are 1.43 and 1.29 Å, respectively.

Figure 7. Ly$\alpha$ escape fraction increases with the blueshift of the Ly$\alpha$ emission wing, defined here as the velocity beyond which 10% of the Ly$\alpha$ emission line flux is measured. The Spearman rank order correlation coefficient is $r_s = 0.83$, and the null hypothesis is rejected at 2.4$\sigma$. The correlation strength is driven by the large $f_{\text{esc}}$(Ly$\alpha$) values inferred for the ULIRGs with the highest AGN fraction.

Figure 8. Correlation of $f_{\text{esc}}$(Ly$\alpha$) with equivalent width of Ly$\alpha$ emission. The ULIRGs with the highest escape fractions also have large equivalent widths. The correlation coefficient is $r = -0.82$ for the nine detections, and the null hypothesis is rejected at the 2.3$\sigma$ level. The lower limits on $|W$(Ly$\alpha$)| arise from the absence of continuum detections. The downward pointing triangles illustrate the upper limits on the two ULIRGs with no Ly$\alpha$ detection; these galaxies were arbitrarily placed at zero equivalent width since the continuum is not detected either.
fractions are far smaller than those estimated from UV and optical lines.

The COS PSA subtends 5.0 kpc at the median redshift of the sample, and measurements of Lyα flux from the COS spectra will underestimate the total Lyα luminosity. A more specific concern relevant for the \( f_{esc}(\text{Ly}α) \) results is that resonance scattering can produce large Lyα halos around galaxies relative to the angular extent of the Hα emission. Extrapolation of the Hayes et al. (2013) results for the LARS galaxies (which found the largest differences in spatial extent among galaxies with very low dust abundance) would suggest little spatial bias for the COS ULIRGs sample. Considering the unusual conditions in the ISM of ULIRGs, it would be quite interesting to directly image the spatial extent of their Lyα emission and test whether they follow the trends for halo emission defined by more normal galaxies. Since the far-UV images have peak sensitivity near the wavelength of the Lyα emission, this may be possible using using sophisticated spectral fitting techniques as outlined, for example, by Hayes et al. (2009).

### 3.3. Implications

Our discovery of blue wings on the Lyα line profiles raises the question of whether ULIRGs might have gas flows with bulk velocities of roughly \( \sim 1000 \text{ km s}^{-1} \). The large Doppler shift of the Lyα photons does not necessarily require fast outflows. The frequency diffusion which accompanies repeated scatterings can produce a large Doppler boost. For example, a resonance photon scattered back and forth repeatedly between opposite sides of an expanding shell could get a Doppler boost that greatly exceeds the shell velocity. Distinguishing bulk motion from frequency diffusion is the first critical step toward understanding the conditions that produce the line wings.

From our analysis of \( f_{esc}(\text{Ly}α) \) in Section 3.1, we concluded that the Lyα photons from IRAS12071−0444, IRAS23365+3604, and IRAS10378+1109 do not undergo many scatterings because their attenuation is similar to that of the UV continuum; hence, they probably do not receive their large Doppler boost from frequency diffusion. We also find that \( f_{esc}(\text{Ly}α) \) is most strongly correlated with the Doppler shift of the blue wing on the Lyα profile, the Lyα line width, and the Lyα equivalent width.

We explore these concepts further in Section 4. We use the optical line profiles of the ULIRGs as a template for the intrinsic profile of the emitted Lyα photons, i.e., prior to their passage through the galaxy, and discuss the implications for the Lyα radiative transfer.

### 4. COMPARISON OF H LyMAN AND OPTICAL LINE PROFILES

The optical emission lines in the Keck II/ESI spectra of the ULIRGs provide a view limited to the optically transparent holes. This perspective is, however, closely related to the regions visible in the ultraviolet spectra; many common features can be seen in the images presented in Figure 2 for example. In Figures 9(a), (b), we show the line profiles of the H Balmer lines and [O iii] λ5007 forbidden line on the same velocity scale as the COS G130 Lyα emission. We begin this section by comparing their line cores and then demonstrate the relationship between the highly blueshifted gas seen in the Keck II/ESI and COS G130M spectra.

#### 4.1. Profile Core

In Figure 9, the velocity of the Lyα absorption typically coincides with the velocity of the maximum optical emission which is near the systemic velocity. This absorption in the profile core is relatively narrow and most prominent in the H ii-dominated ULIRGs (IRAS0026+4251, IRAS10378+1109, and IRAS16474+3430) as well as the three systems with prominent AGNs (IRAS11598−0112, IRAS01003−2238, and IRAS12071−0444). The Lyα absorption follows our expectation that neutral hydrogen in these galaxies will scatter Lyα photons away from the systemic velocity.

One unexpected feature of these line cores is the residual intensity at the systemic redshift. In the IRAS16487+5447 spectrum, the central absorption troughs lie to either side of the peak Hα intensity. In IRAS11598−0112, we see emission in Lyα in the broad absorption trough near the velocity of the peak optical emission. We also note that many of the spectra are not completely black in the absorption troughs. In a few cases, this residual intensity near line center may result from the line-spread function smearing out narrower lines which are black at line center. The troughs that are completely black (IRAS11598−0112, IRAS09583+4714, IRAS16474+3430, and IRAS16487+5447) appear significantly broader however, and our highest resolution spectrum, IRAS1003−2238, shows a narrow trough which is not black. The residual intensity requires some sightlines with low column densities of neutral hydrogen, a result we will refine quantitatively in Section 6.

Scattering of resonance photons out of the line core will broaden the Lyα line profile. Following absorption near the resonance, the Lyα photons random walk in frequency space until they are either absorbed by a dust grain or are Doppler shifted to a frequency where they can escape. We therefore expect the Lyα lines to be somewhat broader than the optical lines.

To investigate the relationship between the observed and intrinsic Lyα profiles, we use a non-resonant optical emission-line to approximate the intrinsic Lyα profile shape. We have normalized the Lyα and [O iii] line profiles by their respective areas and overplotted them in Appendix. To make a quantitative comparison, we use the technique based on profile area introduced in Section 3.1.2 and further described in Appendix. We mark the IPV at \( p = 0.80 \) and take this as a measurement of the width of the core of the line profile. In the plot of IPV as a function of profile area, comparison of the Lyα and [O iii] line widths at \( p = 0.80 \) illustrates the systematically broader width of Lyα. Further inspection of these plots shows that IPV(Lyα) exceeds IPV([O iii]) at all values of the fractional profile area \( p \). It follows that the Lyα profiles are systematically broader than the optical line profiles regardless of exactly where the width is measured. The only ULIRG with an [O iii] profile broader than Lyα is IRAS16474+3430 which has been broadened by orbital motion; the 2D version of the ESI spectrum shows a second nucleus offset 1′′ from the center of the COS pointing. We therefore conclude that diffusion of resonance photons in frequency space typically explains the broadening of the cores of the Lyα profiles relative to the non-resonant lines.

#### 4.2. Line Wings

In the optical lines shown in Figure 9, the hydrogen Balmer lines typically show a broad, blueshifted line wing. The median
Figure 9. Comparison of Lyman series and optical line profiles. The Lyα absorption troughs (top row) line up with the velocities of the maxima in the optical emission lines. Comparison of the blended Hα and [N ii] λ6548, 6584 lines with the Hβ line shows the contribution of the broad line wings to the blend. The line profiles for [O iii] λ5007 demonstrate that broad wings are present on the forbidden lines as well as the recombination lines. The systemic velocities were obtained from either CO observations or the average of many optical emission lines as summarized in Table 1. Blended lines from the galaxy are indicated by solid, vertical lines, and Galactic absorption lines are indicated by dotted, vertical lines.
blueshift of the fitted wings is 250 km s$^{-1}$ (Soto et al. 2012), but this emission component often extends to 1000 km s$^{-1}$ due to its large velocity dispersion. This high velocity gas emits strongly in optical forbidden lines of [O III], [S II], [N II], and [O I]. We focus the discussion on the comparison between the [O III] 5007 line and Lyα because the former lies in a spectral region free of blends with other transitions. In contrast, if we use H$\alpha$ or H$\beta$, then the deblending of [N II] 6548, 84 or, respectively, stellar H$\beta$ absorption introduces additional noise into the analysis.

The only measurable consequence of this choice is that our template for the optical emission line profile has slightly stronger wings relative to the line core than it would had we used a Balmer line. The shape of these optical profiles differs slightly due to a change in excitation mechanism. Line ratio diagrams show that the broad component is not excited by the ionizing continuum from massive stars. Since its spatial extent is also typically larger than the broad line region of an AGN, (Soto et al. 2012) have previously fitted the diagnostic line profiles measured for the broad emission component with models for radiative shocks.

