HIGH-METALLICITY Mg II ABSORBERS IN THE $z < 1$ Ly$\alpha$ FOREST OF PKS 0454+039: GIANT LOW SURFACE BRIGHTNESS GALAXIES?\textsuperscript{1,2}

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Received 1997 October 16; accepted 1998 January 7

ABSTRACT

We report the discovery of two iron-group enhanced high-metallicity Mg II absorbers in a search through 28 Ly$\alpha$ forest clouds along the PKS 0454+039 sight line. Based upon our survey and the measured redshift number densities of $W_r$(Mg II) \( \leq 0.3 \) Å absorbers and Ly$\alpha$ absorbers at $z \sim 1$, we suggest that roughly 5% of Ly$\alpha$ absorbers at $z \leq 1$ will exhibit “weak” Mg II absorption to a 5 $\sigma$ $W_\lambda(2796)$ detection limit of 0.02 Å. The two discovered absorbers, at redshifts $z = 0.6248$ and $z = 0.9315$, have $W_r$(Ly$\alpha$) = 0.33 and 0.15 Å, respectively. Based upon photoionization modeling, the H I column densities are inferred to be in the range 15.8 \( \leq \log N$(H I) \( \leq \) 16.8 cm$^{-2}$. For the $z = 0.6248$ absorber, if the abundance pattern is solar, then the cloud has $[\text{Fe/H}] > -1$; if its gas-phase abundance follows that of depleted clouds in our Galaxy, then $[\text{Fe/H}] > 0$ is inferred. For the $z = 0.9315$ absorber, the metallicity is $[\text{Fe/H}] > 0$, whether the abundance pattern is solar or suffers depletion. Imaging and spectroscopic studies of the PKS 0454 + 039 field reveal no candidate luminous objects at these redshifts. We discuss the possibility that these Mg II absorbers may arise in the class of “giant” low surface brightness galaxies, which have $[\text{Fe/H}] \geq -1$, and even $[\text{Fe/H}] \geq 0$, in their extended disks. We tentatively suggest that a substantial fraction of these “weak” Mg II absorbers may select low surface brightness galaxies out to $z \sim 1$.

Subject headings: galaxies: evolution — intergalactic medium — quasars: absorption lines

1. INTRODUCTION

Metal-line absorption in the intergalactic medium, or IGM,\textsuperscript{4} is astrophysically interesting because the absorption properties can be exploited to reveal the star formation, chemical enrichment, and ionization histories of the universe. This provides a motivation for studying metal lines in Ly$\alpha$ absorbers over as wide a redshift range as possible and for sampling transitions covering as many ionization levels and chemical species as possible (Hellsten et al. 1998; Rauch, Heahnelt, & Steinmetz 1997). Observations (Hu et al. 1995; Lu et al. 1996; Kim et al. 1997) and numerical simulations (Miralda-Escudé et al. 1996; Zhang et al. 1997; Davé et al. 1997; Norman et al. 1998) have revealed that the forest is rapidly evolving with redshift from $z \sim 4$ to $z \sim 1$ and that the absorbing gas is housed in a wide range of cosmic structures undergoing a wide range of dynamical processes. At $z \sim 2$, Ly$\alpha$ clouds contain the majority of the baryon content of the universe. At lower redshifts, Ly$\alpha$ clouds are thought to be more directly associated with low surface brightness and/or dwarf galaxies (Salpeter 1993; Shull, Stocke, & Penton 1996; Linder 1998), with the outer disks and halos of high surface brightness galaxies (Lanzetta et al. 1995; Le Brun, Bergeron, & Boissé 1996), or with the remnant material left over from the formation of galaxies and/or small galaxy groups (van Gorkom et al. 1996; Bowen, Blades, & Pettini 1996; Le Brun et al. 1996). Studies of the metal content and ionization conditions in these low-redshift forest clouds, especially in the context of their association (or lack of association) with galaxies, could provide the “missing-link” evidence necessary for inferring the evolving interplay between the IGM and galaxies or the presence of low surface brightness galaxies at higher redshifts.

A limited number of strong metal-line species have now been seen in high-ionization transitions at $z \sim 2.5$ (Tytler et al. 1995; Cowie et al. 1995; Songaila & Cowie 1996). However, the chemical and ionization conditions of Ly$\alpha$ clouds at low redshifts ($z \leq 1$) remain unexplored because they require time-intensive programs using HST. Relative to $z \sim 2.5$, the metagalactic UV background flux (UVB) at $z < 1$ is reduced by a factor of $\sim 5$ and its shape may be softened by stellar photons escaping bright field galaxies (Deharveng et al. 1997; Giallongo, Fontana, & Madau 1997; Bergeron et al. 1994, and references therein). Thus, the IGM ionization conditions may have evolved so that low-ionization species, especially the resonant Mg II $\lambda\lambda2796, 2803$ doublet and several of the stronger Fe II transitions, are detectable in Ly$\alpha$ clouds. As discussed below, these particular species are well suited for understanding chemical enrichment histories.

Songaila & Cowie (1996, hereafter SC96) detected C IV absorption in $\sim$75% of all Ly$\alpha$ clouds at $z \sim 2.5$ with log $N$(H I) $\geq$ 14.5 cm$^{-2}$ and concluded that roughly 50% of log $N$(H I) $\leq$ 14.5 cm$^{-2}$ clouds could have primordial abundances. They also reported Si IV and C II absorption in a

\textsuperscript{1} Based on part in observations obtained at the W. M. Keck Observatory, which is jointly operated by the University of California and the California Institute of Technology.

\textsuperscript{2} Based on part in observations obtained with the NASA/ESA Hubble Space Telescope, which is operated by the STScI for the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

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\textsuperscript{4} Throughout this paper, we use the terms ”Ly$\alpha$ cloud,” ”forest cloud,” and ”IGM” somewhat interchangeably to designate Ly$\alpha$ absorption with $\tau_{512} < 1$. 
fraction of the Ly\textsubscript{z} clouds (including “partial” Lyman limit systems). Based upon the photoionization models of Bergeron & Stasińska (1986), SC96 find the metallicity of \( z \sim 2.5 \) Ly\textsubscript{z} clouds to be \( [Z/Z_0] \sim -2 \) and to be fairly uniform, with about 1 dex of scatter.\(^5\) They also report \([\text{Si}/\text{C}]\) ratios consistent with Galactic halo stars (metal poor late-type stars), in that the \( \alpha\)-group silicon is enhanced by a factor of 3 over the carbon. This conclusion, however, is sensitive to the assumed UVB continuum shape, especially the question of how much starbursting galaxies contribute to the UVB, and its nonuniformity, at higher redshifts (Giroux & Shull 1997).

Considering the mechanisms and range of environments that could plausibly give rise to metals in what are traditionally known as Ly\textsubscript{z} clouds, it is difficult to understand a high level of uniformity in their chemical enrichment histories. As proposed by Tytler et al. (1995), there are at least three obvious mechanisms for the enrichment.

1. The larger N(H\textsubscript{\textsc{i}}) clouds may be gravitationally bound with internal gravitational instabilities in which they produce their own stars, which in turn distribute the metals throughout the cloud. This type of object has little distinction from a galaxy. This in situ process would likely give rise to a strong metallicity dependency with H\textsubscript{\textsc{i}} column density, unless a well-tuned mechanism governing star formation yielded a uniform chemical enrichment history of the IGM, as suggested by Cowie et al. (1995). Such a mechanism would likely represent nonstandard star formation processes.

2. The metals may be produced in protogalaxies and then be widely distributed via mechanical ejection from merging events (Gnedin & Ostriker 1997) or from correlated supernovae (SNe) (Cen & Ostriker 1992). This implies that Ly\textsubscript{z} clouds formed after the metals were distributed around the metal producing galaxies. The scenario also predicts that the metal-enriched Ly\textsubscript{z} clouds, as opposed to “Ly\textsubscript{z}-only” clouds, would cluster like galaxies.

3. Population III stars, formed at \( z > 10 \) and somewhat uniformly spread throughout the IGM, may have distributed metals into the IGM prior to the first protogalaxies. A population of Ly\textsubscript{z} forest clouds that have been enriched by Population III stars may exhibit IGM chemical conditions that are relatively unchanged from the epoch of the first stars. If so, this population would be ideal for studying the intensity and continuum shape evolution of the UVB from \( 0 < z < 4 \), since the changing ionization conditions could be used to deconvolve the non-evolving chemical conditions from the evolving UVB. As such, the detection of extremely metal poor stars in the Galaxy halo would also be very interesting, since their presence would suggest the presence of Population III stars (cf. Ostriker & Gnedin 1996).

