THE CONNECTION BETWEEN GALAXIES AND INTERGALACTIC ABSORPTION LINES AT REDSHIFT 2 ≤ z ≤ 3

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ABSTRACT

Absorption-line spectroscopy of 23 background QSOs and numerous background galaxies has let us measure the spatial distribution of metals and neutral hydrogen around 1044 UV-selected galaxies at redshifts 1.8 ≤ z ≤ 3.3. The typical galaxy is surrounded to radii r ∼ 40 proper kpc by gas that has a large velocity spread (Δv > 260 km s⁻¹) and produces very strong absorption lines (N_\text{C IV} ≥ 10^{14} \text{ cm}^{-2}) in the spectra of background objects. These absorption lines are almost as strong as those produced by a typical galaxy’s own interstellar gas. Absorption with an average column density of N_\text{C IV} ≈ 10^{14} \text{ cm}^{-2} extends out to ∼80 kpc, a radius large enough to imply that most strong intergalactic C IV absorption is associated with star-forming galaxies like those in our sample. Our measurement of the galaxy–C IV spatial correlation function shows that even the weakest detectable C IV systems are found in the same regions as galaxies; we find that the cross-correlation length increases with C IV column density and is similar to the galaxy autocorrelation length (r_0 ∼ 4 h⁻¹ Mpc) for N_\text{C IV} ≥ 10^{12.5} \text{ cm}^{-2}. Distortions in the redshift-space galaxy–C IV correlation function on small scales may imply that some of the C IV systems have large peculiar velocities. Four of the five detected O vi absorption systems in our sample lie within 400 proper kpc of a known galaxy. Strong Lyα absorption is produced by the intergalactic gas within 1 h⁻¹ comoving Mpc of most galaxies, but for a significant minority (∼1/3) the absorption is weak or absent. This is not observed in smooth-particle hydrodynamic simulations that omit the effects of “feedback” from galaxy formation. We were unable to identify any statistically significant differences in age, dust reddening, environment, or kinematics between galaxies with weak nearby H I absorption and the rest, although galaxies with weak absorption may have higher star formation rates. Galaxies near intergalactic C IV systems appear to reside in relatively dense environments and to have distinctive spectral energy distributions that are characterized by blue colors and young ages.

Subject headings: galaxies: formation — galaxies: high-redshift — intergalactic medium — quasars: absorption lines

1. INTRODUCTION

A tremendous amount of gravitational energy is released when a massive galaxy forms, roughly 10^{62} ergs from its billion supernova explosions and another 10^{62} ergs during the assembly of its central 10^8 M_☉ black hole. Although 99% of the supernova energy is carried away by neutrinos, and a similar fraction of the black hole radiation escapes the galaxy, the remaining energy is enough to unbind most of the galaxy’s gas. The fate of the galaxy depends on what happens to the energy. If it is absorbed by sufficiently dense gas, it will be converted into radiation by two-body processes and will stream harmlessly away; but otherwise it will set in motion an enormous blast wave analogous to those produced by nuclear explosions on earth. These blast waves, tearing through galaxies, stripping away material, plowing outward, and coming finally to rest in distant intergalactic space, are believed to have significantly altered the evolution of the baryonic universe.

Indirect evidence for their existence comes in two forms. First, if the gas near galaxies had not been heated by some source, disk galaxies would be smaller than they are (Weil et al. 1998) and the correlation between galaxy clusters’ X-ray temperature and luminosity would have the wrong shape (Kaiser 1991; Ponman et al. 1999). Second, something quenches most galaxies’ star formation at some point in their history, and blast waves seem the best candidate. Without them small galaxies would be too numerous (e.g., Cole et al. 1994), big galaxies would be too blue (Springel et al. 2005), and too large a fraction of baryons would have been turned into stars (e.g., White & Rees 1978; Springel & Hernquist 2003).
Direct evidence remains elusive, however. Although local star-forming galaxies are surrounded by outflowing gas (e.g., Heckman et al. 1990; Martin 2005), typically their observable outflows extend to only a few kpc, far smaller than their virial radii. It is unclear how far these flows will advance before they stall or how severely they will affect the evolution of the galaxies and their surroundings. The presence of metals in the intergalactic medium might be taken as proof that the blast waves spill out of some galaxies’ halos, but even that is controversial. Intergalactic metals could also have been produced by the first generation of Population III stars or stripped from galaxies by other processes (e.g., Gnedin 1998).

Five years ago, our group began to search for direct evidence for large-scale outflows around galaxies at high redshift. High-redshift galaxies were attractive targets because they have larger star formation rates and (possibly) shallower potentials than their nearby counterparts. In addition, the higher density of the universe in the past is a significant advantage, because it strengthens many of the absorption lines that can be used to detect intergalactic gas. We identified three observations that would qualify, in our view, as direct evidence for large-scale outflows: gas at large galactocentric radii moving outward at greater than the escape velocity; a strong association of intergalactic metals and galaxies; and disturbances, near galaxies, to the lattice-work of intergalactic H I that pervades the high-redshift universe.

We searched for this evidence by systematically mapping the relative spatial distributions of star-forming galaxies and intergalactic gas. Early results were presented in Adelberger et al. (2003). This paper is an update. After describing the current data in §2, we review the status of our search. Section 3 shows that the outflowing material responsible for the blueshifted “interstellar” absorption lines in the galaxies’ spectra often lies at a radius of ~20–40 h⁻¹ proper kpc. Weaker absorption lines extend out to radii approaching 200 h⁻¹ kpc. Section 4 describes the galaxy–C IV cross-correlation function and reinforces the idea that detectable intergalactic metals tend to lie near actively star-forming galaxies. Section 5 shows that most galaxies are surrounded by significant amounts of intergalactic H I but that galaxies with little nearby H I are significantly more common than would be expected in the absence of winds. Section 6 discusses the characteristics of galaxies that appear to be associated with unusually weak Lyα or unusually strong C IV absorption. As we discuss in §7, these observations may be suggestive of galactic winds, but they do not rule out other alternatives. Our conclusions are summarized in §8. Throughout the paper we assume a cosmology with Ω_M = 0.3, Ω_Λ = 0.7, h = 0.7.

2. DATA

The galaxies in our analysis were taken from the redshift surveys of Steidel et al. (2003, 2004). These surveys targeted galaxies with magnitude R ≤ 25.5 whose U,G,R colors suggested that they had redshift 2 ≤ z ≤ 3 (Adelberger et al. 2004; Steidel et al. 2003). We restricted our analysis to galaxies in the 13 survey fields that contained one or more background QSOs. Although these fields include those previously analyzed by Adelberger et al. (2003), much of the present analysis relies on near-IR nebular redshifts (see below) that are only available in other fields. As a result, the overlap is small between the samples analyzed here and in Adelberger et al. (2003).

Our 13 fields are scattered around the sky and have typical area ΔΩ ~ 100 arcmin² (Table 1). Redshifts for a total of 1044 objects in these fields were measured from low-resolution (~10 Å) multislit spectra taken between 1995 and 2004 with LRIS (Oke et al. 1995; Steidel et al. 2004) on the Keck I and II 10 m tele-

| Field   | ΔΩa (arcmin²) | NLIRSB | N NIRSPECc |
|---------|--------------|--------|-----------|
| Q0000... | 3.4 × 4.5    | 18     | 1         |
| Q201...  | 6.8 × 7.4    | 25     | 3         |
| Q0256... | 7.3 × 6.6    | 47     | 1         |
| Q0302... | 6.5 × 6.9    | 44     | 1         |
| Q0933... | 8.1 × 8.0    | 64     | 0         |
| Q1305... | 11.8 × 11.0  | 80     | 1         |
| Q1422... | 7.2 × 14.2   | 113    | 1         |
| Q1623... | 16.1 × 11.6  | 213    | 31        |
| Q1700... | 11.5 × 11.0  | 89     | 16        |
| Q2233... | 8.2 × 8.6    | 46     | 1         |
| Q2343... | 22.5 × 8.5   | 194    | 19        |
| Q2346... | 10.9 × 11.0  | 50     | 7         |
| SSA 22a... | 7.8 × 8.4   | 61     | 8         |

a Area imaged in U,G,R and observed spectroscopically.

b Number of galaxies with LRIS redshift z > 1.