Figure 10 compares the extent of the blue wings of the [O III] and Lyα emission. For purposes of illustration, we chose the IPV markers at $p = 20\%$ as a compromise between being away from the line core yet not too sensitive to continuum placement. The velocity of the blue Lyα wing is correlated with that of the [O III] wing. We also see that the measurements of $V_{2000}$ Lyα and $V_{2000}$([O III]) scatter around the locus of equality. Even though the cores of the line profiles are relatively broad in Lyα, the blue wings are not any more extended than the [O III] line wings at the same fractional profile area. This result is noteworthy because the line profiles of the non-resonant line are not affected by scattering. The good agreement suggests the intrinsic profile of the Lyα emission contains blue line wings.

The Doppler shifts of the blue wings therefore arise at least in part from bulk motion along the line of sight and cannot be attributed solely to frequency upscattering in a static medium. Since the same flows are detected in the optical emission lines, the Doppler shift of the optical lines provides as good an indicator of $f_{esc}$ (Lyα) as did Lyα in Figure 7. Figure 11 shows this correlation of the Lyα escape fraction with the velocity of the blue wing on the [O III] profile.

Inspection of the area normalized profiles in the Appendix enables a closer comparison of the blue wings in Lyα and [O III]. The more similar the line profiles, the less radiative transfer shapes the Lyα profile. We draw particular attention to panels d (IRAS10378+1109), f (IRAS12071–0444), and i (IRAS23365+3604). Between velocities of roughly $-200$ and $-1000$ km s$^{-1}$, the shapes of their Lyα profiles are nearly identical to that of the optical line profile. We therefore conclude that radiative transfer effects play little or no role in shaping the blue wings in these ULIRGs. This result further strengthens our conclusion that the bulk velocity of the Lyα emitting gas must reach at least 1000 km s$^{-1}$ in these objects.

In stark contrast to the blue wings, the velocities of the red wings on the Lyα profiles are not correlated with the optical line profiles. Inspection of the area-normalized profiles in Appendix Figure A1(a)–(i) shows that the red wings on the Lyα line profiles extend to larger Doppler shifts than do the [O III] profiles. The greater extent of the red wing in the resonant line makes the linewidths systematically larger for Lyα. The red wings on Lyα also weaken the correlation between the Lyα and [O III] linewidths.$^{10}$ Due to the presence of the red wings, the Lyα profiles are actually less symmetric than the optical line profiles by some measures.

For example, in the Appendix, we define a line asymmetry measurement across the line profile (i.e., computed at each IPV). The asymmetry compares the relative strength of the emission redward and blueward of the median velocity and is positive for a net blueshift. The panels for IRAS12071–0444 illustrate this concept for a Lyα profile with two maxima. Near the core ($p \gtrsim 0.4$ in this spectrum), the red velocity marker is further from the median velocity than is the blue velocity marker at the same IPV; however, in the line wings ($p \lesssim 0.3$) the blueshifted profile has the larger Doppler shift. Since the optical lines do not have the redshifted components in their line

$^{10}$ The linewidths are not quite as strongly correlated as are the velocities of the blue wings. At IPV$_{0.95}$ for example, we measure $r_s = 0.85$ with the null hypothesis rejected at the 2.4σ level.
profiles, their net asymmetry parameter is positive and biased toward the blue. The redshifted component of the Lyα emission is typically not present in the optical line profiles and therefore provides another profile metric that successful models for the Lyα emission must explain.

Indeed, the main conclusion from our comparison to non-resonant line profiles is that resonance scattering does not create the high velocity wings. The absence of red wings on the optical line profiles suggested this emission arises from an outflow near the starburst region. In this scenario, we see emission from blueshifted gas on the near side, but dust in the ULIRGs blocks the redshifted emission from the far side (Soto et al. 2012). Measurements of line profiles at wavelengths that propagate through the dust generally support this interpretation. The CO1–0 line profile of IRAS23365+3604, for example, exhibits broad (albeit very weak) symmetric line wings (Cicone et al. 2014). It therefore seems likely that the blue wings observed on the Lyα line profiles are directly emitted by outflowing gas, and dust between us and the far side of this outflow attenuates the red wings on the intrinsic Lyα profile. The broad Lyα wings must be emitted by gas moving at velocities of 500–1000 km s$^{-1}$.

4.3. Comparison to Absorption-line Kinematics

The fast winds indicated by the line wings present a paradox because their Doppler shifts are significantly larger than the blueshifts of absorption lines from low-ionization-state gas. These blueshifts unambiguously mark outflowing gas because the absorbing gas must lie on the near side of the continuum source. Among ULIRGs, absorption in the Na I λ5890, 96 doublet is typically blueshifted only 200–300 km s$^{-1}$ at the deepest part of the absorption trough (Martin 2005, 2006; Rupke et al. 2005).

Many of our COS targets have weaker Na I absorption than the average ULIRG because we observed the UV brightest ones. Figure 12 illustrates the strong correlation between the Na I equivalent width and the color excess. We interpret this correlation as an ionization effect. Sodium must be shielded from near-UV photons to remain ionized; it takes just 5.1 eV to remove its outer 3s electron. The UV selection picks the ULIRGs with less reddened sightlines, and sodium is therefore more likely to be ionized.

The absence of Na I absorption does not indicate the absence of an outflow of low-ionization-state gas. The ionization state of sodium does not uniquely determine whether hydrogen is neutral or ionized along these sightlines (Murray et al. 2007). The wider range of ionization states accessible with far-UV transitions proves this point. We saw this in both Figure 4 and Figure 6, and we demonstrate it for the H α-dominated ULIRG with the best continuum S/N in Figure 13.

The spectrum of IRAS16487+5447 also demonstrates how the gas kinematics changes with ionization state. The absorption troughs from low-ionization-state gas have their deepest point near the systemic velocity. The greater Doppler shift of their blue wings (relative to the red wings) indicates a contribution from an unresolved outflow component, but these wings do not reach the $-500$ km s$^{-1}$ blueshift of the Lyα emission wing. Absorption in the medium ionization state gas probed by Si IV probably reaches $-500$ km s$^{-1}$. The warmer gas detected via O vi absorption is offset blueward of the systemic velocity and extends to velocities as large as the blueshifted Lyα emission from this object. While general conclusions should not be drawn from a single object, we note that FUSE spectroscopy of nearby starburst galaxies has previously revealed higher mean outflow velocities in O vi than low-ionization-state lines in the same spectra (Grimes et al. 2009). We add to the emerging picture the result that the Doppler shift of the broad emission-line wings appears to be more closely related to the Doppler shift of the O vi absorption than to the absorption from low-ionization-state gas.

5. ORIGIN OF BROAD EMISSION

The presence of broad line wings on the optical emission lines as well as Lyα suggests gas moving at high velocity emits the broad, blueshifted Lyα line wings. The predominance of blueshifted line wings over redshifted wings rules out a scenario involving large random motions and requires bulk flows to generate the asymmetry.

As recognized previously in the context of the narrow line region of AGNs (Whittle 1985), however, the direction of radial flow cannot be determined unambiguously from the asymmetry of an emission-line profile alone. Either wing of the intrinsic line profile can be suppressed in an outflow. Suppression of the red wing corresponds to a source of line opacity distributed throughout the outflow region. In contrast, line opacity internal to discrete clouds preferentially blocks radiation from the near side of the outflow because the ionized side of each cloud faces the central source, and the resulting line profile has a red wing.

We follow Soto & Martin (2012) and argue the bulk flow is almost certainly outward. Our primary consideration is the blueshifted absorption seen in resonance lines such as Na I, Si II, Si III, and O vi. The gas detected in absorption is clearly outflowing because it must lie between us and the galaxy. Sources of energy and momentum for the outflows include massive stars and the central AGN whereas, in contrast, we do not have a physical reason to expect gas to be flowing into galaxies at speeds around 1000 km s$^{-1}$. In the outflow interpretation, emission from the fast outflow on the far side of the galaxy produces broad, redshifted line wings. We interpret the absence of such wings in our spectra as evidence that the receding outflow lies largely behind the dusty galaxy and note that the broad, symmetric line wings on the CO(1–0) profile of IRAS23365+3604 (Cicone et al. 2014).

Our analysis generates two primary puzzles. First, what is the relationship between the fast outflow emitting the broad, emission-line wings and the lower Doppler shifts measured for the low-ionization-state absorption lines? Second, why do only the most extreme galactic outflows show these broad, emission-line wings? For example, the optical spectra of some high-redshift galaxies (Newman et al. 2012; Förster Schreiber et al. 2014; Genzel et al. 2014) show broad, emission-line wings similar to those in ULIRG spectra. We note that one common property of these high-redshift galaxies and ULIRGs appears to be exceptionally high SFR surface densities.