The chemical abundance pattern can serve as a clue to the origin, physical environment, and chemical enrichment history of any given Ly\textsubscript{z} absorber. There are at least two major uncertainties involved in measuring relative abundances using QSO absorption lines: ionization corrections and dust grain depletion patterns. The ionization correction provides good reason for observing a wide range of ionization levels. Moreover, the ionization corrections are sensitive to the intensity and continuum shape of the ionizing radiation, possibly providing even further leverage for understanding local environments and chemical enrichment history. Dust depletion does not affect all \( \alpha\)-group elements (for example, sulfur is not readily incorporated onto dust grains) nor all Fe-group elements (for example, zinc). However, those elements provide neither the strong UV absorption lines needed to accurately probe clouds with \( \tau_{912} < 1 \), nor the transitions observable from the ground for redshifts below \( z \sim 1 \). The strongest observable transitions are the Mg \( \equiv \lambda\lambda 2976, 2803 \) doublet (\( \alpha \) group), and Fe \( \equiv \lambda\lambda 2344, 2382, 2600 \). Unfortunately, both magnesium and iron can deplete onto dust grains, and their depletion levels are environment dependent.

For each of the three scenarios suggested above, it is expected that the relative elemental abundances of an enriched cloud should reflect the \( \alpha\)-group enhanced yield of Type II SNe (note that this is consistent with the results of SC96). In essence, the picture is simple: if the \( \alpha\)-group elements are enhanced relative to the Fe group, then the chemical enrichment has been dominated by Type II SNe. Based upon the \([\text{Si}/\text{Fe}], [\text{S}/\text{Fe}], [\text{O}/\text{Fe}]\) ratios measured in Galactic halo stars, this pattern is seen for \([\text{Fe}/\text{H}] \lesssim -1 \) (see Lauroesch et al. 1996). In the case of scenario (3) presented above, it is likely that only a single burst, or episode, of star formation would have occurred and that the metal production arises exclusively from Type II SNe. In the case of scenario (2), the Ly\textsubscript{z} clouds would be far from the galaxies; the only metal-enriched gas that could infiltrate clouds forming from the primordial IGM would necessarily be ejected from correlated Type II SNe bursts.

If the abundance pattern is more in line with solar proportions (i.e., \([\text{Mg}/\text{Fe}] \sim [\text{Si}/\text{Fe}] \sim [\text{Fe}/\text{H}] \sim 0 \)), then the picture is that Fe-group elements have been built up over a longer timescale via Type Ia SNe. This implies a star formation history local to the cloud that would have been relatively quiescent for the order of Gyr prior to the epoch of the observed absorption. Thus, if a given Ly\textsubscript{z} cloud is measured to have \([\text{Fe}/\text{H}] \geq -1 \) and \([\alpha/\text{Fe}]-group abundance ratios near-solar proportions, then one might infer that Type Ia SNe have played a role in the cloud’s chemical enrichment history. However, based upon uncertainties in Type II SNe yields, Gibson, Loewenstein, & Mushotzky (1997) have cautioned that the relative importance of Type Ia and Type II SNe as intercluster polluters remains uncertain.

A type of extended gas-rich object that is seen to have \([\text{Fe}/\text{H}] \geq -1 \), and even \([\text{Fe}/\text{H}] \geq 0 \), is the class of giant low surface brightness galaxies (Bothun, Impey, & McGaugh 1997; Pickering & Impey 1995; McGaugh 1994). At low redshifts, the general population of low surface brightness galaxies is seen to outnumber high surface brightness galaxies by a factor of at least 2 (Dalcanton et al. 1997). As such, these galaxies are important tracers of low-density dark matter halos and structure formation from small over-density fluctuations. They also may represent environments where the pathways of star formation and chemical evolution reflect nonstandard astrophysical processes (Bothun et al. 1997). If these objects are observable in absorption over a wide range of redshifts, they likely will provide us a unique astrophysical laboratory for broadening our present perspective on star and galaxy formation.

In this paper we report the search for and discovery of Fe \( \equiv \lambda\lambda 2344, 2382 \) doublet absorption in the Ly\textsubscript{z} forest along the PKS 0454 + 039 sight line. In § 2 we describe the data and analysis. In § 3 we describe the sample of Ly\textsubscript{z} lines and our search method. The absorption properties of the
detected systems are presented in § 4. We apply photoionization models to the detected metal-line systems in § 5 and briefly discuss the model results in § 6. The implications of the results are addressed in § 7. A brief summary is provided in § 8.

2. OBSERVATIONS AND DATA ANALYSIS

The Mg II and Fe II transitions were searched for in an R = 45,000 optical HIRES (Vogt et al. 1994) spectrum. The Lyα line list was obtained from the R = 1300 G190H and G270H FOS/HST spectra of Boissé et al. (1998, hereafter BBLD). Three images of the PKS 0454 + 039 field have been incorporated into our study so that we may attempt to identify the luminous objects giving rise to the absorption. Two are high spatial resolution WFPC2/HST images using the F450W and F702W filters (Le Brun et al. 1997, hereafter LBBD). The third is the deep R[6930/1500] image (centered on x6930 with a FWHM bandpass of 1500 Å) taken from Steidel et al. (1995). We also draw upon the published (Steidel et al. 1995) and unpublished (C. Steidel 1997, private communication) spectroscopic redshift measurements of the many objects along the line of sight to the QSO.

The HIRES spectrum was obtained and reduced as described in Churchill (1997) and in Churchill, Vogt, & Charlton (1998b). The HIRES spectrum has wavelength coverage 3767–6198 Å, although there are some breaks in the coverage redward of 5100 Å because the single setting of the 2048 × 2048 CCD did not capture the complete free spectral range at these wavelengths. The FOS spectra were obtained and reduced, and the list of Lyα forest lines used for this study were produced as described in BBLD. The acquisition and analysis of the high spatial resolution WFPC2 images are described in LBBD. They also present a synopsis of candidate galaxies along the line of sight to the quasar available from their study and the literature. The R-band ground-based image and the spectroscopic identifications of objects in the PKS 0454 + 039 field are described in Steidel et al. (1995).

3. SEARCHING THE FOREST

We searched the HIRES/Keck spectrum of PKS 0454 + 039 for Mg II absorption in the Lyα lines reported by BBLD. In the FOS spectra, the redshift range over which Lyα was detected is 0.4163 ≤ z(1215) ≤ 1.3431. The redshift range over which the Lyα 1215 transition could have been detected was 0.41 ≤ z ≤ 1.69. The line list is presented in Table 1. In all cases, they are Lyα-only systems (no other corroborating transitions are detected in absorption). We have included only those lines from BBLD that are not confused by blending or are not coincident in wavelength with strong metal-line transitions from the four known