Table 1

The typical spectroscopic exposure time was 1.5 hr per multislit mask, although a subset of the objects was observed for more than 10 times longer (A. E. Shapley et al. 2005, in preparation). The redshifts obtained from these spectra are imprecise, because they rely on features (Lyα emission and various far-UV interstellar absorption lines) that are redshifted or blueshifted relative to the galaxy’s stars. D. K. Erb et al. (2005, in preparation) used NIRSPEC (McLean et al. 2000) on the Keck II Telescope to obtain more precise redshifts from the nebular emission lines ([O ii] λ3727, Hα, Hβ, [O iii] λλ4959, 5007) of 90 galaxies in this sample, many near the sight lines to background QSOs, and we adopt their redshifts wherever possible. If nebular redshifts were unavailable, we estimated the stellar redshifts with the relationships defined in the following paragraph. Precise redshifts were required for much of the analysis, however, and in these cases we ignored galaxies that had not been observed with NIRSPEC.

We measured the relationship between redshifts from Lyα emission (z_Lyα), interstellar absorption (z_SSM), and near-IR nebular emission (z_neb) for the full 138 object NIRSPEC sample of D. K. Erb et al. (2005, in preparation), and used the results to help assign systemic redshifts to galaxies when NIRSPEC redshifts were unavailable. Figure 1 shows the observed velocity offsets for the galaxies in the full NIRSPEC sample. The least-squares first-order fits to the data can be written

for galaxies with no detected interstellar absorption lines,

\[ z_{\text{neb}} = z_{\text{Ly}α} - 0.0033 - 0.0050(z_{\text{Ly}α} - 2.7) \]  

(1) for galaxies with no detected Lyα emission, and

\[ z_{\text{neb}} = \frac{z_{\text{Ly}α} + z_{\text{SSM}}}{2}, \quad \Delta z = z_{\text{Ly}α} - z_{\text{SSM}}, \]  

(2) for galaxies with detectable Lyα emission and interstellar absorption. The rms scatter around the three relationships is σz = 0.0027, 0.0033, 0.0024, respectively. In each equation the final term accounts for the weak apparent trend of smaller velocity offsets at lower redshifts. Figure 2 shows the expected error distributions for the galaxies that lack near-IR nebular redshifts, calculated by combining...
the observed error distributions for equations (1), (2), and (3) after weighting by the number of galaxies in each class (233 with $\text{Ly}_\alpha$ emission only, 425 with interstellar absorption only, 296 with both). For comparison, repeated observations of galaxies in the NIRSPEC sample suggest that these galaxies’ redshifts have a random uncertainty of $60 \text{ km s}^{-1}$.

The criteria used to select galaxies for spectroscopy were irregular. We favored objects with $23 < R < 24.5$ and objects near any known QSOs, and strongly disfavored objects far from the field centers. Near QSOs we often observed objects whose colors satisfied any of the $U_{0.7}$GR selection criteria of Steidel et al. (2003) or Adelberger et al. (2004). Far from QSOs our spectroscopic selection tended to be prejudiced toward one or the other color selection criterion, “BX/BM” or “LBG,” depending on the field. This haphazard approach imposes a complicated selection bias on our data. Rather than try to correct it with elaborate simulations, we restrict our analysis to quantities that are not affected by irregular angular sampling or the assumed redshift selection function. Further details of the galaxy observations can be found in Steidel et al. (2003, 2004) and D. K. Erb et al. (2005, in preparation).

The QSO spectra we analyzed were obtained between 1996 and 2003 with either the HIRES echelle spectrograph (Vogt et al. 1994) or the ESI echellette (Sheinis et al. 2000) on the Keck I and II Telescopes. The HIRES spectra were reduced using the standard procedures of T. Barlow’s Makee package. The ESI spectra were reduced with the “Dukee” suite of custom IRAF scripts and C programs written by K. L. A. and M. Hunt. The shape of the continuum was removed from the QSO spectra interactively by fitting a high-order ($\sim 30$) b-spline to regions of the spectra that appeared to be free from absorption. C IV absorption systems in the QSO spectra were identified interactively by scanning for absorption doublets with the right wavelength spacing. Column densities were estimated by fitting each doublet’s absorption profile with two Gaussians in optical depth. This is equivalent to Voigt-profile fitting at the low (i.e., undamped) column densities of interest to us. Occasionally the velocity profiles were unresolved in our spectra. If this happened and the doublet ratio suggested that the lines were saturated, we obtained a crude estimate of column density from the weaker line only. Otherwise both lines were used. See Adelberger et al. (2003) for further details. Our ability to detect C IV systems depended on the quality of the QSO spectrum. Table 2 lists the minimum detected C IV column density in each QSO’s spectrum. This should be roughly equal to the spectrum’s C IV detection limit.

Figure 3 shows the redshift distributions of the different objects in our sample.

3. GALAXIES’ GASEOUS ENVELOPES

Numerous authors have noticed that the interstellar absorption lines in high-redshift galaxies’ spectra tend to be blueshifted, presumably because they are produced by outflowing gas (e.g., Franx et al. 1997; Pettini et al. 1998, 2001; Frye et al. 2002; Shapley et al. 2003; Erb et al. 2004). Little is known, however, about how far the outflowing gas might propagate. This section shows that the absorbing material often lies at radii approaching 80 proper kpc and that weaker lines can be detected much farther away. It does not clearly show, however, that the absorbing material detected at large radii is part of an outflow. Other scenarios are considered in §§ 4 and 8.

3.1. Radii $r \lesssim 80$ proper kpc

A $\sim 40$ kpc radius for galaxies’ strongly absorbing material is implied by the presence of foreground galaxies’ absorption lines in the spectra of nearby background galaxies. The left panel of Figure 4 illustrates the idea. The right panel shows one example from our survey. Two galaxies with redshifts $z = 1.60, z = 2.17$ and angular separation $\theta = 2''$ were placed on the same slit on one of our multislit masks. Light from the background galaxy passed within 17 proper kpc of the foreground galaxy as it traveled toward earth, and this was close enough for the foreground galaxy’s absorption lines to be imprinted in its spectrum. The absorbing material must therefore have a radius of at least 17 kpc.

Similar absorption lines are observed in galaxy pairs with impact parameters of up to 40 kpc, but the absorption weakens significantly at greater separations. This can be seen by measuring the dependence on angular separation $\theta$ of the mean absorption produced by foreground galaxies. We calculated the strength of the mean absorption in two bins of angular separation. For each bin, we identified all the galaxy pairs in our sample (18 for $1'' < \theta < 5''$, 64 for $5'' < \theta < 10''$; 10'' corresponds to 81 proper kpc at $z = 2.5$ for a cosmology with $\Omega_m = 0.3, \Omega_{\Lambda} = 0.7, h = 0.7$), collected the background spectra, masked parts of the spectra that were contaminated by sky lines or by any

![Figure 1](image1.png)

**Fig. 1.—**Velocity differences between the $\text{Ly}_\alpha$ emission line, interstellar absorption lines, and near-IR nebular lines for galaxies in the NIRSPEC sample. Each point represents one galaxy; shaded regions show the mean velocity difference ± standard deviation of the mean for two redshift bins. The value of Spearman’s rank correlation coefficient and its significance are $r_s = 0.16$, $P = 0.19$ and $r_s = -0.197$, $P = 0.03$ for the data in the left and right panels, respectively. The weak apparent correlations of velocity offset with redshift are therefore significant at only the 1–2 $\sigma$ level.

![Figure 2](image2.png)

**Fig. 2.—**Estimated histogram of velocity errors $\Delta v = v_{\text{rest}} - v_{\text{true}}$ for galaxies without near-IR nebular redshifts.

Voigt-profile fitting at the low (i.e., undamped) column densities of interest to us. Occasionally the velocity profiles were unresolved in our spectra. If this happened and the doublet ratio suggested that the lines were saturated, we obtained a crude estimate of column density from the weaker line only. Otherwise both lines were used. See Adelberger et al. (2003) for further details. Our ability to detect C IV systems depended on the quality of the QSO spectrum. Table 2 lists the minimum detected C IV column density in each QSO’s spectrum. This should be roughly equal to the spectrum’s C IV detection limit.