5.1. Cool Gas Condensing Out of a Hot Wind

We are suggesting a new picture wherein the emission wings come from filaments that condense out of the cooling hot wind. The large velocity of the blueshifted nebular emission provides the primary motivation for considering a power source associated with the hot wind fluid. Support for this picture comes from the scaling of the Lyα luminosity with the SFR.
and the structure of simple models for galactic winds launched from regions of extremely high SFR surface density.

5.1.1. Velocity of Hot Wind Fluid

When some of the supernova energy associated with star formation is thermalized, a hot wind is driven out of the starburst region. Chevalier & Clegg (1985) provided a simple analytic solution for the Mach number, thermal pressure, and density in a fast, adiabatic wind. The wind reaches Mach 1 at the launch radius $R_0$, where the mass and energy injection from the starburst region terminates. At $r = R_0$, the wind temperature in the CC85 solution, as shown for example in Equation (6) of Zhang et al. (2014), is

$$T(r) = 1.8 \times 10^7 \text{K} \mu^{\alpha/\beta}$$

where $\mu$ is the mean molecular weight per gas particle, and $\alpha$ and $\beta$ are parameters of order unity which describe the efficiency of thermalizing the supernova energy ($\alpha = E_{\text{SN}}/E_{\text{SN}}$) and entraining gas into the wind ($\beta = M_{\text{SN}}/SFR$). The specific thermal energy of this gas is sufficient to accelerate every particle up to a velocity

$$v_{\infty} = 950 \text{ km s}^{-1} \sqrt{\frac{\alpha \mu}{\beta 1.8 \times 10^7 \text{K}}}$$

The similarity between the specific thermal energy of hot winds and the specific kinetic energy of the gas emitting the nebular line wings motivates a conjecture that the highly blueshifted nebular emission arises from gas condensing out of a hot wind. Since the initial velocity of these clouds would be the speed of the hot wind, this picture explains their high velocities without introducing the problem of accelerating cool clouds to velocities much larger than their internal sound speeds; clouds tend to be destroyed by such processes.

5.1.2. Gas Density and Instability of a Cooling Hot Wind

Zhang et al. (2014) also show that the gas density in the CC85 solution increases linearly with the SFR surface density, hereafter $\Sigma_\phi \equiv SFR/\pi R_0^2$. Adopting the radiative cooling function for gas in collisional ionization equilibrium (e.g., Draine 2011 and references therein), one finds that the cooling timescale for the hot wind,

$$t_{\text{cool}}(R) = \frac{P(n, T)}{(\gamma - 1)\Lambda(T)n_e n_H}$$

declines as the starburst becomes more concentrated, i.e., $t_{\text{cool}} \propto \Sigma_\phi^{-1}$.

We can define a cooling radius where the cooling time is reduced to the outflow timescale, $t_{\text{out}} = R/v(R)$, and this cooling radius moves inward as $R_{\text{cool}} \propto \Sigma_\phi^{-1}$ for the CC85 solution and standard cooling function. Plugging in typical numbers for ULIRGS, we expect the hot wind to be cooling very close to the starburst region, in the central few kiloparsec of ULIRGS. We propose that the ULIRG winds start to cool at smaller radii than do winds in starbursts like M82 because the higher SFR surface density drives winds with higher densities and smaller cooling radii.

The high gas density at relatively small radii leads to a much higher emission measure at the cooling radius than would be expected in more typical starburst galaxies. As the wind cools, we expect a variety of unstable situations to develop as the temperature drops from the free–free portion of the cooling curve to a minimum (near $T \approx 2 \times 10^7 \text{K}$ for solar metallicity gas in CIE). Between $10^7 < T(K) < 10^{7.3}$, the cooling rate per atom begins to increase rapidly as the gas cools, $\Lambda(T) \propto T^{-0.7}$ (Draine 2011). Resolving this process and the associated condensations of clouds in numerical simulations would be enlightening.

5.1.3. The Correlation of Lyα and Bolometric Luminosity

The ULIRG Lyα luminosities span a much larger dynamic range, about four orders of magnitude, than do their far-IR luminosities. Figure 14 illustrates that a power-law scaling, $L(Ly\alpha) \propto L_{\text{FIR}}^2$, describes the luminosities of the ULIRGs not dominated by AGNs. Including the two AGNs, IRAS11598–0112 and IRAS01003–2238, the exponent steepens to approximately four.

A quadratic scaling like this has been predicted, but not observed, for the X-ray luminosity emitted by starburst winds. Using the analytic solution for a strong wind driven out of a starburst region where most the supernova energy has been thermalized (Chevalier & Clegg 1985), Zhang et al. (2014) calculate the 0.5–8.0 keV luminosity of the hot wind fluid and find $L_X \propto SFR^2$. This scaling requires constant thermalization and mass-loading efficiencies. It is interesting that Zhang et al. (2014) found that the $L_X - SFR$ relation measured among star-forming galaxies is shallower than their prediction. The shallow relation can be attributed at least in part to the diffuse X-ray emission from galaxies being brighter than the hot wind fluid. The hot wind fluid is extremely challenging to detect directly due to its low emission measure. The extended X-ray emission surrounding starburst galaxies is widely believed to emanate from intermediate temperature gas at the boundary between gas phases because it is spatially correlated with Hα emission (Strickland et al. 2004). That the Lyα luminosity increases as roughly the square of the SFR, as traced by $L_{\text{FIR}}$. 
suggests to us that this luminosity may be physically related to the cooling of the hot wind.

Zhang et al. (2014) predict the 0.5–8.0 keV X-ray luminosity of the hot wind fluid per unit SFR,

$$L_X^{\text{hot}}[0.5-8.0\,\text{keV}] = 10^{43}\,\text{ergs s}^{-1}\left(\frac{\text{SFR}}{100\,M_\odot\,\text{yr}^{-1}}\right)^{2} \times \left(\frac{200\,\text{pc}}{R_0}\right),$$ (8)

where $R_0$ describes the radius of the starburst region. We substitute the Kennicutt (1998) relation between SFR and far-IR luminosity and obtain

$$\frac{L_X^{\text{hot}}}{L_{\text{FIR}}} \approx 0.0045 \left(\frac{\text{SFR}}{100\,M_\odot\,\text{yr}^{-1}}\right) \left(\frac{200\,\text{pc}}{R_0}\right).$$ (9)

The dashed lines in Figure 14 compare the Ly$\alpha$ luminosity to $L_X^{\text{hot}}$, the predicted cooling luminosity. Among the starburst-dominated ULIRGs, the Ly$\alpha$ luminosity is $\approx 0.3\%$ of the predicted cooling radiation from the hot wind fluid. The closet analogy may be the cooling of hot gas in the centers of galaxy clusters where calculations for $T \sim 10^7$ K gas cooling non-uniformly show of order 1% of the losses in strong UV and optical emission lines (Voit et al. 1994).

As shown in Section 4.1, most of the Ly$\alpha$ photons emitted near the systemic redshift are scattered by neutral hydrogen, but the blueshifted wing on the Ly$\alpha$ profiles does not arise from scattering and may therefore be emitted at larger radii. The luminosity of just this highly blueshifted component may be more directly related to the cooling wind than is the total Ly$\alpha$ luminosity.

We compare just the Ly$\alpha$ luminosity emitted blueward of $-500$ km s$^{-1}$ with the far-IR luminosity in Figure 15. The luminosity of the highly blueshifted Ly$\alpha$ emission increases with the far-IR luminosity. Among the H II-dominated ULIRGs, the highly blueshifted Ly$\alpha$ emission is about 0.1% of the far-infrared luminosity. The blueshifted Ly$\alpha$ emission is a larger fraction of $L_{\text{FIR}}$, roughly 5%, in the AGN-dominated

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**Figure 13.** Absorption lines in the COS G130M and ESI (top left only) spectra of IRAS16487+5447. Note the lack of Na I absorption compared to the strong Si II 1190, 1193, and 1260 lines. The Si I lines are not as broad as the Si II 1206 absorption. The O VI 1032 absorption trough reaches even higher blueshifts of at least $-500$ km s$^{-1}$. (Note the blended O VI 1038 trough precludes the same measurement.) The O V absorption may have some contribution from stellar winds as well as warm gas in a galactic outflow. Precise measurements of these troughs are sensitive to the modeling of the line spread function and the continuum placement.
ULIRGs. The steeper than quadratic rise in $L_{\text{Ly}\alpha}$ with $L_{\text{FIR}}$ between the H\textsc{i}-dominated AGN-dominated ULIRGs shows that the emergence of the AGN increases the Ly\textalpha emission from ULIRGs.

5.2. Fermi Acceleration of Ly\textalpha Photons

The framework for the fast outflows should explain the shock speeds measured from optical emission-line ratios in addition to the lower Doppler shifts of resonance absorption lines. The scattering of Ly\textalpha photons across shock fronts could be one such mechanism. Neufeld & McKee (1988) have shown that scattering of resonance photons across shock fronts systematically blueshifts the photons. Since the photons pick up a Doppler shift of $0.5v_{sh}$ on each scattering, the blueshift exceeds the shock velocity after only a few reflections across the shock front.