### TABLE 1

| BOISSÉ ET AL. 1998 | H I | Mg II |
|-------------------|-----|-------|
| \( z_{\text{ex}}(\text{Ly} \alpha) \) | \( W(\text{Ly} \alpha) \) | \( \log N_{500} \) | \( \log N_{300} \) | \( \log N_{15} \) | \( W_{v, \text{lim}} \) | \( \log N \) |
| (Å) | (Å) | (cm\(^{-2}\)) | (cm\(^{-2}\)) | (cm\(^{-2}\)) | (Å) | (cm\(^{-2}\)) |
| 0.4163 | 1.03 | 14.9 | 18.1 | 18.5 | 0.025 | 11.8 |
| 0.4662 | 0.37 | 14.0 | 14.4 | 16.7 | 0.017 | 11.6 |
| 0.5577 | 0.36 | 14.0 | 14.4 | 16.5 | 0.013 | 11.5 |
| 0.5898 | 0.63 | 14.3 | 16.3 | 17.8 | 0.013 | 11.5 |
| 0.6251 | 0.35 | 13.9 | 14.3 | 16.4 | 0.012 | 11.4 |
| 0.6428 | 0.33 | 13.9 | 14.3 | 16.4 | 0.012 | 11.4 |
| 0.6447 | 0.75 | 14.5 | 17.2 | 18.1 | 0.015 | 11.6 |
| 0.6768 | 0.28 | 13.8 | 14.0 | 15.4 | 0.009 | 11.3 |
| 0.6968 | 0.19 | 13.6 | 13.7 | 14.2 | 0.009 | 11.3 |
| 0.7566 | 0.29 | 13.8 | 14.1 | 15.5 | 0.012 | 11.4 |
| 0.7934 | 0.11 | 13.3 | 13.4 | 13.5 | 0.009 | 11.3 |
| 0.7986 | 0.11 | 13.3 | 13.4 | 13.5 | 0.009 | 11.3 |
| 0.8069 | 0.39 | 14.0 | 14.5 | 16.9 | 0.011 | 11.4 |
| 0.8125 | 0.35 | 13.9 | 14.3 | 16.4 | 0.011 | 11.4 |
| 0.8816 | 0.53 | 14.2 | 15.4 | 17.6 | 0.008 | 11.3 |
| 0.9084 | 0.59 | 14.3 | 15.9 | 17.8 | 0.008 | 11.3 |
| 0.9183 | 0.78 | 14.5 | 17.3 | 18.2 | 0.011 | 11.4 |
| 0.9315 | 0.15 | 13.5 | 13.6 | 13.9 | 0.008 | 11.3 |
| 0.9384 | 0.51 | 14.2 | 15.3 | 17.6 | 0.008 | 11.3 |
| 0.9781 | 1.63 | 16.5 | 18.8 | 19.2 | 0.008 | 11.3 |
| 0.9948 | 1.19 | 15.3 | 18.4 | 18.7 | 0.008 | 11.3 |
| 1.0558 | 0.50 | 14.1 | 15.2 | 17.5 | 0.008 | 11.2 |
| 1.0679 | 0.41 | 14.0 | 14.6 | 17.0 | 0.008 | 11.2 |
| 1.0922 | 0.31 | 13.9 | 14.2 | 15.8 | 0.007 | 11.2 |
| 1.0995 | 0.40 | 14.0 | 14.6 | 17.0 | 0.007 | 11.2 |
| 1.1674 | 0.86 | 14.6 | 17.7 | 18.3 | 0.007 | 11.2 |
| 1.1749 | 0.31 | 13.9 | 14.2 | 15.8 | 0.007 | 11.2 |
| 1.1871 | 0.16 | 13.5 | 13.6 | 13.9 | 0.007 | 11.2 |

Note.—Cols. (1) and (2) give the redshift and rest-frame Lyα equivalent width as measured by Boissé et al. 1998, except where noted. Cols. (3), (4), and (5) give the estimated neutral hydrogen column density for b(H I) = 80, 30, and 15 km s\(^{-1}\), respectively. Cols. (6) and (7) give the 5σ rest-frame Mg II \( \lambda 2796 \) equivalent width limit and Mg II column density assuming linear curve of growth analysis for the \( W_{v, \text{lim}}(\text{Mg II}) \).

* These two systems were detected in Mg II, but are presented here for purpose of illustration.
FIG. 1.—The 5σ rest-frame equivalent width detection limit of the Mg II 2796 transition as a function of redshift. The decrease in sensitivity toward lower redshift is due to the HIRES throughput and CCD efficiencies. The higher frequency features are due to the blaze efficiency function of the individual echelle orders. Gaps in the redshift coverage appear at \( z \approx 0.83 \) and above.

Metal-line systems \((z = 0.072, 0.859, 1.068, 1.153)\) along the line of sight. The first two columns of Table 1 are the redshift of Lyα absorption and the rest-frame 21215.67 equivalent width, respectively. In columns (3)–(5), values of the neutral hydrogen column density, log \( N(H_I) \), are tabulated for Doppler \( b \) values of 80, 30, and 15 km s\(^{-1} \), respectively. These are shown only to illustrate the plausible \( N(H_I) \) range that might be inferred from the equivalent widths. A \( b = 30 \) km s\(^{-1} \) is representative of the median \( b \) value of 34 km s\(^{-1} \) found by Kim et al. (1997) at redshifts \( 2 < z < 3 \). There is evidence that the median \( b \) value increases with decreasing redshift, which is believed to be due to kinematic substructure evolution for \( N(H_I) > 14 \) cm\(^{-2} \) clouds. For the higher column density clouds, the widths likely reflect nonshock heated cloud temperatures (Haehnelt, Steinmetz, & Rauch 1996). A \( b = 80 \) km s\(^{-1} \) is plausible for kinematically broadened and/or shock heated clouds (Kim et al. 1997). Doppler parameters greater than \( \sim 80 \) km s\(^{-1} \) are likely due to blending (Lu et al. 1996), possibly of physically distinct systems. The \( b = 15 \) km s\(^{-1} \) value is the “lower cutoff” value found at high redshift (Lu et al. 1996, but also see Hu et al. 1995).

The sensitivity of the search, as a function of redshift, is quantified in terms of the rest-frame limiting equivalent width of the Mg II 2796 transition. In Figure 1, we present the sensitivity curve, where we have chosen to use a 5σ significance level. The redshift range over which Mg II doublets could be detected in the HIRES spectrum is \( 0.336 \leq z(2796) \leq 1.2134 \). There are small gaps in the coverage above \( z(2796) = 0.8340 \) that increase with increasing redshift. The 5σ observed equivalent width detection limit ranged from 0.007 to 0.020 Å, except for \( z(2796) \leq 0.4662 \), where it ranges from 0.020 to 0.035 Å. The results, including the detection limits and the limiting

### TABLE 2

**Measured Properties of Absorbing Systems**

| Transition | \( \lambda_{\text{obs}} \) (Å) | \( W_e \) (Å) | \( \log N \) (cm\(^{-2} \)) | \( b \) (km s\(^{-1} \)) |
|------------|------------------|--------------|----------------|-----------------|
| H I 1216   | 1997.10          | 0.33 ± 0.03  | 12.46 ± 0.06  | 4.29 ± 1.25    |
| Fe II 2383 | 3914.504         | 0.031 ± 0.002| 12.40 ± 0.06  | n.d.           |
| Fe II 2600 | 4211.654         | 0.029 ± 0.001| 12.31 ± 0.06  | n.d.           |
| Mg II 2796 | 4593.924         | 0.120 ± 0.001| 12.74 ± 0.02  | 5.73 ± 0.28    |
| Mg II 2803 | 4605.719         | 0.086 ± 0.004| n.d.           | n.d.           |

| Transition | \( \lambda_{\text{obs}} \) (Å) | \( W_e \) (Å) | \( \log N \) (cm\(^{-2} \)) | \( b \) (km s\(^{-1} \)) |
|------------|------------------|--------------|----------------|-----------------|
| H I 1216   | 2348.07          | 0.15 ± 0.04  | 12.24 ± 0.09  | 2.28 ± 1.57    |
| Fe II 2383 | 4602.312         | 0.020 ± 0.003| 12.29 ± 0.08  | 2.19 ± 0.46    |
| Mg II 2796 | 5401.148         | 0.041 ± 0.002| 12.32 ± 0.09  | n.d.           |
| Mg II 2803 | 5415.035         | 0.020 ± 0.001| n.d.           | n.d.           |

**Note.**—Cols. (4) and (5) are based upon Voigt profile fits to the HIRES data. The tabulated column densities and \( b \) parameters apply to all transitions of a given ion species; however, they are given opposite only to the strongest transition for the species.

* Based upon the Monte Carlo simulations, the equivalent width of this transition may actually be 0.023 Å.
column densities of Mg II, which are based upon linear curve of growth analysis, are presented in columns (6) and (7) of Table 1. Only those redshifts for which both transitions of the Mg II doublet could be observed are tabulated.

Absorption features were defined using our own interactive software, which is based upon the detection algorithms of the QSO Absorption Line Key Project (Schneider et al. 1993). The criteria that define a confirmed Mg II doublet are presented by Churchill et al. (1998a), who have searched 26 HIRES/Keck QSO spectra for weak Mg II systems. These lines are fitted with Gaussians to obtain their equivalent widths and observed central wavelengths.
To locate candidate Mg II doublets, the candidate λ2796 line centroid and detection aperture (full width at the continuum) is shifted to the expected location of the λ2803 line and the significance level is measured. An acceptable candidate for the weaker member of the doublet occurs when the detection significance level is greater than or equal to the ratio of the transition fλ times the significance level of the stronger member. Then, a “chance probability” is computed by scanning the spectrum with the detection aperture over the spectrum for ~50 Å to both sides of the candidate and computing the fraction of detected features (both emission and absorption) with a significance level greater than or equal to the candidate λ2803 line. Most bona fide Mg II doublets have chance probabilities of ~10^{-6}, although a very few have probabilities as large as ~10^{-3}.

To a 5σ limit of log N(Mg II) ~ 11.3 cm^{-2}, the Mg II doublet was detected in two of the 28 Lyα lines in the list, which is a success rate of ~7%. The two weak Mg II systems found in the HIRES spectra have z = 0.6428 and z = 0.9315. The data for these systems are presented in Figure 2, and their measured properties are listed in Tables 2 and 3. For both, the Mg II doublet and at least one transition of Fe II was detected. Below, we describe the measured properties of the two detected systems.