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TABLE 2

| QSO        | Field       | $\alpha$ (J2000.0) | $\delta$ (J2000.0) | $z$ | $G_{\text{AB}}$ | $n_{\text{CIV}}$ | $\log (N_{\text{CIV}}/\text{cm}^2)$ |
|------------|-------------|--------------------|--------------------|-----|-----------------|-----------------|-------------------|
| PKS 0201+113 | Q0201       | 02 0346.7          | 11 34 45           | 3.610 | 20.1            | 0               | …                 |
| LBQS 0256-0000 | Q0256      | 02 59 05.6         | 00 11 22           | 3.324 | 18.0            | 32              | 12.02             |
| LBQS 0302-0019 | Q0302      | 03 04 49.9         | 00 08 13           | 3.267 | 17.8            | 46              | 12.03             |
| FBQS J0933+2845 | Q0933      | 09 33 37.3         | 28 45 32           | 3.401 | 18.8            | 34              | 12.00             |
| Q1305k9c       | Q1305      | 13 07 42.7         | 29 19 36           | 2.462 | 21.3            | 7               | 13.56             |
| Q1305k16c      | Q1305      | 13 08 06.1         | 29 22 39           | 2.526 | 20.9            | 4               | 13.03             |
| Q1305k22c      | Q1305      | 13 08 11.9         | 29 25 13           | 2.979 | 19.0            | 16              | 13.02             |
| Q1422+2309     | Q1422      | 14 24 38.1         | 22 56 01           | 3.515 | 16.5            | 74              | 11.81             |
| Q1422+2309b    | Q1422      | 14 24 40.6         | 22 55 43           | 3.084 | 23.4            | 3               | 13.45             |
| Q1422+2309c    | Q1422      | 14 24 40.6         | 22 55 43           | 3.084 | 23.4            | 3               | 13.45             |
| Q1422+2309b    | Q1422      | 14 24 40.6         | 22 55 43           | 3.084 | 23.4            | 3               | 13.45             |
| Q1623kp76      | Q1623      | 16 25 48.1         | 26 44 33           | 2.246 | 18.5            | 13              | 12.72             |
| Q1623kp77      | Q1623      | 16 25 48.1         | 26 46 59           | 2.529 | 16.5            | 41              | 12.03             |
| Q1623kp78      | Q1623      | 16 25 57.4         | 26 44 49           | 2.578 | 19.0            | 47              | 12.14             |
| Q1623kp79      | Q1623      | 16 26 06.2         | 26 50 33           | 2.180 | 19.2            | 12              | 12.99             |
| Q1623BX234     | Q1623      | 16 25 33.7         | 26 53 44           | 2.464 | 19.5            | 4               | 14.06             |
| Q1623BX603     | Q1623      | 16 26 02.4         | 26 43 39           | 2.529 | 20.5            | 8               | 13.32             |
| HS 1700+6416   | Q1700      | 17 01 00.6         | 64 12 09           | 2.717 | 16.0            | 57              | 11.71             |
| Q2333+136      | Q2333      | 22 36 27.2         | 13 57 13           | 3.209 | 18.7            | 25              | 12.09             |
| Q2342+125      | Q2342      | 23 45 22.8         | 12 45 47           | 2.497 | 18.2            | 9               | 12.57             |
| Q2343+125      | Q2343      | 23 46 23.8         | 12 48 58           | 2.579 | 17.0            | 38              | 12.25             |
| Q2344+125      | Q2344      | 23 46 46.1         | 12 45 27           | 2.785 | 17.5            | 44              | 12.33             |
| Q2343BX415     | Q2343      | 23 46 25.4         | 12 47 44           | 2.578 | 20.3            | 19              | 13.22             |
| Q2345+0000     | Q2346      | 23 48 25.4         | 00 20 41           | 2.652 | 19.7            | 3               | 13.31             |
| SSA 22d13      | SSA22a     | 22 17 22.3         | 00 16 41           | 3.343 | 21.6            | 6               | 13.22             |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

a QSO magnitude; numbers are unreliable brighter than our saturation magnitude $G \sim 18$.

b Number of detected C IV systems.

c Log of the minimum column density (in cm$^{-2}$) among the detected C IV systems.

d C IV absorber catalog not constructed owing to gaps in our echelle spectrum.

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of the background galaxy’s 10 strongest spectral features, shifted each spectrum into the rest frame of its foreground galaxy, spline-interpolated the rest-frame spectra onto common abscissae, removed the shape of the continuum by forcing each spectrum to have a constant 140 Å running-average flux, and averaged the spectra together with inverse-variance weighting after first rejecting the highest and lowest 10% of the flux values at each output wavelength. Finally, we restored a realistic continuum shape by multiplying the resulting spectrum by the mean running-average continuum shape of the sample.

Figure 5 shows the result. The strength of the interstellar C IV absorption line appears roughly constant for $\theta \leq 5''$ (~40 proper kpc at $z = 2.2$) but drops sharply afterward. Chen et al. (2001) found similar results at lower redshifts.

It would be wrong to conclude from Figure 5, however, that the observed C IV absorption at $5'' < \theta < 10''$ is weak to the point of insignificance. The estimated rest-frame equivalent width of the absorption, $W_\lambda$ (doublet) ~ 0.7 Å [i.e., $W_\lambda(1548) \geq 0.4$ Å, or $N_{\text{CIV}} \geq 10^{14}$ cm$^{-2}$], is large by intergalactic standards. According to Steidel (1990), only 1.2 ± 0.4 C IV systems with $W_\lambda(1548) > 0.4$ Å are found per unit redshift at $2 \leq z \leq 3$. Since our color selection criteria find nine galaxies per arcmin$^2$ per unit $z$ at the same redshifts (e.g., Steidel et al. 2004), they would account for the majority of all C IV systems with $W_\lambda(1548) > 0.4$ Å if each galaxy produced absorption with $W_\lambda(1548) > 0.4$ Å out to $\theta = 10'' = 0.167\times 9 \times \pi (0.167)^2 \approx 0.8$ C IV absorbers per unit redshift. In fact, as we will see below (Fig. 8), only about

4 Ly$\alpha$/O vi, Ly$\beta$/Si iv, Si iv, C iv, Fe ii

5 Note that part of the C IV feature in the top panel of Fig. 5 is stellar P Cygni absorption.
half of the galaxies within $10''$ ($\sim 80$ kpc) are associated with C IV absorption so strong. This implies that the galaxies in our sample can account for roughly one-third of C IV lines with $W_0(1548) > 0.4$ Å. Galaxies missed by our UV color selection techniques could easily account for the remainder.

The large equivalent width $W_0$ (doublet) $\approx 2.7$ Å of the absorption at $\theta < 5''$ has an interesting implication. C IV can attain so high an equivalent width only if peculiar velocities spread the absorption over a large range of wavelengths. The minimum velocity spread is $\Delta v = 260$ km s$^{-1}$, but this assumes a contrived situation in which each line in the doublet is saturated and has a boxcar (i.e., maximally compact) absorption profile. In realistic situations the C IV absorption will have complicated substructure (e.g., Pettini et al. 2002) and a significantly larger velocity spread will be required to produce $W_0$ (doublet) $\approx 2.7$ Å. Our lower limit to the velocity spread ($\Delta v = 260$ km s$^{-1}$) is smaller than the likely escape velocity at 40 kpc from a galaxy with $M \sim 10^{12}$ $M_\odot$ (e.g., Adelberger et al. 2004), but it nevertheless shows that significant chaotic motions in the gas extend to large radii.

Further evidence comes from one of the two cases in our survey where a foreground galaxy lies within $15''$ of the QSO sight line and the QSO is lensed into two detectable components with $\sim 1''$ separation. In this case, shown in the left panel of Figure 6, the galaxy’s gas produces significantly different absorption profiles in the spectra of the two QSO components. The implied substructure on half-kpc scales would be erased by thermal motions in a few dozen Myr if it were not maintained somehow. The gas along the two sight lines might have supersonic relative motions or might be gravitationally confined in two separate minihalos. Substructure of this sort is rare in the low-density intergalactic medium (Rauch et al. 2001a) but common among C IV systems (Rauch et al. 2001a).

3.2. Radii $r \gtrsim 80$ proper kpc

Although the metal absorption lines continue to weaken beyond $r \sim 80$ kpc, they are not always absent. High signal-to-noise QSO spectra reveal that absorbing gas extends out to 100–200 proper kpc in at least some cases. Figure 7 shows three. Absorption from metal-enriched, multiphase gas is detected in each. (See §3.2.13 and 2.5.15 of Simcoe et al. 2002 for a discussion of the physical conditions in two of these absorption systems.) These three cases are not typical, but neither are they extraordinarily rare. Figure 8 shows the total detected C IV column density within 100–500 km s$^{-1}$ of the 29 galaxies in our NIRSPEC sample that lie within 1.0 $h^{-1}$ projected comoving Mpc of a QSO with detected C IV. The C IV column densities of the three examples in Figure 7 are the second, third, and seventh highest in this 29 object sample.