We considered the shocks identified by Soto et al. (2012) IRAS00262+4251 as a preliminary test of this idea. A shock speed of $v_{sh} = 225 \pm 50$ km s$^{-1}$ fit the optical emission-line ratios well. In the Fermi acceleration model, only three such scattering encounters are sufficient to produce the observed line wing in IRAS00262+4251 which has $v_{20} = -326$ km s$^{-1}$. The Doppler shift of the peak scattered emission scales as $v_{pb} = 270(N_{20}v_{20})^{1/3}$ in their model.

The scaling of this model predicts the velocities of the blue wings increase with shock speed and the column density of the neutral gas, $N_{20}$. Comparison of the shock velocities from Soto & Martin (2012), reproduced here for convenience in Table 5, against the velocity of the blue wings from Table 4 reveals no correlation between the two velocities. It follow that the column density of neutral gas would have to be correlated with the velocity of the blue wing for the data to support Fermi acceleration acceleration as the primary explanation for the Ly\alpha line wings. We have argued, however, that the column densities are lowest in the objects with the bluest line wings because we measure the largest $f_{\text{esc}}(\text{Ly}\alpha)$ in those objects. Hence, we find no compelling evidence that Fermi acceleration shapes the blue wings on the ULIRG Ly\alpha profiles. We emphasize, however, that the correspondence between the shapes of the Ly\alpha and optical line wings varies considerably among the ULIRGs. And Fermi acceleration seems like an important physical process that could play a role in some objects although it awaits compelling empirical support.

5.3. Relation between Outflow Velocity and Galaxy Size

Some wind models predict the fastest outflows from the most compact starbursts. For example, Murray et al. (2011) argue that the cluster luminosity cannot grow much beyond its Eddington limited value due to outflows driven by radiation-pressure which disrupt giant molecular clouds faster than the cloud dynamical timescale. Momentum conservation requires terminal velocities scale as

$$V_{\text{term}} \propto R_0^{-1/2},$$

where $R_0$ again describes the radius of the region where the wind is launched. In general support of this scenario, the galaxies with the most blueshifted resonance absorption turn out to indeed be very compact with radii of roughly 100 pc (Tremonti et al. 2007; Heckman et al. 2011; Diamond-Stanic et al. 2012). The discovery of fast outflows from ULIRGs therefore begs the question of the starburst size in ULIRGs and the SFR surface density.

The starbursts in ULIRGs have long been considered concentrated, and one of the main differences between ULIRGs and the sub-millimeter-selected galaxies at high redshift is the smaller size of the starburst region in the former. One estimates the effective size of the starburst region in a ULIRG from a blackbody argument. This approach assumes the galaxy is optically thick. For example, Scoville et al. (2013) give

$$R_{\text{FIR}} = 1.09 \text{kpc} \left(\frac{L_{\text{FIR}}}{10^{12}L_\odot}\right)^{1/2} \left(\frac{35 \text{ K}}{T_d}\right)^2,$$

where the fiducial dust temperature, $T_d$, was chosen to represent starburst dominated ULIRGs. If the source is optically thin, then this equation provides a lower limit on the radius.

Substituting the far-IR luminosities from Table 1 into Equation (11), we estimate the starburst radii range from 0.85 to 1.2 kpc and greatly exceed those of the DCO and the massive, post-starburst samples. This result is clearly sensitive, however, to the assumed dust temperature. If $T_d \approx 100$ K in the AGN-dominated ULIRGs IRAS11598–0112, then Equation (11) gives a size for the emitting region of just $R_{\text{FIR}} \approx 0.18$ kpc (100 K/$T_d$)$^2$.

From Equation (11), we can see that far-IR sizes for starburst-dominated ULIRGs will increase as the square-root of their luminosity, $R_{\text{FIR}} \propto L_{\text{FIR}}^{1/2}$. Hence, any correlations between starburst size and fast outflows in the COS ULIRGs sample reduces to the strength of the correlation between the blue wings and the far-IR luminosity. Regardless of whether we consider Ly\alpha or optical emission lines, the line wings extend to
higher velocities in more luminous systems.\footnote{Formally, the correlation coefficient between $V_{20,\alpha}$ (Ly$\alpha$) and $L_{\alpha}$ (Ly$\alpha$) is $R_5 = -0.62$ at only 1.74σ significance. The Ly$\alpha$ luminosity correlates more strongly with the velocity of the blue wing on the [O~III] line, $V_{20,\alpha}$ ([O~III]), and we measure a correlation $R_5 = -0.80$ at 2.26σ significance. The correlation of the Ly$\alpha$ luminosities with the far-infrared luminosities is not one-to-one, and it is interesting that the correlations weaken when we replace $L_{\alpha}$ with $L_{\text{FIR}}$. The correlation coefficient between $V_{20,\alpha}$ (Ly$\alpha$) and $L_{\text{FIR}}$ is $R_5 = -0.60$ at 1.79σ significance. The far-infrared luminosity correlates less strongly with the velocity of the blue wing on the [O~III] line, $V_{20,\alpha}$ ([O~III]), and we measure a correlation $R_5 = -0.57$ at 1.61σ significance.} We conclude that among the starburst ULIRGs, those with larger far-IR sizes tend to show more extended blue wings in Ly$\alpha$. Only when the starburst dominated ULIRGs are compared to the AGN-dominated ULIRGs as a class would we recover the inverse scaling of faster outflows from smaller launch regions that the escape velocity argument would favor.

For completeness, we also estimate NUV sizes using the WFC3/F225W images shown in the middle panel of Figure 3. Specifically, we measured the area of the aperture enclosing all the pixels with surface brightness greater than a fiducial value of $S_{\nu}^\text{cut} (\lambda 2366) = 7.1 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ kpc$^{-2}$. This threshold represents a SFR of 0.1 $M_\odot$ yr$^{-1}$ kpc$^{-2}$ for continuous star formation (of duration greater than 100 Myr with a Salpeter initial mass function) and is of interest because it is widely believed to be the minimum value required to drive galactic winds Heckman et al. (2003). We find values of this $R_{\text{NUV}} \equiv (A/\pi)^{1/2}$ from 0.5 to 8.2 kpc. We find no correlation between these NUV sizes and the FIR sizes; the assumed dust temperature is irrelevant to this comparison because our imaging sample excludes the ULIRGs with the strongest AGN. We find that IRAS12071–0444 has a large size $R_{\text{NUV}} = 5.3$ kpc which supports our argument (Section 2.1.2) that the starburst is at least as luminous as the AGN in this object. These NUV sizes show no correlation with $V_{20,\alpha}$.

The notable point here is that for a constant dust temperature, the larger starbursts show higher outflow velocities, and this trend is opposite to both the theoretical prediction for clouds accelerated by radiation pressure and the Doppler shifts of resonance absorption lines in spectra of extremely compact starbursts. In our proposed picture, however, the broad wings on emission lines come from condensation of the hot wind whereas the resonance absorption lines come from clouds accelerated by some combination of radiation pressure, cosmic rays, and/or the hot wind. The difference between the scaling relation for the broad line wings and the resonance absorption lines therefore poses no obvious contradiction but should be explored further via numerical simulations. We also emphasize the need for resolved measurements of the starburst sizes in ULIRGs and/or SED constrained dust temperatures; short of these, the size estimates too uncertain to consider them compelling evidence for the condensation scenario.

### 5.4. Evolution of Ly$\alpha$ with Merger Progression

ULIRGs are examples of $L^*$ galaxies caught during their transition to the red sequence. As we do not yet understand what makes, and keeps, galaxies “red and dead,” direct measurements of feedback in these objects are of particular interest. What we know already is that toward the final merger stage a larger fraction of the bolometric luminosity in ULIRGs appears to be powered by an accreting, supermassive black hole (Veilleux et al. 2009), and the accompanying increase in bolometric luminosity correlates with an increase in the speed of the molecular outflows (Veilleux et al. 2013). It is interesting to explore how the broad line wings fit into this picture.

To make this comparison, we refer back to the AGN fractions introduced in Section 2.1.2 and supplement those classifications with measurements of the far-IR luminosities. In Figure 14, for example, we saw that the ULIRG with the dominant AGN is 25% more luminous than any of the other objects in the sample; this result is consistent with the trend that more luminous ULIRGs have a higher AGN fraction on average. What Figure 14 shows that had not been seen before is a high ratio of Ly$\alpha$ to far-IR luminosity in IRAS11598–0112 and in the ULIRG with the next highest AGN fraction, IRAS1003–2238. We note that the enormous increase in the strength of the Ly$\alpha$ emission (relative to $L_{\text{FIR}}$ in these two ULIRGs) and attribute it to the emergence of the AGN. This increase in Ly$\alpha$ production may be directly related to the AGN spectrum or (indirectly) to changes in the ISM induced by AGN feedback which enhance the escape fraction of Ly$\alpha$ photons. The take-away point is that the ULIRGs with a dominant AGN show evidence for additional production of Ly$\alpha$ emission.