4. PROPERTIES OF THE ABSORBERS

In this work, we concentrate on the properties of the two absorbers for which Mg II has been detected. Here we note that the Lyα equivalent widths are among the smallest in the sample of 28 (there are seven as small as or smaller than the z = 0.6428 absorber and two as small as or smaller than the z = 0.9315 absorber). Also, we note that the Mg II and Fe II transitions have been detected a factor of 5–10 above the 5σ detection limits of the HIRES spectra. Given the stringent limits on the Mg II column densities for the remaining Lyα absorbers, and the fact that majority appear to have higher N(H I) than the two exhibiting Mg II, it may be that there is a large dynamic range in the N(Mg II)/N(H I) ratio. As noted in §1, this is not the case for C IV absorption in the Lyα forest.

However, we note that upper limits on the metallicities are not very restrictive if we assume a typical b parameter of 30 km s^{-1} and photoionization by the UVB (using CLOUDY; see Fig. 11 of Churchill et al. 1998a). For a Lyα cloud with W_Lyα ~ 0.6 Å and N(Mg II) < 11.4 cm^{-2}, the upper limit on [Z/Z_{⊙}] ranges from ~0.5 to ~2.8, depending upon ionization level. For a Lyα cloud with W_Lyα ~ 0.4 and N(Mg II) < 11.4 cm^{-2}, the upper limit ranges from ~0.4 to ~2.2 as the cloud becomes highly ionized. Thus, a great deal can be said about the range of metallicities in the Lyα forest at z = 1 based upon our Mg II upper limits.

4.1. The z = 0.6428 System

In the left-hand panels of Figure 2, the Mg II and Fe II HIRES profiles are presented. Also shown (top panel) is the FOS spectrum, with the position of the corresponding Lyα line marked with a tick. Along with the Mg II doublet, Fe II λ2383 and λ2600 were clearly detected. The weaker Fe II transitions were covered by the spectrum, but were not found to the 5σ significance level. In part, this is due to the decreasing signal-to-noise ratio below 4000 Å where the HIRES sensitivity drops rapidly (see Fig. 1). In the upper panel of Table 2, the measured rest-frame equivalent widths, column densities and Doppler b parameters are presented.

The Mg II doublet ratio is 1.4 ± 0.1, and both the Mg II and Fe II lines are partially resolved. Based upon the apparent optical depth profiles (cf. Savage & Sembach 1991), there is evidence for unresolved saturation in the Mg II doublet. It may be that there are two or more very narrow absorbing components giving rise the profile, but the signal-to-noise ratio is not high enough to model the data to this level. The column densities and b parameters are obtained using Voigt profile (VP) fits that incorporated both the atomic physics and the instrumental spread function. We used the program MINFIT (Churchill 1997), which performs an iterative χ² minimization between the data and the model spectra (see Churchill 1997 for a detailed description of the convergence criteria and the error computations). A VP model with two components was handed to MINFIT, but it returned a single component model based upon the
criterion that there was no statistically significant difference between the best-fit single component and two component models. The measured VP column densities for the HIRES profiles are log $N$(Mg II) = 12.74 ± 0.02 cm$^{-2}$ and log $N$(Fe II) = 12.46 ± 0.06 cm$^{-2}$. Their respective $b$ parameters are $b_{\text{tot}}$(Mg II) = 5.7 ± 0.3 km s$^{-1}$ and $b_{\text{tot}}$(Fe II) = 4.3 ± 1.3 km s$^{-1}$. The reduced $\chi^2$ for the simultaneous VP fit to the Mg II doublet and the two Fe II transitions is 0.96, where the degrees of freedom are $v = 107$. In principle, the contribution of turbulent broadening to the profiles, $b_{\text{turb}}/b_{\text{tot}}$, could be determined from the ratio of the atomic masses of iron and magnesium (see eq. [1] and eq. [3]), but the uncertainties are too large to directly place useful limits on $b_{\text{turb}}$.

As we will discuss below, well-determined uncertainties in the VP quantities are central to constraining the ionization, thermal, and chemical conditions in the absorbing gas “cloud.” VP fits are particularly robust for profiles in this regime of column density and width. As shown in Churchill (1997), the quoted uncertainties in the VP quantities are consistent with the spread in these quantities measured from VP fits to 1000 simulated spectra with similar signal-to-noise ratios. Thus, the measured column density and line broadening, and their uncertainties, are considered to be robust.

In the FOS spectrum, the Ly$\alpha$ absorption is the central line in a triple-blend feature. In Figure 3, we show the deblending fit. The adjacent lines in the blended feature are Ly$\beta$ at $z = 1.1536$, and Ly$\alpha$ at $z = 0.6448$. The lone feature at 2004.5 Å is Ly$\gamma$ at $z = 1.1536$, which is the redshift of a strong Mg II absorber studied elsewhere (Churchill et al. 1999b). Although the fit is not unique, we have adopted the presented result, which yielded a rest-frame Ly$\alpha$ equivalent width of $W_{\lambda} = 0.33 ± 0.03$ Å. Because of the low resolution of the FOS spectrum, we could not obtain estimates of the H I column density and $b$ parameter directly from the data. There is no coverage at the expected position of the Lyman limit; so we cannot place an observed upper limit on $N$(H I). The Ly$\beta$ falls just blueward of the Lyman limit at 1695 Å due to the $z = 0.8596$ damped Ly$\alpha$ absorber, and thus cannot be detected. If the H I and the Mg II arise in the same physical locations in the absorber, then the total H I $b$ parameter is constrained to be $5.7 \leq b$(H I) $\leq 29.8$ km s$^{-1}$ (see Fig. 6a) including the spread introduced by the uncertainty in the measured $b_{\text{tot}}$(Mg II). The lower limit corresponds to the case in which turbulence or bulk motions dominate the line broadening and the upper limit corresponds to a thermal motions scaling, $(24)^{1/2}$ $b_{\text{tot}}$(Mg II). From the curve of growth, we have estimated that the inferred $b$(H I) range translates to a neutral hydrogen column density range of $14.2 \leq log N$(H I) $\leq 17.6$ cm$^{-2}$. For this estimate, we have included the spread introduced by the uncertainty in the measured $W_{\lambda}$(Ly$\alpha$), which dominates over the uncertainty in $b_{\text{tot}}$(H I).

The FOS spectrum also covers several other transitions from a variety of species and over a wide range of ionization potentials. It is important to thoroughly check for the presence of absorption from these species and to place limits on their column densities when no absorption is detected. These limits may be useful for further constraining the chemical and ionization conditions of the absorber, even if the sensitivity level of the FOS spectrum is not very high. Thus, we have systematically searched the FOS spectrum for other transitions associated with the $z = 0.6428$ absorber, using the detection method described by Schneider et al. (1993). Details of the search are presented in Appendix A and selected results are tabulated in Table 3.

### 4.2. The $z = 0.9315$ System

In the right-hand panels of Figure 2, the Mg II and Fe II HIRES profiles are presented. Also shown (top panel) is the FOS spectrum, with the position of the corresponding Ly$\alpha$ line marked with a tick. Along with the Mg II doublet, the Fe II $\lambda 2383$ transition was detected. The Fe II $\lambda 2600$ transition may have been measurable as well, but its predicted location coincided by chance with that of the pen mark (i.e., “The Blob”) on the HIRES Tektronic’s CCD. The weaker Fe II transitions were covered by the spectrum, but were not found to the 5σ significance level. Their limits are consistent with the Fe II $\lambda 2383$ detection.

In the lower panel of Table 2, the measured rest-frame equivalent widths, column densities, and Doppler $b$ parameters are presented. The measured Mg II doublet ratio is $2.0 ± 0.1$, although it may be closer to 1.8, as we discuss below. The Mg II and the Fe II lines are unresolved. For unresolved lines, it is difficult to accurately determine the column densities and $b$ parameters from profile fitting.

We have performed extensive VP fitting simulations of the Mg II doublet for this system. The constraints for adopting the best model were the measured Mg II $\lambda 2796$ equivalent width and the doublet ratio. Using the curve of growth, we explored a grid of column densities and $b$ parameters that were consistent with the measured equivalent width of the Mg II $\lambda 2796$ transition. The grid range was $12.1 \leq log N$(Mg II) $\leq 14.2$ cm$^{-2}$, corresponding to $4.0 \geq b$(Mg II) $\geq 0.4$ km s$^{-1}$. The increments in column density were 0.1 dex. For each grid location, 500 spectra were simulated, convolved with the HIRES instrument spread function, sampled at the HIRES pixelization, and degraded to the signal-to-noise ratio of the observed data. The simulation output consisted of the Mg II $\lambda 2796$ equivalent width, the doublet ratio, and the VP column densities and $b$ parameters from MINFIT.