6 A small fraction of our QSOs were too faint to allow us to detect significant numbers of C IV systems.
One way to show that the detected metals are associated with a nearby galaxy, and are not chance alignments, is to measure the galaxy–C iv correlation strength $\xi_{\text{gg}}$ on small spatial scales. As pointed out by Adelberger et al. (2003), $\xi_{\text{gg}}$ cannot easily exceed $\xi_{\text{gg}}^2 / \sigma_{\text{gg}}^2$, the geometric mean of the galaxy-galaxy and C iv–C iv clustering strengths, unless the existence of galaxies affects (or is affected by) the presence of nearby C iv systems. Since $\xi_{\text{gg}}$ and $\xi_{\text{gg}}$ are roughly equal (Quashnock & vanden Berk 1998; Adelberger et al. 2003), a value of $\xi_{\text{gg}} / \sigma_{\text{gg}}$ significantly greater than unity on small scales would imply a direct relationship between the galaxies and C iv systems.

We estimated $\xi_{\text{gg}} / \sigma_{\text{gg}}$ with the following approach. For each C iv system, we counted the observed number $n_i$ of NIRSPEC galaxies with velocity separation $|\Delta v| < r_{\text{max}}$ and transverse separation $R_{\text{trans}} < R < R_{\text{max}}$. Call these galaxies the C iv system’s neighbors. (We took $r_{\text{max}} = 500 \text{ km s}^{-1}$ and $R_{\text{max}} \approx 1 \text{ h}^{-1}$ co-moving Mpc, since these are roughly the maximum separations expected for a galaxy’s ejecta.) Given the galaxies’ known angular distances to the QSO, the expected number of neighbors is (see, e.g., Adelberger 2005)

$$n_i = \sum_{j=1}^{\text{galaxies}} \frac{\Delta z}{\Delta z_{\text{z}}} \int_0^{\Delta z_{\text{z}}} dz P(z)[1 + \xi(r)]$$

where the sum runs over all NIRSPEC galaxies in the QSO’s field, $\Delta z$ is the redshift difference corresponding to $r_{\text{max}}$, $P(z)$ is the survey selection function normalized so that $\int_0^\infty P(z) = 1$, $\xi$ is the correlation function, and $r_{\text{max}}$ is the distance between the C iv system at redshift $z_i$ and a point at redshift $z$ with the galaxy’s angular separation $\theta$. The number of neighbors expected in the absence of clustering, $n_i^{\text{BG}}$, can be calculated from equation (4) with $\xi = 0$, allowing us to estimate the galaxy–C iv clustering strength through $\xi_{\text{gg}} = -1 + \Sigma n_i / \Sigma n_i^{\text{BG}}$. This is the mean value of $\xi_{\text{gg}}$ within a complicated volume consisting of many parallel skewers of length $2r_{\text{max}}$. To estimate the mean value of the galaxy-galaxy correlation function within the same volume, we inserted $\xi_{\text{gg}} = (r/4 \text{ h}^{-1} \text{ co-moving Mpc})^{-1.6}$ (e.g., Adelberger et al. 2005a) into equation (4), integrated numerically, called the result $n_i^{\text{BG}}$, and used the formula $\xi_{\text{gg}} = -1 + \Sigma n_i / \Sigma n_i^{\text{BG}}$. The estimates of $\xi_{\text{gg}}$ and $\xi_{\text{gg}}$ do not depend on any assumptions about the redshift selection function of the C iv systems or the angular selection function of the galaxies. This is fortunate since neither is well known.

Figure 9 shows $\xi_{\text{gg}} / \sigma_{\text{gg}}$ for $R_{\text{max}} = 0.4, 0.4, 1.0 \text{ h}^{-1}$ co-moving Mpc. Our data are consistent with no increase in $\xi_{\text{gg}}$ over $\xi_{\text{gg}}$ on small scales. They are therefore consistent with the idea that galaxies and C iv systems are spatially correlated only because they trace the same large-scale structure. We cannot rule out a more direct association, however, both because the error bars in Figure 9 are large and because the statistical test itself can
detect only the strongest direct associations of galaxies and C IV systems.

We conclude this subsection by emphasizing one of its corollaries: many of the strongest intergalactic absorption lines are produced by material that lies close to star-forming galaxies. Figure 10 helps illustrate the point. The figure’s vertical lines mark the redshifts of strong C IV galaxies and metal absorption lines for a small number of specific galaxies and intergalactic metals tend to be surrounded by vacant expanses with neither. The correspondence between star-forming galaxies and strong metal lines is not perfect, but one could do worse than assume that the presence of one implies the presence of the other.

4. THE GALAXY–C IV CROSS-CORRELATION FUNCTION

The previous section discussed the relationship between galaxies and metal absorption lines for a small number of specific cases. This section takes a more systematic approach, calculating the cross-correlation function between the positions of galaxies and C IV absorption systems.

4.1. Large Scales

Our approach on large spatial scales is similar to that of Adelberger (2005): we assume that the cross-correlation function has the form \( \xi(r) = (r/r_0)^{-1.6} \) (e.g., Adelberger et al. 2003); count the number \( n_{\text{obs}}(0, l) \) of galaxy–C IV pairs in our sample that have \( \Delta \theta < 300'' \), \( |\Delta Z| < l \) for \( l = 20, 40 \) h\(^{-1}\) comoving Mpc\(^2\); calculate the expectation value of \( n_{\text{obs}}(0, 20)/n_{\text{obs}}(0, 40) \) as a function of \( r_0 \) with the equation (Adelberger et al. 2005a; Adelberger 2005)

\[
\frac{n_{\text{obs}}(0, l)}{n_{\text{obs}}(0, 2I)} \approx \frac{\sum_{i,j} \int_0^{R_{ij}} dZ [1 + \xi(R_{ij}, Z)]}{\sum_{i,j} \int_0^{2R_{ij}} dZ [1 + \xi(R_{ij}, Z)]},
\]

(5)

where \( \xi(R, Z) = \xi[(R^2 + Z^2)^{1/2}] \), \( R_{ij} \equiv (1 + z_i)D_A(z_i)\theta_{ij}, \) \( D_A(z) \) is the angular diameter distance, and the summation is over all galaxies \( i \) and C IV systems \( j \); and finally take as our best estimate of \( r_0 \) the value that makes the right-hand side of equation (5) equal the observed ratio \( n_{\text{obs}}(0, 20)/n_{\text{obs}}(0, 40) \). As discussed in Adelberger et al. (2005a) and Adelberger (2005), the resulting estimate of \( r_0 \) is insensitive to angular selection effects and only weakly dependent on the assumed shape of the selection function—two significant advantages given the irregular selection criteria we employed (§ 2).

Figure 11 shows the estimated cross-correlation length as a function of the C IV system’s column density. To estimate the uncertainty, we broke our galaxy and C IV catalogs into many smaller subcatalogs by rejecting a random fraction \( p = 0.5–0.8 \) of the sources, observed how the dispersion in best-fit \( r_0 \) among
produced by peculiar velocities, they should reveal whether the galaxy–C IV relationship between intergalactic C IV could place metals near galaxies. One way to learn about the metals are part of a galactic superwind. Many other processes systems have similar spatial distributions, reinforcing the idea (Simcoe et al. 2002). The absorption-line catalogs are reasonably reached a similar conclusion.

Also drawn in Figure 11 is the 1 σ confidence interval for the galaxy–C IV correlation length at similar redshifts, taken from Adelberger et al. (2005a). The good agreement of the galaxy-galaxy and galaxy–C IV correlation lengths for $N_{\text{C IV}} \geq 10^{12.5}$ cm$^{-2}$ shows that bright star-forming galaxies and stronger C IV systems have similar spatial distributions, reinforcing the idea (§ 3) that they are often the same objects. Adelberger et al. (2003) reached a similar conclusion.

4.2. Small Scales

As mentioned above, an observed spatial association of galaxies and C IV systems does not by itself imply that the detected metals are part of a galactic superwind. Many other processes could place metals near galaxies. One way to learn about the relationship between intergalactic C IV and nearby galaxies is to look for anisotropies on small scales in the redshift-space galaxy–C IV correlation function. Since these anisotropies are produced by peculiar velocities, they should reveal whether the C IV tends to be falling toward, flowing away from, or orbiting around the nearest galaxy. Figure 12 shows the observed spatial separation of every galaxy–C IV pair in our NIRSPEC sample that had comoving redshift separation $|\Delta Z| < 10 h^{-1}$ Mpc and comoving angular separation $b < 1 h^{-1}$ Mpc. Vertical lines mark the impact parameters of each galaxy-QSO pair. Circles on these lines show the velocities (relative to the nearby galaxy) of any detected C IV absorption in the QSO's spectrum. Only galaxies with NIRSPEC redshifts are shown in the plot, since precise redshifts are crucial to our arguments.