Starbursts, in contrast to AGNs, produce the majority of the bolometric luminosity in the typical COS ULIRG, so an important question is whether the blueshifted wing on the Ly$\alpha$ profile in a starburst-dominated spectrum could be directly related to an AGN, albeit a less luminous one. In our opinion, the properties of the starburst ULIRGs measured to date suggest the answer is no. First, we have demonstrated that the kinematics of the Ly$\alpha$ wings indicate they come from the same parcels of gas emitting the weaker, but equally broad, wings on the optical emission lines. Among the starburst-dominated
ULIRGs, the region of broad optical emission subtends an angle along the ESI slit that corresponds to up to 20 kpc with an average radius of 3 kpc. Due to the large size of the excited region, it is more natural to attribute the shock-like line ratios of the broad component to outflows rather than to the narrow-line region of an AGN (Soto et al. 2012; Soto & Martin 2012). Second, we found that the ratio $L(\text{Ly}$α)/$L_{\text{FIR}}$ is over an order of magnitude higher in the AGN-dominated ULIRGs than in the starburst-dominated ULIRGs. This abrupt jump indicates strong evolution in either the production mechanism or escape fraction of Ly$\alpha$ emission as the AGN luminosity grows. We would have expected a continuous increase in $L(\text{Ly}$α)/$L_{\text{FIR}}$ with $L_{\text{FIR}}$ if the AGN produced the Ly$\alpha$ emission in the starburst-dominated ULIRGs.

In our initial discussion of Figure 3, we noted that the Ly$\alpha$ wings extend to larger blueshifts as the Ly$\alpha$ luminosity increases. Since the AGN fraction is known to grow with increasing bolometric luminosity, we plot the velocity of the blue wing against far-IR luminosity in Figure 16. In this plane, the correlation between the Doppler shift and luminosity is less pronounced (than $V_{B20}$ versus $L(\text{Ly}$α)) because IRAS01003−2238 has the second highest Ly$\alpha$ luminosity but an average $L_{\text{FIR}}$. It is the broad Ly$\alpha$ and optical emission-line wings on the mini-BAL, IRAS11598−0112, which give the impression of increasing Doppler shift with increasing $L_{\text{FIR}}$ in Figure 16.

Veilleux et al. (2013) found that the velocities of the molecular outflows in ULIRGs increased gradually with AGN fraction but showed no significant dependence on the SFR. While the overall correlation seen in Figure 16 is not inconsistent with the trend seen among the molecular outflows, neither do the data strongly support it when one looks closely at the AGN fraction among individual systems. For example, the Seyfert 2 galaxies IRAS01003−2238 and IRAS12071−0444 have AGNs which produce up to 50% of $L_{\text{bol}}$, but their $V_{B20}$ measurement are nearly the same as that of IRAS10378+1109 and lower than that of IRAS23365+3604, two ULIRGs with small AGN fractions.

Detailed mapping of the Ly$\alpha$, optical, and molecular line wings is needed to clarify the relationships among these outflow diagnostics. As a prelude to such work, we simply note that Veilleux et al. (2013) provide measurements of the molecular outflow speeds for two of the COS ULIRGs: IRAS12071−0444, $V_{B20}(\text{OH}) = -321 \text{ km s}^{-1}$, and IRAS23365+3604, $V_{B20}(\text{OH}) = -604 \text{ km s}^{-1}$. The blueshifts of the broad Ly$\alpha$ wings ($V_{B20}(\text{Ly}$α) = −743 and −1046 km s$^{-1}$, respectively) indicate faster outflows than do the OH measurements. Whether these discrepancies reveal different components of the bulk flow or merely variations in measurement technique remain to be determined.

Further exploration of the variation in outflow diagnostics along the merger sequence promises to provide an empirical description of how feedback disrupts the ISM of a galaxy. We will show in Section 6 that modeling the Ly$\alpha$ wings places significant limitations on the column density of neutral hydrogen along the ULIRG sightlines. In the most extreme cases, which are the AGNs, the feedback has generated holes in the ISM which have become optically thin to Lyman continuum radiation.

6. RADIATIVE TRANSFER MODELING

To better determine the physical conditions along the UV-selected sightlines, we performed Monte-Carlo radiative transfer simulations for the Ly$\alpha$ emission. We first tried a simple model consisting of a thin spherical shell moving radially at velocity $V_r$ (Ahn et al. 2003; Verhamme et al. 2006). The shell has a column density $N(\text{H}1)$ in neutral hydrogen and dust optical depth $\tau$. We found it difficult to produce emission at the systemic velocity and the broad blue wings with this model, so we added a single parameter, $f_s$, to the shell model to describe the covering factor of neutral gas; in this fiducial model, a fraction of sightlines $1 - f_s$ intersect a “hole” which contains no neutral gas and dust (Behrens et al. 2014).

The spectrum of Ly$\alpha$ photons emerging from a spherical shell that contains a hole depends on direction (see Behrens et al. 2014 for a detailed analysis). Here, we capture this effect in a simplified (but faster) way, which is based on the fact that sightlines through the holes contain a superposition of the intrinsic (unscattered) and the scattered spectrum. We denote the (normalized) spectrum a function of velocity offset $\nu$ (of Ly$\alpha$ photons that scatter at least once with $S_{\text{int}}(\nu)$) while we denote the intrinsic spectrum with $S_{\text{int}}(\nu)$. Under the assumption that scattered radiation emerges isotropically$^{12}$ the normalized spectrum of Ly$\alpha$ photons along sight lines passing through holes is

$$S_{\text{holes}}(\nu) \propto f_s S_{\text{scat}}(\nu) + S_{\text{int}}(\nu),$$  

(12)

in which $f_s$ denotes the fraction of photons that scatter, which depends on the hole covering factor $1 - f_s$.

We carried out the calculations using the code described previously in Dijkstra et al. (2006a, 2006b). We used $10^7$ Ly$\alpha$ photons initially distributed in frequency according to a model line profile matched to the H$\beta$ profile. This intrinsic Ly$\alpha$
spectrum implicitly associates the source of the Lyα photons with recombination in HII regions. We start with a Doppler parameter $b = 12.9 \, \text{km s}^{-1}$ but find it necessary to increase it to 40–50 km s$^{-1}$ to fit IRAS01003–2238, IRAS10378+1109, and IRAS09584+4714–B. Since Behrens et al. (2014) showed that the spectrum which emerges from a shell containing holes depends on direction, we also explored the directional dependence of the spectrum. We studied Lyα transfer through shells that contain holes and predicted spectra for those sightlines passing through the holes. We found the best fitting models were consistent (within a factor of roughly two) with those obtained from the fiducial model. We use our fiducial model, however, because it requires significantly fewer photons to construct spectra (it assumes spherical symmetry), and is therefore better suited to exploring the parameter space describing the shell.

Our approach was to find shell models that reproduce the basic properties of the COS Lyα profiles and then gain physical insight from the model parameters. The detailed Lyα shape will clearly depend on factors in addition to the model parameters including viewing angle, source size, and shell thickness which are not directly constrained. Figure 17 shows examples of models that describe the main features of each of the 9 COS Lyα profiles. The parameters, which are shown on each plot, span a substantial range but generally indicate low column densities of neutral gas ($N_{H_\alpha} \lesssim 2 \times 10^{20}$ cm$^{-2}$), median shell velocity of 80 km s$^{-1}$, covering fractions from 0.3 to 1, and relatively low dust optical depths ($\tau_d \lesssim 2$). The model parameters, however, are likely representative of the true values (along the least obscured sightlines) to within a factor of a few as supported, for example, by our finding similar parameters for models in which we accounted for the directional dependence of the spectra that is naturally associated with shells that contain holes.