For $b \leq 1$ km s$^{-1}$, we found that we could not recover the measured equivalent width, nor the doublet ratio; they both decrease dramatically with decreasing $b$. This is due to the finite pixelization of HIRES. As $b$ is reduced, the line depth increases. As the preinstrumentally broadened line width drops below that of a single pixel, saturation losses...
It could be argued that the measured equivalent width already reflects this (that the absorption is actually stronger than the measured value) and that larger equivalent widths should be explored. Fortunately, the VP fits recovered the input values to both high accuracy and precision over the full range explored. For \( b \leq 1 \text{ km s}^{-1} \), no matter the value of the equivalent width, the doublet ratio could never be made consistent with the data (within 3 \( \sigma \)). For the lower limit on \( b \), we adopted the criterion that the measured doublet ratio would be a 3 \( \sigma \) outlier in the distribution of simulated VP fits. For the upper limit on \( b \), we adopted the criterion that the measured \( b \) would be a 3 \( \sigma \) outlier from the mode of the fitted distribution.

A caveat is worth noting. We also explored simulations in which the Mg II doublets were fitted individually, rather than simultaneously. From this we concluded that the observed \( \lambda 2803 \) transition is likely compromised by a possible flat-fielding artifact in its blue wing. This is consistent with the visual appearance of the data in comparison to the many simulated spectra and to the measured \( \chi^2 \) for the VP fits. The value of \( \chi^2 \) was 1.29 with \( n = 74 \) when all three transitions were fitted simultaneously. If just the Mg II doublet was fit, then \( \chi^2 = 1.47 \) with \( n = 51 \). This value is dominated by the “poorer” fit to the \( \lambda 2803 \) transition, which by itself was \( \chi^2 = 2.13 \) with \( n = 24 \). In contrast, the VP fit to just the \( \lambda 2796 \) transition yielded \( \chi^2 = 0.97 \) with \( n = 24 \). The effect of this residual flux in the \( \lambda 2803 \) transition was to push the measured \( b \) value down to 1.5 km s\(^{-1}\) when the doublet was fitted simultaneously. When the observed \( \lambda 2803 \) transition was omitted from the VP fit to the data, the resulting Mg II \( b \) parameter was consistent with the mean of the simulations. Based upon these considerations, we have omitted the observed \( \lambda 2803 \) transition from the VP fit results; the measured \( b \) parameter used for interpreting the simulations was obtained by a fit to the \( \lambda 2796 \) transition only. Since we have adopted the assumption that the observed \( \lambda 2803 \) transition has been compromised, we have adopted the “best” doublet ratio (DR) from the simulations, DR = 1.8 \( \pm 0.1 \). This implies that the equivalent width of the \( \lambda 2803 \) line is slightly larger than that formally measured from the data. If the Mg II DR is 1.8, then rest-frame \( \lambda 2803 \) equivalent width is \( \sim 0.023 \text{ Å} \).

The adopted VP column densities are \( N(\text{Mg II}) = 12.24 \pm 0.09 \text{ cm}^{-2} \) and \( N(\text{Fe II}) = 12.29 \pm 0.08 \text{ cm}^{-2} \). Their respective \( b \) parameters are \( b_{\text{tot}}(\text{Mg II}) = 2.2 \pm 0.5 \text{ km s}^{-1} \) and \( b_{\text{tot}}(\text{Fe II}) = 2.3 \pm 1.6 \text{ km s}^{-1} \). As with the \( z = 0.6428 \), the value of \( b_{\text{tot}}/b_{\text{tot}} \) for the system could be determined from the ratio of the atomic masses of iron and magnesium (see eq. [1] and eq. [3]), but the uncertainties are too large to directly place useful limits on \( b_{\text{tot}} \).

Because of the low resolution of the FOS spectrum, we could not obtain estimates of the \( N(\text{H I}) \) column density and \( b \) parameter directly from the data. However, the wavelength range over which the Lyman limit break could be observed is present in the spectrum at 1760.9 Å. There is no apparent flux decrement at the expected position of the break. However, the signal-to-noise ratio is low, \( \sim 5 \), and this places a 3 \( \sigma \) limit of 1.6 on the flux ratio across the break. This corresponds to an upper limit log \( N(\text{H I}) \) \( \sim 16.5 \text{ cm}^{-2} \). The \( \text{Ly}\beta \) transition is covered at 1981.2 Å, but the region is dominated by the \( z = 1.1537 \) Ly9 line at 1983.1 Å, so \( \text{Ly}\beta \) does not provide a constraint on \( N(\text{H I}) \). If the \( \text{H I} \) and the Mg II arise in the same physical locations in the absorber, then the total \( N(\text{H I}) \) parameter is constrained to be \( 1.8 \leq b(\text{H I}) \leq 13.0 \text{ km s}^{-1} \) (see Fig. 7a), including the spread introduced by the uncertainty in the measured \( b_{\text{tot}}(\text{Mg II}) \). The lower limit corresponds to the case in which turbulence or bulk motions dominate the line broadening and the upper limit corresponds to a thermal motions scaling, \( (24)^{1/2} b_{\text{tot}}(\text{Mg II}) \). From the curve of growth, we have estimated that the inferred \( b \) range translates to a neutral hydrogen column density range of \( 13.6 \leq N(\text{H I}) \leq 16.5 \text{ cm}^{-2} \), where we have adopted the upper limit from the Lyman limit break constraint. We have included the spread introduced by the uncertainty in the measured \( W(\text{Ly}\alpha) \) in this estimate, which dominates over the uncertainty in \( b_{\text{tot}}(\text{Mg II}) \).

As with the \( z = 0.6428 \) absorber, we have systematically searched the FOS spectrum for other transitions associated with the \( z = 0.9315 \) absorber using the detection technique described by Schneider et al. (1993). Details of the search are presented in Appendix A and selected results are tabulated in Table 3.

### 5. Modeling the Absorbers

In order to better understand the two absorbers, we have attempted to constrain their physical conditions, i.e., ionization and chemical conditions, nonthermal motions, and sizes. In particular, we are interested in the relationship between the ionizing flux, whether it is UVB or stellar/galaxy, and the inferred metallicity/abundance pattern. Taken together, constraints on these two quantities may reveal a great deal about the origin, history, and local environment of the absorbers.

We have modeled the absorbers as single-phase photoionized clouds using CLOUDY (Ferland 1996). The clouds were assumed to have constant density and plane-parallel geometry. A grid of models was produced; for each model cloud the specified physical conditions were (1) the ionizing continuum shape and intensity, (2) the abundance pattern of the metals, and (3) the cloud neutral column density, \( N(\text{H I}) \). These input quantities constitute the biggest uncertainties in modeling the absorbers. We used CLOUDY in optimize mode, in which the residuals between the model and the measured Mg II and Fe II column densities were minimized. The two quantities allowed to vary (optimized) were (1) the metallicity of the assumed metal abundance patterns, and (2) the total hydrogen density, \( n_\text{H} \). For these ionization species for which column density upper limits were available, we applied the upper limits to the models.

#### 5.1. The Photoionizing Sources

The two physical conditions within the absorbers that are the most telling of its formation history are their abundance pattern/metallicity and their photoionization source, either local stellar radiation or the UV background (UVB). In fact, the inferred chemical conditions are sensitive to the intensity and shape of the ionizing flux continuum. There are several scenarios, and we address a few of the more obvious ones below.

#### 5.1.1. The UVB Scenario

The two absorbers, whether associated with galaxies or not, may have photoionization conditions dominated by the UVB. To model this possibility, we have employed the UVB spectrum of Haardt & Madau (1996), where the intensity has been normalized at \( z = 0.5 \) and \( z = 1.0 \) for the \( z = 0.6428 \) and the \( z = 0.9315 \) absorbers, respectively. The Haardt & Madau (1996) UVB spectrum accounts not only...
for the UV flux emitted by QSOs and active galactic nuclei, but also for additional UV flux due to the reprocessing of soft X-rays (also from the QSOs and active galactic nuclei) in intervening absorbers at all redshifts.

The UVB spectra are shown in Figure 4, where only a select range of energies is shown. Also illustrated are the locations of the ionization potentials of a few key ionization species. The relevant ionization potentials that we are studying are all just above 1 ryd, the ionization potential of H I, Mg II and Fe II have ionization potentials of 1.11 and 1.19 ryd, respectively. The C II ionization potential is 1.79 ryd, and that of C III is 3.52 ryd. We mention C II and C III because they probe the He I edge at 1.81 ryd and because we have limits on the C II and C III absorption strengths.