The peculiar velocities of C IV systems relative to galaxies can be estimated roughly from this plot as follows. The expected number of galaxy–C IV pairs with impact parameter $b$ and radial separation $|\Delta Z| < Z_1$ is proportional to $[1 + \xi(b, < Z_1)]Z_1$, where

$$\xi(b, < Z_1) \equiv \frac{1}{Z_1} \int_{0}^{Z_1} dZ \xi(b, Z) \quad (6)$$

and $\xi(b, Z)$ is the galaxy–C IV correlation function. On average, then, half of the plot's galaxies with impact parameter $b$ should have comoving redshift separation $|\Delta Z| < Z_{1/2}(b)$ with

$$Z_{1/2}(b) = \frac{Z_{\text{max}}}{2} \left( \frac{1 + \xi(b, Z_{\text{max}})}{1 + \xi(b, < Z_{1/2})} \right) \quad (7)$$

where $|\Delta Z| < Z_{\text{max}}$ is the range of redshift separations shown on the plot. If peculiar velocities were negligible, $\xi(b, Z)$ would be equal to the real-space galaxy–C IV correlation function $\xi'$, which must be isotropic in an isotropic universe: $\xi'(b, Z) = \xi'(b^2 + Z^2)^{1/2}$. Since $\xi'(r) = (3.7 h^{-1}$ Mpc/r)$^{1.6}$ is a reasonably good approximation to the real-space correlation function (see Fig. 9), one can solve for $Z_{1/2}(b)$ numerically by inserting this correlation function into equations (6) and (7).

The dotted triangular envelope in Figure 12 shows $Z_{1/2}(b)$. Half of the C IV systems would be expected to lie within the dotted envelope in the absence of peculiar velocities. In fact 65 of 81 lie outside. Peculiar velocities appear to be substantial. The observations seem inconsistent with an infall model, since infall tends to compress correlation functions in the redshift direction; it would place more than half of the C IV systems inside the

FIG. 10.—Redshifts of galaxies near the sight line to QSO HS 1700+6416 compared to the redshifts of C IV and O VI absorption systems in the QSO's spectrum. Circles mark galaxy redshifts and impact parameters. The area of each circle is proportional to the galaxy's apparent luminosity in the $R$ band. Vertical lines mark the redshifts of O VI and C IV absorption. Thicker lines in the C IV panel mark systems with multiple components. O VI absorption redshifts are taken from Simcoe et al. (2002). The absorption-line catalogs are reasonably complete down to their limiting equivalent widths, but owing to imperfect color selection criteria and limited time for follow-up spectroscopy, it is unlikely that the galaxy catalogs contain more than half of the galaxies brighter than $R = 25.5$ at these redshifts. (We obtained redshifts for 15 of the 20 photometric galaxy–C IV pair in our NIRSPEC sample that had comoving redshift separation $|\Delta Z| < 10 h^{-1}$ Mpc and comoving angular separation $b < 1 h^{-1}$ Mpc. Vertical lines mark the impact parameters of each galaxy-QSO pair. Circles on these subcatalogs depended on the number of objects in the catalogs, and extrapolated to the full catalog sizes. This accounts for random uncertainties but not completely for cosmic variance.

Also drawn in Figure 11 is the 1 σ confidence interval for the galaxy-galaxy correlation length at similar redshifts, taken from Adelberger et al. (2005a). The good agreement of the galaxy-galaxy and galaxy–C IV correlation lengths for $N_{\text{C IV}} \geq 10^{12.5}$ cm$^{-2}$ shows that bright star-forming galaxies and stronger C IV systems have similar spatial distributions, reinforcing the idea (§ 3) that they are often the same objects. Adelberger et al. (2003) reached a similar conclusion.

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After noticing that none of the three galaxies closest to background QSOs in their sample seemed to be associated with strong Ly$\alpha$ absorption lines, Adelberger et al. (2003) speculated that superwinds extending to $\sim 0.5\ h^{-1}\ Mpc$ might drive most intergalactic hydrogen away from young galaxies. Our larger sample puts this speculation to rest.

The present analysis differs from theirs in three main ways: our sample puts this speculation to rest. The top panel of Figure 13 shows the measured transmissivity of every Ly$\alpha$ forest pixel in our QSO spectra that lies within $1\ h^{-1}\ Mpc$ of a galaxy with precisely known (i.e., near-IR nebular) redshift. The distances shown on the $x$-axis are imprecise, because they were calculated from redshift differences under the assumption that peculiar velocities are negligible, but nevertheless it is clear that strong H$\alpha$ absorption is common near the galaxies.

The bottom panel of Figure 13 shows the same data with the pixels grouped by galaxy. Each point marks $f_{\text{Mpc}}$, the mean Ly$\alpha$ transmissivity of the pixels within $1\ h^{-1}\ Mpc$ of a single galaxy, and the error bar shows the rms spread among these pixel values. Table 3 lists the impact parameters and redshifts for the galaxies in this figure. Also listed is $c$, the smoothed mean transmissivity in the QSO’s spectrum at the galaxy’s redshift, calculated by convolving the continuum-normalized QSO spectrum by a boxcar with width 100 Å and fitting a second-order polynomial to the result.

Figure 14 shows that the mean transmissivity declines monotonically as one approaches a galaxy. This appears inconsistent with the earlier result of Adelberger et al. (2003; dashed circles). The present analysis differs from theirs in three main ways: our redshifts are more precise, our sample is larger, and our galaxies’ typical redshift is lower. Each difference could contribute to the

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5. INTERGALACTIC H I NEAR GALAXIES

After noticing that none of the three galaxies closest to background QSOs in their sample seemed to be associated with strong Ly$\alpha$ absorption lines, Adelberger et al. (2003) speculated that superwinds extending to $\sim 0.5\ h^{-1}\ Mpc$ might drive most intergalactic hydrogen away from young galaxies. Our larger sample puts this speculation to rest.
change in this plot. The good agreement of the results for the NIRSPEC-only and full samples in Figure 14 suggests that the redshifts' precision might not be primarily responsible for the change. This suspicion is reinforced by our NIRSPEC observations of galaxies in the sample of Adelberger et al. (2003). Although two of their three galaxies with $r < 0.5 \ h^{-1}$ comoving Mpc had redshifts that placed the nebular lines outside of atmospheric windows, the near-IR nebular redshift we obtained for the third confirmed the reported lack of nearby Ly$\alpha$ absorption. Another possibility is that genuine evolution from $z \sim 3$ to $z \sim 2$ is partly responsible for the increased absorption near galaxies in this sample. The thought is not absurd: at lower redshifts, galaxies have marginally slower outflows (see Fig. 1) and a larger fraction of intergalactic H I absorption is produced by gas in deep potential wells that is more difficult to disrupt. These changes are not enormous, however, and it seems unlikely to us that they would have a dominant effect. The most obvious difference from Adelberger et al. (2003) is the sample size, especially at small separations. The following simple argument suggests that a statistical fluctuation could plausibly be responsible. The most obvious difference from Adelberger et al. (2003) is the sample size, especially at small separations. The following simple argument suggests that a statistical fluctuation could plausibly be responsible.

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large fluctuations occur often in samples drawn from a bimodal underlying distribution. The results in this paper and in Adelberger et al. (2003) are clearly not the same, but they are less inconsistent than one might naively suppose.

In any case, although strong HI absorption is the norm at small separations, we continue to find some galaxies with little absorption. The existence of these galaxies is surprising: one would expect all galaxies to reside in dense regions with significant hydrogen and an elevated neutral fraction from the $\rho^2$ dependence of the recombination rate (e.g., Croft et al. 2002; Kollmeier et al. 2003; Maselli et al. 2004; Desjacques et al. 2004). Figure 15 illustrates this point by comparing the observed distribution of HI absorption among the galaxies in Figure 13 to a preliminary prediction from the windless smooth-particle hydrodynamic (SPH) simulation of J. Kollmeier et al. (2005, private communication; this simulation is similar to that of Kollmeier et al. [2003] but is matched to the mean redshift of this sample). If the real world resembled the simulations, a 24 galaxy sample would have $n_{\text{obs}} = 7$ or more members with decrement $D < 0.2$ only 2 times in a thousand (i.e., $\sum_{n_{\text{obs}} = 7} \exp(-n_{\text{exp}}) = 0.002$, where $n_{\text{exp}} \approx 1.75$ is the predicted mean number of galaxies with $D < 0.2$ in a 24 object sample).