The absorption troughs in the COS spectra determine the velocity of the neutral gas in the shell model. In our description...
of IRAS09583+4714-B, for example, an expanding shell absorbs the Lyα photons emitted slightly blueward of line center due to the Doppler shift of the source in the frame of the shell. Figure 17 shows the fit with log $N_{\text{H I}}$(cm$^{-2}$) = 20.0, $V$ = −80 km s$^{-1}$ (blueshift), and near unity covering fraction, $f_C$ = 0.9. The flux minimum in the IRAS23365+3604 Lyα profile is also well modeled with a shell moving, but the strong transmission at the systemic velocity precludes neutral gas at the systemic velocity and requires a shell velocity near 400 km s$^{-1}$. Similarly, a shell moving at ±150 km s$^{-1}$ allows transmission near the systemic velocity in IRAS15198−0112. The redshifted absorption in the IRAS16474+3430 COS spectrum, which exhibits an inverted P Cygni profile with blueshifted emission, is well described by an shell falling toward the galaxy at roughly 250 km s$^{-1}$. We produced the redshifted dip in the IRAS01003−2238 Lyα profile with infall at 200 km s$^{-1}$. In contrast to these neutral gas flows, a static shell or simply the galactic ISM absorbs Lyα photons near the systemic velocity in the spectra of IRAS00262+4151 and IRAS12071−0444, and the low shell velocities in IRAS10378+1109 (30 km s$^{-1}$) and IRAS16487+5447 (50 km s$^{-1}$) could plausibly arise from wavelength calibration errors rather than bulk motion.

Transmission at the shell velocity can be recognized by emission lines within saturated absorption troughs or absorption troughs that are not black and requires either partial covering, and therefore some leakage of the intrinsic spectrum, or a low column $N$(H I) < 10$^{17}$ cm$^{-2}$ (Behrens et al. 2014). The model for the Lyα spectrum of IRAS01003−2238 requires columns of neutral hydrogen which are optically thick to the Lyman continuum. The transmission at zero velocity in the IRAS15198−0112 COS spectrum required a model with a low H I column to $N$(H I) < 10$^{18.8}$ cm$^{-2}$. It is interesting that while IRAS23365+3604 has substantial emission at the systemic redshift, Lyman continuum radiation will be absorbed by the shell at 400 km s$^{-1}$ and will not escape the galaxy. These results are consistent with a decline in the neutral gas column as the merger progresses since IRAS23365+3604, IRAS15198−0112, and IRAS01003−2238 are classified, respectively, as a close binary/pre-merger, compact merger, and old merger.

The dust optical depth in the models can be directly compared to the measured nebular reddening. The dust optical depth near Lyα is $\tau_d$ = 10.0E(B − V) for the Cardelli et al. (1989) reddening curve, so it is trivial to convert the color excess listed in Table 5 to a measured dust optical depth. Comparison to the model $\tau_d$ in Table 6 shows that the dust optical depth inferred along the UV sightlines is generally lower than that measured toward the H II regions. A number of physical interpretations are possible, and we note only that this result suggests the UV and optical sightlines do not sample exactly the same regions of these complex systems.

This modeling exercise also provides insight into the origin of the broad wings of the COS Lyα profiles. The blueshifted emission in the Lyα line can be attributed primarily to the blue wing of the intrinsic profile.

### 6.1. Comparison to Previous Modeling

Verhamme et al. (2014) and Behrens et al. (2014) have also recently explored the Lyα profiles of shell models with low neutral columns and partial covering. Our results strongly support the primary conclusion of those studies, namely that the emergence of Lyα emission near the systemic velocity boosts the probability that ionizing photons may leak through.

The major difference is that we start with intrinsic profiles which have blue wings. The intrinsic Lyα profile may have a red wing in addition to the blue wing, but we start with the simplest profile with which we can model the data.

The Lyα signatures that betray the escape of Lyman continuum photons may, however, depend quite a lot on the model. For example, Verhamme et al. (2014) suggest that the peak Lyα emission from density-bounded H II regions (Osterbrock & Ferland 2006) shifts by less than 150 km s$^{-1}$ from the systemic velocity. Close inspection of Figure 17 shows that the shift between the absorption feature and the maximum emission ranges from 150 to 300 km s$^{-1}$ in IRAS00262+4251, IRAS10378+1109, IRAS16474+3430, and IRAS12071−0444; our models for these profiles all have log $N_{\text{H I}}$(cm$^{-2}$) > 18.0, so our results are consistent with the hypothesis that no Lyman continuum escapes. Our model for IRAS01003−2238, however, requires a low enough column density that we expect a significant Lyman continuum escape fraction, yet the emission peaks are still shifted by more than 150 km s$^{-1}$, specifically +200 and −300 km s$^{-1}$ from the absorption feature visible at 200 km s$^{-1}$ in Figure 17. Adding an anisotropic gas distribution to the fiducial model could produce velocity shifts as large as we measure (even for low neutral gas columns) when viewed from specific directions (Behrens et al. 2014).

The Verhamme et al. (2014) study concludes that peak separation will be less than 300 km s$^{-1}$ when Lyman continuum escapes. The peak separation in our radiative transfer simulation of IRAS01003−2238 is larger, close to 500 km s$^{-1}$. In our model, we must have the shell moving at 200 km/s to get the absorption right. We cannot increase the neutral hydrogen column density of the shell much above 10$^{17}$ cm$^{-2}$, or we run into trouble with the observed damping wing. The photons that are absorbed in this shell and then backscatter pick up a redshift of 1 times the outflow velocity (because they appear practically at resonance in the frame of the gas). In this model, the peak-trough separation is twice the shell velocity.

Figure 3 of Verhamme et al. (2014) indicates that the blue peaks go away when the shell velocity exceeds 100 km s$^{-1}$. Our model for IRAS01003−2238 (the thin case) as well as those for IRAS16474+3430, IRAS11598−0112, and IRAS23365+3604 all have blue peaks even though the shell velocity in the model is larger than 100 km s$^{-1}$. This difference further emphasizes our result that the intrinsic Lyα profiles of the COS ULIRGs, prior to processing by radiative transfer, must have high velocity blue wings and suggests the above quantitative result might change with assumptions about the shape of the intrinsic line profile.

### 6.2. Other Evidence for the Escape of Ionizing Radiation

While radiative transfer models clearly provide extremely useful insight into the physical conditions in ULIRGs which shape their unusual emergent Lyα profiles, the simple geometry inherent to these models probably precludes detailed quantitative assessment of Lyman continuum escape from the separation of profile peaks alone (see Section 6.3 for a discussion). What they confirm, however, is that the shapes of the Lyα profiles is the COS spectra make ULIRGs leak some Lyman continuum radiation. A quantitative measurement of this leakage requires direct detection of the Lyman continuum. Short of that, however, we can only consider other indirect tracers of the optical depth.
Table 6
Radiative Transfer Models for a Neutral Shell

| Name                   | log $N_{\text{H}}$ (cm$^{-2}$) | $V$ (km s$^{-1}$) | $\tau_d$ | $\beta$ |
|------------------------|---------------------------------|------------------|----------|---------|
| IRAS00262+4251         | 19.9                            | 0                | 0        | 0.3     |
| IRAS01003–2238         | 17.0                            | 200              | 0.01     | 0.5     |
| IRAS09585+4714B        | 20.0                            | -80              | 0.4      | 0.9     |
| IRAS10378+1109         | 19.5                            | -30              | 0.01     | 0.5     |
| IRAS11598–0012         | 18.8                            | +150             | 2.8      | 1.0     |
| IRAS12071–0444         | 20.3                            | 0                | 0        | 0.8     |
| IRAS16474+3340         | 18.5                            | +250             | 2.0      | 1.0     |
| IRAS 16487+5447        | 19.5                            | -50              | 0.6      | 1.0     |
| IRAS 23265+3604        | 19.6                            | -400             | 0.05     | 1.0     |

Note. Col 1: name. Col 2: column density of neutral hydrogen. Col 3: shell velocity using the convention that outflows have a negative sign. Col 4: dust optical depth. Col 5: covering fraction of neutral gas.

In particular, the ESI spectra cover the $\lambda\lambda$3726, 29 doublet as well as the [O iii] $\lambda\lambda$4959, 5007 doublet. Extreme flux ratios, $F$[O iii]/$F$[O ii] $\gtrsim$ 9 can be an indication of density bounded H ii regions that have undersized O$^+$ zones (Jaskot & Oey 2013). Hence, our radiative transfer modeling results predict a very high flux ratio for IRAS01003–2238. In support of this prediction, we confirm that this AGN has the highest flux ratio in the COS ULIRG sample, $F$[O iii]/$F$[O ii] $\approx$ 6.0. The only other COS ULIRG with a flux ratio greater than 2 is IRAS12071–0444, a possible AGN, with $F$[O iii]/$F$[O ii] $\approx$ 4.5 and a much higher fitted neutral gas column in Table 6. These line ratios would hardly be compelling evidence for Lyman continuum escape on their own because the high ratios could also be produced by large ionization parameters in these nebulae, but they support our conclusions that (1) IRAS01003–2238 almost certainly has the lowest neutral gas column in the COS ULIRGs sample, and (2) it is plausibly optically thin to the Lyman continuum.

Another approach would be to measure the relative residual intensity in the cores of the strongest low-ionization-state absorption lines (Heckman et al. 2001; Grimes et al. 2009; Heckman et al. 2011; Jones et al. 2013). Partial covering of low ionization state gas can be measured from the depth of saturated absorption lines (Martin and Bouché 2009). Deeper COS spectra, such as one might obtain for purposes of directly measuring the Lyman continuum, could be used to measure the covering fraction via lines of Si ii or C ii.