5.1.2. The Stellar/Galaxy Scenario

These particular clouds could be embedded within galaxies that are aligned with the QSO on the plane of the sky (zero-impact parameter), or they could be in the outskirts of the galaxies, i.e., in the extended halo or outer disks. In the latter scenario, the radiating stars can be treated as if they are all equidistant from the clouds. For any stellar/galaxy scenario, the number of stars and their spectral types, metallicities, and distances (quantities that determine the intensity and continuum shape of the ionizing flux) must be consistent with known objects in the universe.

The stellar/galactic UV flux could arise from a late-type solar-metallicity stellar population, which would give rise to a rapidly falling continuum with large H I and He I breaks. A “soft” spectrum is required by the observed upper limits on the high-ionization species. A central question defining the scenario is “What level could stellar/galaxy flux be contributing to the UVB or be completely dominating the UVB?” We have explored this question and have outlined the astrophysical principles in Appendix B. We constructed stellar/galactic CLOUDY grids that included three galactic spectral energy distribution models over a range of intensities and covered cases in which the stellar/galactic flux was progressively stronger compared to the UVB and the case in which the UVB was locally “extinct.”

For the “dominant stellar-type” scenarios, in which the cloud could be near a dominant single star, we used Atlas stellar models (Kurucz 1991). We produced a grid of optimized CLOUDY models using solar-metallicity stars with $T_{\text{eff}} = 6000, 10000, 15000, 20000, 30000$ K, and log $g = 4.4$ (the solar value). The spectral shape is not sensitive to the surface gravity, but is quite sensitive to the metallicity and the effective surface temperature. The continuum falls more rapidly toward the UV for solar-metallicity stars, so these stars have “softer” continua than what would be expected in a low-metallicity early-type galaxy.

To account for various metallicities and/or stellar populations, we also produced optimized CLOUDY grids using synthetic galaxy spectra. We used a 12 Gyr single-burst Worthey (1994) model with metallicity $[Z/Z_{\odot}] = -0.7$, and a somewhat younger Worthey model with an 8 Gyr single burst with metallicity $[Z/Z_{\odot}] = -2$. We also used a later type galaxy model from Bruzual & Charlot (1993) with an exponentially decreasing star formation rate (SFR). This model is a 16 Gyr stellar population with 1% of the total star-forming mass in stars after a Gyr. These models serve to bracket a reasonable spread in galaxy spectral properties, given that an extreme scenario such as a starbursting galaxy can be ruled out for two reasons. First, a starburst spectrum would highly ionize the gas, giving rise to Si IV and C IV absorption out to a galactocentric distance of $\sim 100$ kpc (cf. eq. [2] of Giroux & Shull 1997). In fact, we found that it was difficult to not produce too much Si IV and C IV even with the exponential SFR model. Second, images of the PKS 0454+039 field, in which point-spread function removal of the QSO has been performed to high accuracy, reveal no unidentified luminous objects with the characteristics of a starbursting galaxy to a limiting K magnitude of $\sim 20.5$.

5.2. The Metallicity and Abundance Pattern

Different chemical enrichment histories and different environments can give rise to a wide variety of chemical and ionization conditions. Given the possible high iron-to-magnesium abundance ratio in these absorbers, it is reasonable to assume that the clouds could arise in or near galaxies. Thus, to better understand the origin of the absorbers, we modeled three abundance patterns that are taken from typical gaseous objects in galaxies. The first is the solar abundance pattern, taken from Grevesse & Anders (1989) and Grevesse & Noels (1993).

In the interstellar medium (ISM), both magnesium and iron deplete onto dust grains (cf. Lauroesch et al. 1996; Savage & Sembach 1996). Since the main constraints on the CLOUDY optimization are the measured Mg II and Fe II column densities, we also considered the effects of heating and cooling by grains and the dust-depleted abundance patterns of two common interstellar environments. We used the H II abundance depletion pattern taken from Baldwin et al. (1991), Rubin et al. (1991), and Osterbrock, Tran, & Viellemux (1992). For this abundance pattern we used the “large-R” grains (Baldwin et al. 1991), which are characterized by a more or less gray UV extinction. Like the solar abundances, the H II pattern, which has $[\text{Mg/Fe}] = -0.07$, provides a good template for an iron-group enhanced chemical evolution history.

We have also explored the possibility that these absorbers may actually be $\alpha$-group enhanced. Thus, we used the abundance patterns reported by Cowie & Songaila (1986) for the cold and warm phases of the ISM. This pattern is characterized by $[\text{Mg/Fe}] = 1.23$, and overall enhanced $\alpha$-group elements. The dust grains used in these ISM models are a mixture of the graphite and silicates.

The presence of grains also affects the cooling and heating balance, and thus the ionization balance, of the
clouds. As mentioned, the metallicity, or the scaling factor of the input abundance pattern for elements heavier than helium, was allowed to vary. As the metallicity in a cloud is increased by factors of a few, the cooling rates are dramatically increased and the cloud equilibrium temperatures drop significantly. For some clouds, the optimal metallicity was 10–100 times the initial input and the cloud equilibrium temperature in the 100 K range.

5.3. Turbulent and/or Bulk Motions

It is not possible to obtain a direct determination of the H I column densities for the two Mg II absorbers. For each, the extreme range of plausible H I column densities can be estimated from the measured Mg II parameter for the assumption of a thermal line broadening [lower N(H I) limit] or turbulent broadening [upper N(H I) limit]. The range turns out to be large, 13.8 ≤ log N(H I) < 17.0 cm⁻², when the uncertainties in log N(H I) and W(Lyα) are considered. We have modeled clouds with log N(H I) = 14.50, 15.50, 15.75, 16.00, 16.25, 16.50, 16.75, 17.00, and 17.50 cm⁻². As will be shown, there were no log N(H I) ≤ 15.75 cm⁻² cloud models consistent with the data. Since, for a known equivalent width, the curve of growth provides a direct relationship between the H I column density and the parameter due to possible turbulence, f = bₜₜ / bₜₐ, the uncertainties in T, based upon the 1σ uncertainties in the Mg II parameter due to possible turbulence, are given by the dotted curves. The shaded regions give the typical range of T for various objects in the Galactic ISM and for Mg II QSO absorption-line (Mg II/QAL) clouds at z = 1. The observed absorbers are consistent with Mg II/QAL clouds, H II regions, and warm H I clouds (see text).

\[ b_{\text{tot}}(X) = \left( \frac{A_{Mg}}{A_X} \right) (1 - f^2) \int b_{\text{tot}}(\text{Mg II}) \, \text{km s}^{-1}, \]  

where A is the nucleon number (A_{Mg} = 24).

5.4. Application of Constraints to Models

In the absence of direct measurements of N(H I), the most acceptable cloud models are those that are self-consistent in that their N(H I), temperatures, and f are simultaneously consistent with those allowed by the data. With the above formalism in hand, the application for constraining a given cloud model is as follows: The range of acceptable f values parameterize the clouds and give the inferred nonthermal component to the line broadening. The range is determined from the model cloud kinetic temperature, T, using a modified version of equation (2).

\[ f(\tau) = 1 - \frac{1}{b_{\text{tot}}(\text{Mg II})} \left( \frac{T}{1450} \right)^{1/2}, \]  

where \( b_{\text{tot}}(\text{Mg II}) = b_{\text{tot}}(\text{Mg II}) \pm \sigma_b \). The cloud temperature was taken as a simple average, given that the model clouds are constant density by definition. For clouds with N(H I) ≤ 16.5 cm⁻², the temperature was constant as a function of depth. For the higher column density clouds, ionization and temperature structure were present, but by no more than 10%. Equation (3) was then used to obtain the inferred \( b_{\text{tot}}(\text{H I}) \), as illustrated in Figures 6a and 7a. Using curve of growth analysis, we obtain the range of acceptable hydrogen column densities from the measured Lyα equivalent width (and its uncertainty) and the range of acceptable \( b_{\text{tot}}(\text{H I}) \).