Although a number of explanations are possible, the data in Figure 15 seem qualitatively consistent with the idea that the galaxies are surrounded by anisotropically expanding winds. Leaking out along the paths of least resistance, these winds would turn moderate absorption into weak absorption while leaving the strongest absorption systems in place.

Ionizing radiation from any neighboring QSOs might also preferentially eliminate weaker absorption systems. As Figure 16 shows, many of the galaxies with $\dot{f}_i$ Mpc have bright QSOs in their vicinity. Although these QSOs have similar or larger redshifts than the galaxies, as is required for their (presumably) short-lived radiation to have an observable effect on the galaxies’ surroundings (e.g., Fig. 12 of Adelberger 2004), the prevalence of neighboring QSOs is not significantly different for galaxies with $\dot{f}_i$ Mpc $\geq 0.5$ and $\dot{f}_i$ Mpc $< 0.5$. Four galaxies of nine with $\dot{f}_i$ Mpc $\geq 0.5$ have a QSO within $\Delta v = 3000$ km s$^{-1}$, compared to two of 15 with $\dot{f}_i$ Mpc $< 0.5$. The one-sided $P$-value from Fisher’s (1934, § 12) exact test is 0.11 and would increase (i.e., become less significant) if we changed $\Delta v$ to 2000 km s$^{-1}$ ($P = 0.25$) or 4000 km s$^{-1}$ ($P = 0.21$). These numbers could be misleading, however, since even a profound QSO influence might be difficult to detect with significance in a sample so small. More convincing is the fact that the QSOs are too faint to alter the ionization balance of material that lies $\sim 30$ proper Mpc away (i.e., $\Delta v = 2000$ km s$^{-1}$, see, e.g., Adelberger 2004). Their ionizing radiation could explain the galaxies’ weak HI absorption only if the QSOs’ redshifts differ significantly from our estimates.

A search for other explanations would have to explore possible faults with the data themselves. Precise measurements of a galaxy’s redshift are required to recognize that it is associated with a narrow absorption feature in a QSOs spectrum. Any errors in the redshift will tend to move the galaxy away from the feature, artificially reducing the apparent absorption. If such errors were responsible for galaxies with weak absorption, one would expect those galaxies always to have strong absorption features nearby. Figure 16 shows the nearby absorption features for all nine of the galaxies from Figures 13 and 15 that had transmissivity $\dot{f}_i$ Mpc $> 0.5$. Strong nearby HI absorption is present for about half of the galaxies, but systematic wavelength errors could make our data consistent with the windless
simulation only if their magnitude is much worse than the value $\sigma_v = 60 \text{ km s}^{-1}$ that we estimate from repeated observations of individual galaxies.

6. CHARACTERISTICS OF POSSIBLE SUPERWIND GALAXIES

The previous sections discussed two characteristics of intergalactic absorption that might reflect the influence of a nearby galaxy’s superwind: unusually strong metal absorption or unusually weak H I absorption. The two are contradictory, since metal lines are almost always produced by gas with a large H I column density. The association of either with superwinds could be strengthened if their presence was correlated with properties of the nearby galaxy.

Figure 17 compares various properties of galaxies with $f_1 \text{Mpc} < 0.5$ (light bars) and $f_1 \text{Mpc} > 0.5$ (dark bars). Star formation histories and stellar masses $M_*$ were estimated by fitting model spectral energy distributions (SEDs) to the galaxies’ observed photometry ($U,G,R,J,K,Spitzer$-IRAC 3.6, 4.5, 5.8, 8.0 $\mu$m for galaxies in Q1700; $U,G,R,K$, for galaxies in Q1623 and Q2343; and $U,G,R,K$, for the galaxy in Q2346). The models assumed exponentially declining star formation rates with varying time constants and ages, and each was subjected to a varying amount of reddening by dust that followed a Calzetti (2000) law.
See Shapley et al. (2005) and D. K. Erb et al. (2005, in preparation) for details.

Velocity differences between the galaxies’ interstellar absorption lines, \(\Delta v_{abs}\), and the Ly\(\alpha\) emission line, \(\Delta v_{\text{Ly} \alpha}\), were calculated as in \(\S\) 2. The rms widths of the nebular lines were estimated by fitting the each line’s profile with a Gaussian and subtracting the resolution in quadrature. Further details can be found in Erb et al. (2004). The data in these figures are available in Table 3. Numbers above each panel give the approximate Kolmogorov-Smirnov probability of observing the data if the two distributions were drawn from the same parent population. This probability is calculated with an approximation (subroutine \(\text{probks}\) in Press et al. 1992) that becomes poor for very small sample sizes (as, e.g., in the bottom center panel.) The abscissae show \(\tau\), a time constant in the assumed exponential star formation history \(\frac{SFR}{e^{\tau}}\); \(SFR\), star formation rate; \(M_\ast\), stellar mass; \(E(B-V)\), dust reddening, for a Calzetti (2000) dust curve; age, the estimated time since beginning of current episode of star formation; \(\Delta v_{abs}\), the velocity difference between galaxy’s near-IR nebular redshift and its interstellar absorption lines; \(\Delta v_{\text{Ly} \alpha}\), the velocity difference between the near-IR nebular redshift and the Ly\(\alpha\) emission line (which was usually not detected); and \(\sigma_{10}\), the velocity width of the near-IR nebular emission lines.

Fig. 17.—Characteristics of galaxies with little nearby intergalactic H\(\text{i}\) (\(f_{\lambda_{h\text{i}}} > 0.5\)). The distributions of these galaxies’ properties are shown with dark bars; the distributions for the rest of the \(<1\ h^{-1}\) Mpc NIRSPEC sample are shown with light bars. The number above each panel shows the approximate Kolmogorov-Smirnov probability of observing the data if the two distributions were drawn from the same parent population. This probability is calculated with an approximation (subroutine \(\text{probks}\) in Press et al. 1992) that becomes poor for very small sample sizes (as, e.g., in the bottom center panel.) The abscissae show \(\tau\), a time constant in the assumed exponential star formation history \(\frac{SFR}{e^{\tau}}\); \(SFR\), star formation rate; \(M_\ast\), stellar mass; \(E(B-V)\), dust reddening, for a Calzetti (2000) dust curve; age, the estimated time since beginning of current episode of star formation; \(\Delta v_{abs}\), the velocity difference between galaxy’s near-IR nebular redshift and its interstellar absorption lines; \(\Delta v_{\text{Ly} \alpha}\), the velocity difference between the near-IR nebular redshift and the Ly\(\alpha\) emission line (which was usually not detected); and \(\sigma_{10}\), the velocity width of the near-IR nebular emission lines.
nearby H i absorption may have somewhat higher star formation rates.

Figure 18 is similar, except here the sample is divided by the total detected C iv column density within 200 km s$^{-1}$ of the galaxy redshift. Galaxies with $N_{C\text{iv}} > 10^{13}$ cm$^{-2}$, where $N_{C\text{iv}}$ is the total detected intergalactic C iv column density (cm$^{-2}$) within 200 km s$^{-1}$ of the galaxy redshift, and light bars are for galaxies with $N_{C\text{iv}} < 10^{13}$ cm$^{-2}$.

Fig. 18.—Similar to Fig. 17, except here we compare galaxies with and without substantial nearby intergalactic C iv absorption. Dark bars are for galaxies with $N_{C\text{iv}} > 10^{13}$ cm$^{-2}$, where $N_{C\text{iv}}$ is the total detected intergalactic C iv column density (cm$^{-2}$) within 200 km s$^{-1}$ of the galaxy redshift, and light bars are for galaxies with $N_{C\text{iv}} < 10^{13}$ cm$^{-2}$.

Missing from Figures 17 and 18 is any indication of the large-scale environments that contain the different galaxy types. Shot noise prevents us from estimating the local galaxy density near any single object, but we can estimate the mean galaxy density around an ensemble of objects by summing their observed assumed star formation histories are grossly oversimplified. The figure suggests, however, that there are genuine differences between the SEDs of galaxies with and without nearby C iv absorption. The main empirical difference is a bluer mean optical to near-IR color for galaxies near C iv systems, which our SED fitting interprets as an excess of A stars relative to F and G stars.
number of galaxy neighbors and dividing by the number expected in the absence of clustering. Figure 19 shows the result for the different galaxy ensembles discussed above. Galaxies in denser environments are more likely to have detectable intergalactic C iv absorption within 1 h⁻¹ comoving Mpc, but local galaxy density does not seem to affect whether a galaxy has \( f_{\text{1 \ Mpc}} > 0.5 \) or \( f_{\text{1 \ Mpc}} < 0.5 \).