6.3. Other Explanations for Ly$\alpha$ Escape at Line Center

Shell models are frequently used to model Ly$\alpha$ lines because of the relatively small number of parameters (Verhamme et al. 2008). We found that ordinary shell models could not fit these lines. We therefore introduced a hole, which represents a simple way to include anisotropic escape. These models allow for more Ly$\alpha$ photons to escape without scattering, and at line center. We stress that however, that the escape of Ly$\alpha$ photons at line center is not a unique signature of clear sight lines to the nebular regions. Two alternative explanations exist in the literature.

1. Garavito-Camargo et al. (2014) have shown that Ly$\alpha$ transfer through rotating optically thick clouds can give rise to Ly$\alpha$ photons escaping at line center.
2. The “Neufeld mechanism” (Neufeld 1991) allows photons emitted at line center to escape at line center from an optically thick medium if they only scatter off the surfaces of clumps in a multiphase medium. In order for the Neufeld mechanism to transmit photons at line center, we need stationary clumps (line center photons would not appear at line center in the frame of out-or-inflowing clumps). We can replace our “empty” holes with holes that are fully covered by stationary clumps with $N_{\text{H}} \sim 10^{17}$ cm$^{-2}$. This would not affect the RT much in models in which shells contain $N_{\text{H}} \gg 10^{17}$ cm$^{-2}$, but it would modify the radiative transfer in e.g., object IRAS01003–2238 in which we inferred $N_{\text{H}} = 10^{17}$ cm$^{-2}$.

Our models for the observed Ly$\alpha$ lines are therefore likely not unique: for example, it remains possible that some observed line profiles allow our “holes” to contain enough H ii to be opaque to ionizing radiation. However, in some models (e.g., IRAS01003–2238) there is so little scattering at all frequencies that this is likely not possible. Addressing both the effects of rotation and clumps in a systematic way is well beyond the scope of this paper, but we expect to explore this in more detail in a separate paper, in which we will also study the additional constraining power of observing the Ly$\beta$ regime (repeated surface scattering of Ly$\beta$ photons is limited by the conversion probability of Ly$\beta$ into H$\alpha$ + 2$\gamma$ continuum).

7. SUMMARY AND IMPLICATIONS

Feedback from star formation on interstellar gas is central to theories for galaxy formation and evolution, and the most plausible mechanism for powering the removal of gas and metals from galaxies remains a galactic wind. The challenge at present revolves around translating the observable signatures of these winds into physical properties. One promising path forward would be to connect measurements of outflows to simple, analytic descriptions of the wind physics. Our confidence in this mapping would be enhanced if we could understand different observational diagnostics in the context of a simple physical framework.

In this paper, we used new far-UV spectroscopy from HST/ COS in concert with high-resolution optical spectroscopy to compare signatures of galactic outflows. The sample includes the most luminous and dusty starbursts found at low redshift, yet we detected Ly$\alpha$ emission from 9 of the 11 galaxies. Even more surprising, however, only the spectrum of the galaxy that is not a ULIRG (IRAS09583+4714-B) shows the classic P Cygni profile produced by resonance scattering off an expanding, neutral medium. We do identify signatures of resonant scattering in the Ly$\alpha$ profiles; these include absorption near the systemic velocity, broad line cores compared to non-resonant lines, and a redshifted component absent in the optical lines.

The unanticipated feature of the Ly$\alpha$ line profiles is their broad, blue wings. The blueshift of this emission exceeds 500 km s$^{-1}$ in five of the COS ULIRGs. It seems plausible, perhaps likely, that these wings arise from AGN activity in IRAS11598–0112 and IRAS01003–2238, the two objects where an active nucleus provides $\gtrsim 50\%$ of the bolometric luminosity. In contrast, the total Ly$\alpha$ luminosity is over an order of magnitude lower (when measured relative to the far-IR luminosity) in the ULIRGs with starburst-dominated spectra and cool far-IR colors. We find it more natural to consider origins for the broad wings related to the starburst winds in these systems.

We attribute the large Doppler shifts (of order 1000 km s$^{-1}$) to bulk outflow based on (1) the close correspondence between the
shapes of the blue wing on the Lyα and optical emission-line profiles, (2) the similar attenuation of the Lyα line and the underlying continuum, and (3) the need to include these wings on the intrinsic Lyα profile in radiative transfer modeling of the emergent line profile. This blueshifted Lyα emission must come from the near side of the galaxy and hence outflowing; otherwise the resonance photons would be scattered by the neutral hydrogen column. The velocity of the outflowing gas in the line wings is two to three times the escape velocity from the starburst.

The high velocity of the Lyα emission compared to the lower blueshift of resonance absorption lines poses a paradox. The low-ionization-state gas traced by Na I and Si II absorption is moving outwards more slowly than the denser gas seen in emission. The Doppler shifts of the emission-line wings also exceed the shock velocities fit to emission-line ratios by a factor of two to three. We do detect gas in absorption at these high velocities via the O VI 1032, 1038 doublet. This tantalizing factor of two to three we do detect gas in absorption at these high velocities via the O VI 1032, 1038 doublet. This tantalizing factor of two to three.

Motivated by our initial goal of tying attributes of the line profiles to simple, physical models for galactic outflows, we advance the conjecture that this cool, fast gas is a direct product of gas condensing out of the hot phase of the wind (Chevalier & Clegg 1985; Wang 1995). In support of this scenario, we demonstrated that the luminosity of this component increases steeply with the SFR, following predictions for the total power radiated by the hot wind. While most of that energy would be radiated in X-rays, we believe we have identified the few times 0.1% of that cooling radiation emitted in Lyα and optical lines (by its large Doppler shift). Since the cooling timescale will be decreasing rapidly as the wind temperatures falls to where the gas emits strongly in these lines, we expect it to be unstable and forms dense clumps or filaments. On qualitative grounds, some association with fast shocks seems likely; however it remains to be shown (using numerical simulations for example) why the shock speeds are lower than the fastest outflowing gas. Indeed, the low-ionization-state absorption is widely believed to mark outflowing clouds accelerated by the hot wind and/or radiation, and the shocks could be generated by the interaction of this low-ionization-state component with the cooling hot wind.

If the broad emission-line wings do in fact mark the cooling hot wind, then the absence of this feature in the spectra of many starburst galaxies requires explanation. While fully exploring this topic is beyond the scope of this paper (see T. A. Thompson et al. 2015, in preparation), the winds from the galaxies with the highest SFR surface densities would appear to be good candidates for small cooling radii. Denser winds cool faster and reach the critical inflection in the cooling curve closer to the starburst region where the emission is brighter due to the higher density (prior to geometrical dilution by the expansion).

The relationship between the various outflow diagnostics in ULIRGs should be applicable to a wide range of intensely star-forming galaxies over cosmic time. These ULIRGs share a common property with high-redshift galaxies, namely high gas accretion rates, and evolve toward a quiescent state on the merger timescale. When ordered in a temporal sequence based on the merger progression, we find the fastest outflows and the lowest columns of neutral gas in the most advanced merger stages. These late stages show a larger contribution to L_{FIR} from AGNs, but the outflows develop long before the AGN dominates L_{FIR}. The combination appears to drill holes through the neutral gas which allow a small percentage of the Lyman continuum to escape from even these extremely dusty galaxies.

One of the important outcomes of this study is the prominent blue wings on the Lyα profiles also exist on the optical emission lines; the optical wings are less prominent but cover the same velocity range as the Lyα wings. It should be possible to resolve and study these fast outflows over much of cosmic time using highly multiplexed, infrared spectroscopy from the James Webb Space Telescope. Deeper observations with COS could provide detections of resonance absorption lines across a broad range of ionization states further defining the relationship between the signatures of outflows in absorption and emission lines.

This research was supported by the National Science Foundation under AST-1109288 (C.L.M.) and was partially carried out at the Aspen Center for Physics which is supported by the National Science Foundation under grant No. NSF PHYS-1066293 and the Kavli Institute for Theoretical Physics under support from the National Science Foundation under grant No. NSF PHY11-25915. We thank Tim Heckman, Norman Murray, and Todd Thompson for stimulating discussions about this work. We also wish to recognize and acknowledge the highly significant cultural role that the summit of Mauna Kea has always had within the indigenous Hawaiian community. It is a privilege to be given the opportunity to conduct observations from this mountain.

Facilities: Keck:II, HST

APPENDIX

VELOCITY MEASUREMENTS

In order to compare Lyα profile to the optical emission lines in this work, we require quantitative measurements of the shapes of the emission-line profiles. Below, we follow the method introduced by Whittle (1985) to describe the [O III] profiles of active galaxies. This quantitative descriptions should also facilitate comparison of the highly unusual Lyα profiles of ULIRGs to those of other samples of Lyα emitting galaxies.