5.5. Caveats Regarding the Model Design

The quoted upper limits on the ionization species covered by the FOS spectrum were estimated assuming a single-phase isothermal cloud. There are a priori reasons that we have adopted this assumption. First, if the absorbers are Lyα clouds that are pressure confined by a warmer, more tenuous medium (more than one thermal phase giving rise to absorption), they cannot be heated by the UVB
The presence of dust can affect the modeling in two ways. First, for the model clouds using the H II/ISM dust-depleted abundance pattern, there is a breakdown in the inferred metallicity when the temperatures are below $T \sim 1000$ K. The condensation temperature (the temperature at which 50% of an element is removed from the gas phase due to depletion) of both magnesium and iron is $\sim 1300$ K. This means that these cool clouds would have a significantly higher depletion than the warmer clouds, and this has not been accounted for in the CLOUDY modeling. The implication is that the optimized metallicity is in fact an underestimate of the gas-phase abundances, given that the depletion would be larger than that input into the model. Second, if dust is present, it can seriously modify the intensity and shape of the incident UV spectrum, which would have implications for the inferred source of the radiation from the photoionization models. We discuss this point further in § 6.3.

Central to the model interpretation is the assumption that the line broadening is governed by Gaussian distributions for the particle velocities. $N$-body simulations with hydrodynamics (Norman et al. 1998; Davé et al. 1997; Zhang et al. 1997) have shown that the absorbers are filamentary structures and that the concept of an absorbing "cloud" is not altogether valid. Often, the simulations result in gas that is collapsing toward (or expanding along) a filament; this results in hydrodynamic features and shocks in which the distribution function of velocities is not Gaussian. If the Mg II absorption profiles give any indication of the velocity distribution function, then the absorbers are not inconsistent with a Gaussian; in fact, very quiescent gas is suggested by the HIRES profiles.

A final caveat is that we did not include turbulence physics in the CLOUDY models (only microturbulence and not bulk motions could have been modeled using CLOUDY). Thus, turbulence is not treated self-consistently within the framework used to infer the absorber physical conditions. The inclusion of turbulence would result in an additional pressure source, which would affect the balance between the model cloud density and its depth. However, the model cloud densities were allowed to vary in an optimized fashion, and since the cloud depth is adjusted with each equilibrium calculation the pressure adjustment has little effect. The second consequence of modeling turbulence is that the line-center optical depths of absorption transitions decrease, while they increase in the line wings. However, since the majority of the model clouds in our grids were optically thin to neutral hydrogen, any change in the line profile shape had little effect on the model cloud equilibrium.

6. MODEL RESULTS

In the final analysis, only the scenario in which the model clouds are photoionized by the UVB was both astrophysically plausible and consistent with the data. Here, we focus on the results for the UVB scenario with the solar and H II/ISM abundance patterns and then address to what level the stellar/galactic scenarios can be ruled out as viable ionizing sources. We defer discussion of the implications of the model results until § 7.

The optimized metallicities and densities are given for both abundance patterns in Tables 4 and 5. Cloud models with the $\alpha$-group enhanced abundance pattern (Cowie &
Songaila (1986) did not converge within the allowed uncertainties in the Mg II and Fe II column densities. Thus, we conclude that neither the $z = 0.6428$ nor the $z = 0.9315$ absorber have $z$-group enhanced abundance patterns. This implies a gas-phase $[\text{Fe/H}] \geq -1$ (Lauroesch et al. 1996; Savage & Sembach 1996), and possibly iron-group enrichment by Type Ia SNe, although this remains somewhat controversial (Gibson et al. 1997). The $N(\text{H i})$ versus $f$ parameter space is illustrated in Figures 6 and 7 for the data and for the model clouds. The adopted ranges for the absorber H i column densities are defined by the overlap of the allowed ranges constrained by the data and by the CLOUDY models. Interestingly, the results indicate that the clouds have a substantial nonthermal line broadening (i.e., they are turbulent or are undergoing differential bulk motions). However, it is striking that the Mg II profiles reveal a velocity dispersion of only a few kilometers per second. This provides a counterexample to the expected large $b$ parameters if the gas was not dynamically settled (as found in hydrodynamic simulations of the Lyα forest). The very quiet nature of these absorbers indicates that our assumption of a well-defined temperature for a settled gas “cloud” is well founded. A possible, although unlikely, counterexample would be if the absorbers were streaming filaments seen perpendicular to their elongation and streaming motion.

### TABLE 4
HAARDT & MADAU UVB: $z = 0.6428$ OPTIMIZED CLOUDY MODELS

| $Z_{\text{scale}}$ | $\Delta(\text{Mg ii})$ (dex) | $\Delta(\text{Fe ii})$ (dex) | $\log n_{\text{HI}}$ (cm$^{-3}$) | $N(\text{H i})$ (cm$^{-2}$) | $N(\text{H ii})$ (cm$^{-2}$) | Temperature (K) | $b_{\text{tur}}/b_{\text{tot}}$ | Note$^b$ |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|--------|
| Solar Abundance Pattern; No Grains |
| 2.0 ....... | 0.03 0.00 | -2.4 | 14.50 15.2 | 170 | 0.99–1.00 | N |
| 0.9 ....... | 0.03 0.00 | -1.2 | 15.50 16.3 | 720 | 0.98–1.00 | Y |
| 0.7 ....... | 0.03 0.00 | -2.0 | 16.00 17.4 | 6310 | 0.93–0.94 | N |
| 0.6 ....... | 0.01 0.00 | -2.0 | 16.25 17.8 | 7940 | 0.88–0.92 | Y |
| 0.4 ....... | 0.03 0.00 | -2.0 | 16.50 18.0 | 10000 | 0.87–0.90 | Y |
| 0.6 ....... | 0.00 0.00 | -1.7 | 16.75 18.1 | 10200 | 0.86–0.89 | Y |
| 0.8 ....... | 0.03 0.00 | -1.6 | 17.00 18.3 | 11200 | 0.85–0.88 | Y |
| 1.0 ....... | 0.00 0.00 | -1.5 | 17.25 18.4 | 11500 | 0.84–0.88 | N |
| H ii Abundance Pattern; Grains |
| 3.0 ....... | 0.00 0.00 | -2.9 | 14.50 15.3 | 90 | 0.99–1.00 | N |
| 2.0 ....... | 0.00 0.01 | -2.4 | 15.50 16.4 | 200 | 0.99–1.00 | N |
| 1.5 ....... | 0.00 0.01 | -2.2 | 16.00 16.9 | 490 | 0.98–1.00 | N |
| 1.2 ....... | 0.00 0.00 | -2.1 | 16.25 17.3 | 1170 | 0.97–1.00 | N |
| 0.7 ....... | 0.01 0.00 | -2.1 | 16.50 18.0 | 4170 | 0.95–0.96 | N |
| 0.4 ....... | 0.00 0.00 | -2.1 | 16.75 18.3 | 6310 | 0.92–0.94 | Y |
| 0.2 ....... | 0.00 0.00 | -2.1 | 17.00 18.6 | 8130 | 0.90–0.92 | Y |
| -0.1 ....... | 0.00 0.00 | -2.1 | 17.25 18.8 | 10000 | 0.88–0.90 | N |

$^a$ Optimal logarithmic scaling factor applied to all elements heavier than helium for the given abundance patterns.

$^b$ Notes (Y = yes, N = no) indicate whether CLOUDY conditions are consistent with inferred $f = b_{\text{tur}}/b_{\text{tot}}$ and allowed values of $N(\text{H i})$ and $b_{\text{tot}}$ shown in Fig. 6. A colon indicates a borderline case.

### TABLE 5
HAARDT & MADAU UVB: $z = 0.9315$ OPTIMIZED CLOUDY MODELS

| $Z_{\text{scale}}$ | $\Delta(\text{Mg ii})$ (dex) | $\Delta(\text{Fe ii})$ (dex) | $\log n_{\text{HI}}$ (cm$^{-3}$) | $N(\text{H i})$ (cm$^{-2}$) | $N(\text{H ii})$ (cm$^{-2}$) | Temperature (K) | $b_{\text{tur}}/b_{\text{tot}}$ | Note$^b$ |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|--------|
| Solar Abundance Pattern; No Grains |
| 2.0 ....... | 0.03 -0.03 | -1.1 | 14.50 14.5 | 100 | 0.98–1.00 | N |
| 0.9 ....... | 0.03 -0.04 | -0.8 | 15.50 15.6 | 420 | 0.95–0.98 | N |
| 0.7 ....... | 0.03 -0.03 | -0.6 | 15.75 15.9 | 810 | 0.90–0.96 | Y |
| 0.5 ....... | 0.03 -0.03 | -0.6 | 16.00 16.3 | 3310 | 0.50–0.82 | Y |
| 0.1 ....... | 0.03 -0.04 | -0.4 | 16.25 16.6 | 4790 | 0.00–0.73 | Y |
| -0.1 ....... | 0.03 -0.03 | -0.2 | 16.50 16.7 | 5980 | 0.00–0.63 | N |
| -0.7 ....... | 0.03 -0.03 | -0.2 | 17.00 17.3 | 8910 | 0.00–0.38 | N |
| H ii Abundance Pattern; Grains |
| 2.9 ....... | 0.00 0.00 | -1.8 | 14.50 14.8 | 80 | 0.98–1.00 | N |
| 2.0 ....... | 0.00 0.00 | -1.2 | 15.50 15.6 | 110 | 0.98–1.00 | N |
| 1.8 ....... | 0.00 0.00 | -1.1 | 15.75 15.8 | 130 | 0.97–1.00 | N |
| 1.6 ....... | 0.00 0.00 | -0.9 | 16.00 16.0 | 200 | 0.96–0.99 | Y |
| 1.3 ....... | 0.01 0.01 | -0.8 | 16.25 16.3 | 440 | 0.94–0.97 | Y |
| 0.7 ....... | 0.01 0.00 | -0.8 | 16.50 17.1 | 3890 | 0.35–0.79 | Y |
| 0.2 ....... | 0.00 0.00 | -0.6 | 17.00 17.6 | 6920 | 0.00–0.55 | N |

$^a$ Optimal logarithmic scaling factor applied to all elements heavier than helium for the given abundance patterns.