7. DISCUSSION

7.1. Superwinds at \( 2 \leq z \leq 3 \)

Galaxies would presumably be associated with QSO absorption lines even if there were no winds. This subsection discusses how strongly (or weakly) our observations support the existence of superwinds around the galaxies. We consider below the possibility that intergalactic metals were produced at very high redshifts (\( z \sim 10 \)).

The blueshifted absorption and redshifted Lyα emission in high-redshift galaxies’ spectra is the strongest evidence for winds from the galaxies. It is expected in a wide range of models in which the stars are surrounded by outflowing gas (e.g., Tenorio-Tagle et al. 1999; Zheng & Miralda-Escudé 2002) and is not (as far as we know) expected in any other class of realistic models. The statistical significance is high, since the same pattern has been observed in the spectra of dozens of galaxies (e.g., Fig. 1). This observation shows only that the outflowing gas lies somewhere outside the stellar radius, however. It does not imply that the outflow will be driven into the surrounding intergalactic medium (IGM).

The strength of C iv absorption at \( b = 40 \) kpc (Fig. 5) may suggest that the outflows have normally advanced to this radius, but even so this is only about halfway to the virial radius (for \( M_{\text{total}} \sim 10^{12} M_\odot \) in the ΛCDM cosmology favored by the Wilkinson Microwave Anisotropy Probe; Spergel et al. 2003). The minimum allowed velocity range of the gas at \( b = 40 \) kpc (\( \sim 300 \) km s⁻¹) is not large enough to guarantee escape. In any case the similarity of the C iv absorption strength in Lyman break galaxy (LBG) spectra and at impact parameter \( b = 40 \) kpc could just be a coincidence; it does not rule out the idea that the gas at 40 kpc is falling into or orbiting within the galaxy’s potential. Although anisotropies in the galaxy–C iv system correlation function seem to disfavor infall and favor rapid outflows for the origin of the C iv, C iv systems tend to be found near galaxies that may be too young to have driven winds far into their surroundings. The small number of distinct galaxy–C iv pairs leaves the situation unclear.

Measuring the spatial correlation of galaxies and metals on large (Mpc) scales would seem to provide a powerful way to distinguish between different scenarios for intergalactic metal enrichment. If the metals were produced in LBGs, they would have a spatial bias¹¹ similar to the galaxies’ bias of \( b \sim 2.5 \) at \( z = 3 \) (Adelberger et al. 2005a). They would have \( b = 1 \) if they were produced at any redshift by the numerous dwarf galaxies that are 1 σ fluctuations, and \( b \sim 1.9 \) at \( z = 3 \) if (as envisioned by Madau et al. 2001) they were produced at \( z = 9 \) by galaxies that were 2 σ fluctuations. These estimates of the bias exploit Mo & White’s (1996) high-redshift (i.e., \( \Omega \approx 1 \)) approximation,

\[
b(z) \approx 1 + \frac{(\nu^2 - 1)(1 + z)}{1.69 (1 + z_i)},
\]

for the bias at redshift \( z \) of objects that were \( \nu \sigma \) fluctuations at the earlier redshift \( z_i \). The galaxy-metal cross-correlation length would therefore be equal to the galaxy-galaxy correlation length if the metals were produced by LBGs and smaller for the other two cases. Unfortunately the implied bias for enrichment at \( z \sim 10 \) depends sensitively on the unknown value of \( \nu \). The parameter \( \nu \) would not have to be very different from the default assumption of Madau et al. (2001) to make the bias exactly equal to the bias for enrichment at \( z \sim 3 \). In any case, we have measured the galaxy–C iv correlation length, not the galaxy-metal correlation length. Our measured cross-correlation function therefore does not have an unambiguous interpretation.

There are only nine galaxies in our sample with precise (near-IR nebular line) redshifts and little H i within 1 h⁻¹ comoving Mpc, and their statistical significance is even lower than one might imagine. There are two reasons. First, as discussed above, the measurement is difficult. To determine whether a galaxy lies within \( \lesssim 1 \) h⁻¹ Mpc of a narrow absorption line in a QSO spectrum, one needs a good understanding of many possible sources of random and systematic error in the estimated redshifts. In about half the cases there is no absorption line anywhere near the galaxy redshift, but in the remainder the galaxies could conceivably be associated with nearby absorption lines if redshift errors were somewhat larger than we estimate. Reducing the number of galaxies with little nearby H i by 50% would begin to make our observations consistent with the predictions of windless SPH simulations. Second, five of the nine galaxies lie within a single field, Q1623, which contains one of the largest known concentrations of QSOs with \( 2 \leq z \leq 3 \). This is a consequence of the dense spectroscopic sampling we obtained in the field, but it raises the possibility that our result might have been different had we surveyed a more representative part of the universe. The spatial clustering strength of the high-redshift galaxies in this

¹¹ On scales larger than the maximum wind radius.
field is certainly not typical, for example (Adelberger et al. 2005b).

Even without its questionable statistical significance, the apparent lack of H i near some galaxies would not have a straightforward interpretation. This is due to the complexity of the interaction between winds and galaxies’ inhomogeneous surroundings. Analytic models treat this in an extremely crude way, and existing numerical simulations are unable to resolve either the shock fronts or the instabilities that result when the hot wind flows past cooler intergalactic material. As a result, it is unclear whether winds would destroy the H i near galaxies. Other effects that simulations do not resolve (e.g., cooling instabilities) might reduce the covering fraction of H i near galaxies. Even if there were low-density regions near galaxies in SPH simulations, they might not be recognized since the density is generally estimated by smoothing over the few dozen nearest particles, particles that were low-density regions near galaxies in SPH simulations, they follow from the fact that the total intergalactic metal density at high redshifts seems implausible on other grounds. Figure 20 illustrates a major problem: stars that form before high redshifts. In the few cases where the two scenarios have correlations on small scales, the observations seem to favor lower metal enrichment. In addition, enrichment at very high redshifts seems implausible on other grounds. Figure 20 illustrates a major problem: stars that form before 0 < z < 10 probably produce an inconsequential amount of metals compared to the stars that form afterward, so their metals could be dominant in the IGM only if virtually no metals were able to escape into the IGM at later times. In order for 90% of the intergalactic metals observed at 0 < z < 3 to have been produced at 10 < z < 15, for example, supernovae ejecta would have to be at least 100 times more likely to escape their galaxy at z = 10 than at z = 3. This follows from the fact that the total intergalactic metal density at z = 2, ρmet ≈ 0.02 Ωmet ≈ 1.2 × 10^3 M☉ Mpc^-3 for Ωmet ≈ 4.4Ωc and Ωc ≈ 2.3 × 10^-7 (Schaye et al. 2003), would be roughly twice the total metal production at 0 < z < 15 and 5 times smaller than the metal production at 2 < z < 15 if the cosmic star formation density were roughly constant for 2 < z < 15, the stellar density at z = 2 were ~5 × 10^7 M☉ Mpc^-3 (e.g., Dickinson et al. 2003; Rudnick et al. 2003), and 100 M☉ of star formation produced 1 M☉ of metals.

Is the metal escape fraction likely to be 100 times larger at z = 10 than z = 3? Two factors are commonly thought to in-crease the likelihood of escape at high redshift: galaxies are less massive and the intergalactic medium lies closer to them than at later times when the universe has expanded more. Both are offset by competing effects, however, and it is not clear to us that very high redshift galaxies have much of an advantage at all.

First consider the galaxy masses. The gravitational potential energy of a galaxy scales as M^2/r, or M^3/r, while the energy released by a galaxy’s supernovae scales as fM, where f is the efficiency of star formation. If f were independent of M, smaller galaxies would be more easily unbound by supernova explosions. This is the standard assumption, but in fact f increases with M and the situation is not clearcut. For example, compare the star formation efficiencies of LBGs at z = 3 to those of galaxies at z < 10. The ratio of stellar to baryonic mass for LBGs at z = 3 is M*/M_b = 0.1 (Adelberger et al. 2004), which implies f = 0.1. An upper limit to the star formation efficiency at z = 10 can be derived by assuming that the star formation density is constant for 2 < z < 15. (In fact it appears to be significantly lower at z = 5; Bunker et al. 2004.) In this case the stellar density at z = 10 will be Ωb/Ωh = 0.001, scaling from the z = 2 stellar density estimated by Dickinson et al. (2003) and Rudnick et al. (2003), while the fraction of baryons in the halos with v_h = 10 km s^-1 that are able to host star formation (Dijkstra et al. 2004) is Omega_b/Omega_h ~ 0.08. That implies an upper limit to the star formation efficiency of f ≈ Omega_b/Omega_h ~ 0.01 for typical galaxies at z = 10. The order-of-magnitude increase in star formation efficiency at lower redshift removes any advantage higher redshift galaxies might gain from their smaller masses. A similar argument shows that the star formation efficiencies of LBGs are far higher than those of smaller galaxies at similar redshifts 2 < z < 3.