The strategy rests on measuring line widths at a specified fraction of the total profile area. We take the profile area to be the net area in emission where the integration is over the entire line profile; any other definition would be sensitive to spectral resolution. For purposes of measuring the line width, asymmetry, etc., one chooses a value of the fractional area that isolates the desired profile feature such as the line core, wings, etc.

We call the width at a specific fractional profile area the IPV. In summary, IPV_{0.1}, IPV_{0.2}, IPV_{0.3}, IPV_{0.5}, IPV_{0.9} mark the bandpasses that include, respectively, 90, 80, 70, ..., and 10% of the profile area. To measure IPV_{0.2}, for example, we integrate the velocity profile up to a velocity V_b that includes 10% of the total area and then continue integrating up to a velocity, V_p, that includes 90% of the total area. The IPV width IPV_b includes the central 1 − p percent of the line flux, where p denotes the fraction the line emission detected at velocities larger than the IPV width. Following Whittle (1985), we define

$$IPV_b = V_{bp} + V_{RP}$$  \hspace{1cm} (A1)
and an asymmetry parameter
\[ A_p = \frac{V_{Bp} - V_{Rp}}{V_{Bp} + V_{Rp}}. \] (A2)

When applying this scheme to Ly\(\alpha\), or any line that have absorption as well as emission components, we have chosen to define the area of the line profile as the total area such that absorption components subtract from the total area. We estimate the uncertainty in each marker by varying the continuum placement as described in Section 2.

In Figure A1, we have marked velocities of the blue wing, \(V_{Bp}\), and red wing, \(V_{Rp}\), where 20, 50, and 80% of the total emission in the line lies at higher velocity. These two markers are defined for any percentile \(p\) of the total profile area, so we show how the line width grows as \(p\) decreases to include more of the total profile area. The Doppler shifts of the blue and red wings are generally not symmetric about either the systemic redshift or the median velocity the profile area. When the profile is entirely in absorption blueward of the systemic velocity, as for example in Figure A1, panel c, then the velocity \(V_{B20}\) will be redward of the systemic velocity because it is defined in terms of the net profile area in emission.

Since we have defined profile asymmetry relative to the median velocity of each emission-line profile, a profile with a net Doppler shift can have \(A \approx 0\) (no asymmetry) if the two sides of that profile are symmetric. Returning to the P Cygni profile in Figure A1, panel c as an example, again, we see the emission is only mildly asymmetric about the median velocity of 300 km s\(^{-1}\), and the Ly\(\alpha\) asymmetry parameter is driven slightly redward by the presence of the blueshifted absorption. This gross asymmetry with respect to the systemic redshift is recognized instead by the comparison of \(V_{R,P}\) and \(V_{R,P}\) which have the same sign instead of opposite signs.

As a guide toward interpreting these measurements, we provide a few brief comments on the individual objects.

**IRAS00262+4251**—black Ly\(\alpha\) absorption near the center of the \([\text{O\,III}]\) emission profile. Scattered Resonance photons broaden Ly\(\alpha\). Despite the dissimilar line shapes, the blue marker velocities have similar values in both lines. The \([\text{O\,III}]\) profile shows a distinct blue asymmetry in the line wings whereas the Ly\(\alpha\) profile has a red asymmetry at percentile markers.

**IRAS01003-2238**—this object has a substantial AGN luminosity. The Ly\(\alpha\) profile has a blueshifted (~200 km s\(^{-1}\)) median velocity about which it is fairly symmetric. The \([\text{O\,III}]\) emission has a net blue asymmetry in the line wings.

**IRAS09583+4714-B**—this non-ULIRG spectrum shows the classical P Cygni profile as described in the text. The asymmetry parameter of the Ly\(\alpha\) profile is not very strong because it is measured relative to the median velocity which is redshifted 300 km s\(^{-1}\).

**IRAS10378+1109**—the blue wings of the Ly\(\alpha\) and \([\text{O\,III}]\) profiles share the identical shape blueward of ~200 km s\(^{-1}\). The Ly\(\alpha\) profile is missing photons in its core relative to the \([\text{O\,III}]\) profile but shows more redshifted emission.

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**Figure A1.** Top row: the Ly\(\alpha\) and \([\text{O\,III}]\) line profiles normalized by the net flux in emission. For the Ly\(\alpha\) line, we have marked the interpercentile velocities at \(p = 20\%\) (magenta), \(p = 50\%\) (yellow), and \(p = 80\%\) (cyan) to illustrate the meaning of \(V_{B,p}\) and \(V_{R,p}\). Bottom left: interpercentile velocity width and asymmetry parameter vs. fractional area of the profile for Ly\(\alpha\) and \([\text{O\,III}]\). Note that the asymmetry is measured relative to the median velocity which is marked by the dashed line in the top and right panels. Bottom row left: comparison of the velocity markers for Ly\(\alpha\) and \([\text{O\,III}]\). The blue wings (squares) are more correlated than the red wings (triangles). Blue and white points denote \([\text{O\,III}]\) and Ly\(\alpha\), respectively, and the open symbols denote upper and lower limits on the solid point.

(An extended version of this figure is available.)
wavelengths. The blueshifted component has a prominent wing shapes are very similar blueward of the core. The blue wings of the Lyα velocity. The extra wiggles in the blue wing of the Lyα blueshifted emission at deep absorption trough 200 km s$^{-1}$ emerge at bluer and redder wavelengths. The blueshifted component has a prominent wing shapes are very similar blueward of the core. The blue wings of the Lyα velocity. The extra wiggles in the blue wing of the Lyα blueshifted emission at deep absorption trough 200 km s$^{-1}$ emerge at bluer and redder wavelengths.

**REFERENCES**

Ahn, S.-H., Lee, H.-W., & Lee, H. M. 2003, MNRAS, 340, 863

Allen, M. G., Groves, B. A., Dopita, M. A., Sutherland, R. S., & Kewley, L. J. 2008, ApJS, 178, 20

Atek, H., Kunth, D., Hayes, M., Östlin, G., & Mas-Hesse, J. M. 2008, A&A, 488, 491

Atek, H., Kunth, D., Schaerer, D., et al. 2009, A&A, 506, L1

Atek, H., Kunth, D., Schaerer, D., et al. 2014, A&A, 561, A89

Behrens, C., Dijkstra, M., & Niemeyer, J. C. 2014, A&A, 563, A77

Borguet, B. C. J., Arav, N., Edmonds, D., Chamberlain, C., & Benn, C. 2013, ApJ, 762, 49

Borthakur, S., Heckman, T. M., Leitherer, C., & Overzier, R. A. 2014, Sci, 348, 491

Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682

Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245

Chapman, S. C., Blain, A. W., Smail, I., & Ivison, R. J. 2005, ApJ, 622, 772

Chen, Y.-M., Tremonti, C. A., Heckman, T. M., et al. 2010, AJ, 140, 445

Chevalier, R. A., & Clegg, A. W. 1985, Natur, 317, 44

Cicone, C., Maiolino, R., Sturm, E., et al. 2014, A&A, 562, A21

Cowie, L. L., Barger, A. J., & Hu, E. M. 2010, ApJ, 711, 928

Cowie, L. L., Barger, A. J., & Hu, E. M. 2011, ApJ, 738, 136

Danforth, C. W., Keeney, B. A., Stocke, J. T., Shull, J. M., & Yao, Y. 2010, ApJ, 720, 976

Deharveng, J.-M., Small, T., Barlow, T. A., et al. 2008, ApJ, 680, 1072

Diamond-Stanic, A. M., Moustakas, J., Tremonti, C. A., et al. 2012, ApJL, 755, L26

Dijkstra, M. 2014, arXiv:1406.7292

Dijkstra, M., Haiman, Z., & Spaans, M. 2006, ApJ, 649, 14

Dijkstra, M., Haiman, Z., & Spaans, M. 2006, ApJ, 649, 37

Draine, B. T. 2011, Physics of the Interstellar and Intergalactic Medium (Princeton, NJ: Princeton Univ. Press)
Verhamme, A., Schaerer, D., Atek, H., & Tapken, C. 2008, A&A, 491, 89
Verhamme, A., Schaerer, D., & Maselli, A. 2006, A&A, 460, 397
Voit, G. M., Donahue, M., & Slavin, J. D. 1994, ApJS, 95, 87
Wakker, B. P. 2004, Ap&SS, 289, 381

Wang, B. 1995, ApJ, 444, 590
Whittle, M. 1985, MNRAS, 213, 1
Wofford, A., Leitherer, C., & Salzer, J. 2013, ApJ, 765, 118
Zhang, D., Thompson, T. A., Murray, N., & Quataert, E. 2014, ApJ, 784, 93