Now consider the supposed benefit from the small size of the universe at z = 10. If supernova ejecta at z = 10 extended from their galaxies into the receding Hubble flow, their filling fraction at lower redshift would be boosted by the subsequent expansion of the universe. In fact, however, the ejecta will not normally reach the Hubble flow. Instead they are likely to be swept back into their galaxy by the ongoing process of structure formation. To illustrate the point, we show in Figure 21 the distance to the nearest halo of mass M ≥ 10^11 M☉ at z = 2.12 for every particle in the GIF-ΛCDM simulation (Kauffmann et al. 1999) that lay
suggests that the metals ejected at \( z \) are usually significantly different at the initial and final times.) These shaded histograms show the distribution at \( \frac{h}{\text{comoving Mpc}} \) within 1 \( h^{-1} \) comoving Mpc of a galaxy (i.e., halo) at \( z = 10 \) or \( z = 5 \). The result is stark: the overwhelming majority of these particles end up inside the virial radius of a galaxy at \( z \sim 2 \). Since the stalled ejecta of galaxies at \( z = 10 \) or \( z = 5 \) will be swept along by the movements of the material that surrounds the galaxies, they should largely end up inside galaxies at \( z \sim 2 \) as well. This exercise may be slightly misleading, since the GIF-ΛCDM simulation only resolves halos of mass \( M \gtrsim 10^{11} M_{\odot} \) (i.e., \( \sim 4 \sigma \) fluctuations at \( z \sim 10 \)), not the smaller halos believed to be most responsible for polluting the IGM at \( z \sim 10 \). However, a simple calculation shows that a significant fraction of the metals from the lower mass progenitors should also end up inside galaxies at \( z \sim 2 \). The estimated stalling radius for winds from small galaxies at \( z \sim 10 \) is \( \sim 100 \) comoving kpc (e.g., Madau et al. 2001), which is the Lagrangian radius for a halo of mass \( 1.7 \times 10^{10} M_{\odot} \). If these galaxies’ typical descendants at \( z \sim 2 \) have masses significantly larger than this, the metals will likely have been swept inside them. According to the extended Press-Schechter formalism, \( \sim 85\% \) of the galaxies at \( z \sim 2 \) that descended from \( \sim 2 \sigma \) fluctuations at \( z = 10 \) will have masses that exceed this threshold by an order of magnitude (see, e.g., eq. [2.16] of Lacey & Cole 1993). A substantial fraction of the metals produced at \( 10 \leq z \lesssim 15 \) should therefore be locked inside galaxies at \( z \sim 2 \). Once there, some of them are likely to cool further, fall toward the center, and disappear from view. Since the total metal production at \( 10 \leq z \lesssim 15 \) is at best comparable to the observed metal content of the IGM at \( z \sim 2 \) (Fig. 20), this suggests that the intergalactic metallicity at \( z \sim 2 \) must receive a significant contribution from some other source. A corollary is that the metal content of the IGM would drain into galaxies and decrease over time if it were not continually replenished. The observed constancy of the IGM metallicity (e.g., Schaye et al. 2003) therefore also seems to require metals to escape from galaxies at lower redshifts.\(^{12}\)

8. SUMMARY

We reviewed the status of our search for direct evidence of large-scale outflows around UV-selected star-forming galaxies at \( 2 \leq z \leq 3 \). These are our principal observations:

1. The gas that lies within 40 kpc of LBGs produces extremely strong absorption lines (\( N_{\text{HI}} \gtrsim 10^{14} \text{ cm}^{-2} \)) in the spectra of background galaxies and QSOs (Fig. 5). The large equivalent widths of the C iv absorption in low-resolution spectra imply that the absorbing material has range of velocities of at least \( \Delta v = 260 \text{ km s}^{-1} \). The absorption produced by this gas is similar to the interstellar absorption seen in LBGs’ spectra, suggesting the LBGs’ outflowing “interstellar” gas may actually lie at radii approaching 40 kpc.

2. For roughly half of the LBGs, C iv absorption lines with the hydrogen column density \( N_{\text{HI}} \approx 10^{12.5} \text{ cm}^{-2} \) appear to be the same as the correlation function of galaxies (Fig. 11). This implies that C iv systems and galaxies reside in similar parts of the universe and is consistent with the idea that they are largely the same objects. We also find a strong association of O vi systems with galaxies (Fig. 10). On small scales the redshift-space cross-correlation function is highly anisotropic (Fig. 12). The metal-enriched gas must therefore have large velocities relative to nearby galaxies. The required velocities appear to exceed the galaxies’ velocity dispersions but are similar to the galaxies’ observed outflow speeds.

3. In contradiction to the earlier result of Adelberger et al. (2003), we find that the gas within 1 \( h^{-1} \) comoving Mpc of LBGs usually produces strong Lyα absorption in the spectra of background galaxies (Fig. 14). The absorption is weak (mean transmitted flux within 1 \( h^{-1} \) Mpc of \( f_1 \text{ Mpc} > 0.5 \) in only about one case out of three (Fig. 15)). Even so, the weakness of the absorption in these cases remains difficult to understand. Since high-redshift galaxies reside in dense parts of the universe, with large amounts of hydrogen and high recombination times, one would expect them to be surrounded by large amounts of H i. The H i has presumably collapsed into clouds and sight lines to the background QSOs might occasionally miss every cloud near a galaxy, but the SPH simulations of J. Kollmeier et al. (2005, in preparation) suggest that the chance of this is very low (Fig. 15).

5. We were unable to identify any statistically significant differences in age, dust reddening, stellar mass, kinematics, or environment between galaxies with weak nearby H i absorption

\(^{12}\) If one removes the assumption that the metals injected into the IGM at a given redshift must lie near galaxies that existed at that redshift, then it is possible to find a spatial distribution of intergalactic metals that matches intergalactic absorption-line statistics and does not drain into galaxies at a significant rate for \( 2 \leq z \leq 4 \) (e.g., Schaye et al. 2003). The removal of this assumption seems dubious to us, however. Metals could exist in parts of the IGM that were never near galaxies only if they were produced by Population III stars, presumably, and the amount of Population III star formation would have to be inordinately large to match the observed intergalactic metallicity at \( z \sim 2 \) (e.g., Fig. 20; see also Aguirre et al. 2004).
and the rest, although galaxies with weak absorption may have higher star formation rates (Fig. 17). Galaxies near intergalactic C IV systems appear to reside in relatively dense environments (Fig. 19) and to have distinctive SEDs characterized by blue colors and young ages (Fig. 18).

As discussed in § 7, none of these observations provide unequivocal evidence for superwinds at $z \sim 2$–$3$. This is mostly because it is unclear how superwinds would affect the correlation between galaxies and intergalactic absorption lines. Metals and galaxies would lie near each other at $z \sim 3$ even if there were no active outflows, for example. We argued in § 7 that star formation at $10 < z < 15$ may not produce enough metals to account for the intergalactic metallicity at $z \sim 2$–$3$, and that many of these metals would be buried inside galaxies by $z \sim 2$–$3$, but our simple arguments need to be checked with numerical simulations. The interpretation of our data will remain ambiguous until that time. The arguments presented in § 7 should make it clear that metal enrichment at $5 \lesssim z \lesssim 15$ will be much harder to rule out than metal enrichment at $10 \lesssim z \lesssim 15$.

There is only one case in which the data seem easy to interpret and we are limited by the small size of our sample. This is the redshift-space distribution of metals within $\sim 200$ comoving kpc of galaxies. Mapping the velocity offsets between galaxies’ stars and their metals as a function of impact parameter would help show whether the detected metals are flowing out of, falling into, or orbiting within the galaxies’ halos. The velocity offsets can be mapped by obtaining higher resolution spectra of more close pairs (e.g., the right panel of Fig. 4) or by obtaining more near-IR nebular redshifts for galaxies near the QSO sight line (e.g., Fig. 12). That seems the sensible way to proceed.

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