$^b$ Notes (Y = yes, N = no) indicate whether CLOUDY conditions are consistent with inferred $f = b_{\text{tur}}/b_{\text{tot}}$ and allowed values of $N(\text{H i})$ and $b_{\text{tot}}$ shown in Fig. 7.
Shown in Figure 5 are the predicted kinetic temperatures of the absorbers as a function of $b_{\text{turb}}/b_{\text{tot}}$. Temperature and turbulence limits may provide clues to the nature of the absorbing gas when the range of inferred properties is compared to gaseous objects typically found in galaxies. Planetary nebulae have $T \geq 40,000$ K (Osterbrock 1989; Spitzer 1978).

If the $z = 0.6428$ absorber has $f \leq 0.4$, then its inferred temperature is consistent with that of a planetary nebula. Typical expansion velocities of these objects have line widths of $\sim 20$–$30$ km s$^{-1}$ (Osterbrock 1989). Since the Mg II and Fe II Doppler parameters would also reflect the expansion velocities, it is highly unlikely that the $z = 0.6428$ absorber arises in a planetary nebula. For $0.4 < f < 0.9$, the $z = 0.6428$ absorber temperature is consistent with that of individual clouds in complex Mg II systems (Churchill 1997; Churchill et al. 1998b). Both absorbers are consistent with the temperature range of H II regions and warm H I clouds, $7000 \leq T(\text{H II}) \leq 14,000$ K and $4000 \leq T(\text{H I}) \leq 7000$ K, respectively (Fitzpatrick & Spitzer 1994; Osterbrock 1989; Spitzer 1978). For the $z = 0.9315$ absorber, the inferred $b_{\text{turb}}/b_{\text{tot}}$ would be $f \leq 0.8$, and for the $z = 0.6428$ absorber $f$ would be confined to the narrow range $0.90 \leq f \leq 0.95$. For these $f$ values, the nonthermal broadening would be roughly $b_{\text{turb}}(\text{Mg II}) \leq 5$ km s$^{-1}$ and $\leq 2$ km s$^{-1}$ for the $z = 0.6428$ and the $z = 0.9315$ absorbers, respectively. The typical sound speeds in H II and H I clouds are $\sim 10$ km s$^{-1}$ (Spitzer 1978). If these absorbers are H II or H I clouds similar to those found in the Galaxy, the line-of-sight nonthermal broadening is well below that expected for propagating disturbances in the clouds. If the absorbers are dominated by turbulent motions ($f > 0.98$), they must have $T \leq 150$ K. Diffuse ISM clouds have typical temperatures in the range $30 \leq T \leq 150$ K (Spitzer 1978). In this regime, it would be more likely that the broadening was dominated by bulk flows rather than internal turbulence, given that the turbulent motion would propagate at the $\sim 0.1$ km s$^{-1}$ sound speed typical of diffuse clouds (Spitzer 1978).

6.1. The $z = 0.6428$ Absorber Properties

Assuming the solar abundance pattern, the neutral hydrogen of the $z = 0.6428$ model cloud is in the range $16.3 \leq \log N(\text{H I}) \leq 16.8$ cm$^{-2}$. The range of $b_{\text{turb}}/b_{\text{tot}}$ is $0.85 \leq f \leq 0.93$, which corresponds to the kinetic temperatures $13,000 \leq T \leq 6500$ K. The metallicity and model cloud density are $-0.2 \geq [Z/Z_{\odot}] \geq -0.7$, and $0.01 \leq n_{\text{HI}} \leq 0.02$ cm$^{-3}$, for the range of $N(\text{H I})$. For the H II abundance pattern, the inferred neutral hydrogen column density is slightly higher, in the range $16.7 \leq \log N(\text{H I}) \leq 17.2$ cm$^{-2}$. The range of $b_{\text{turb}}/b_{\text{tot}}$ is $0.90 \leq f \leq 0.95$, making this cloud kinetic temperature somewhat lower than the solar abundance model. The density and metallicity are $n_{\text{HI}} \sim 0.008$ cm$^{-3}$ and $+0.4 \geq [Z/Z_{\odot}] \geq 0.0$, for the range of $N(\text{H I})$. It could be that this cloud has very enhanced metallicity with an H II abundance pattern, but this is a far-reaching suggestion given the range allowed by the solar abundance pattern. Still, the cloud is inferred to have gas phase $[\text{Fe/H}] \geq -1$.

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**Fig. 6.** The $z = 0.6428$ absorber properties. (a) Range of total Doppler $b$ parameters as a function of $f = b_{\text{turb}}/b_{\text{tot}}$. The dotted lines are the spread due to the $1\sigma$ uncertainties in the measured Mg II $b_{\text{tot}}$. (b) and (c) Range of H I column densities as a function of $f$. The thick solid curves are best values of $b_{\text{turb}}/b_{\text{tot}}$ based upon $b_{\text{tot}}(\text{Mg II})$ and $W_{\lambda}(\text{H I})$. The thin curves give the spread of $N(\text{H I})$ based upon the $1\sigma$ uncertainties in $b_{\text{tot}}(\text{Mg II})$ (inner) and $W_{\lambda}(\text{Ly}a)$ (outer). The curves that originate in the lower-right-hand corners and rise upward and then to the left are the allowed locus of $f$ for a cloud model with a given $N(\text{H I})$. (b) Solar abundance patterns. (c) H II abundance pattern.
These model clouds are difficult to understand in terms of objects typical of the Galactic disk or the Magellanic Clouds. For one, the typical $N(\text{H}\ I)$ observed in Galactic objects is $\log N \geq 19.5\,\text{cm}^{-2}$ (Savage & Sembach 1996), 2 or more orders of magnitude greater than what is inferred for this absorber. Second, the typical density of $T \sim 10,000\,\text{K}$ clouds (warm low-density medium) is $n_\text{d} \sim 10^2\,\text{cm}^{-3}$, which is higher than allowed by the optimal models. Third, the inferred gas-phase abundances in the warm and cool disk are $[\text{Fe/H}]_\text{d} \sim 1.1$ and $[\text{Fe/H}]_\text{c} \sim 2.1$, respectively (Savage & Sembach 1996). These fall well below those predicted by the models. However, the metallicity range of the solar abundance pattern model is consistent with $[\text{Fe/H}]_\text{solar} = 0.6$ found for the Galactic halo.

### 6.2. The $z = 0.9315$ Absorber Properties

The $z = 0.9315$ model cloud appears to have a high gas-phase metallicity, whether it be supersolar or an enhanced H II pattern. Assuming the solar abundance pattern, the neutral hydrogen is in the range $15.8 \leq \log N(\text{H}\ I) \leq 16.3\,\text{cm}^{-2}$. Note that this is consistent with the upper limit of $16.5\,\text{cm}^{-2}$ inferred from the lack of a Lyman limit break in the FOS spectrum. The range of $b_{\text{turb}}/b_{\text{tot}}$ is $0.62 \leq f \leq 0.94$, which corresponds to the kinetic temperatures $4600 \geq T \geq 870\,\text{K}$. The metallicity and model cloud density are $+0.7 \geq [Z/Z_\odot] \geq +0.1$ and $0.2 \leq n_\text{H} \leq 0.4\,\text{cm}^{-3}$, for the range of $N(\text{H}\ I)$. The optimal solar abundance model cloud is relatively dense with up to 5 times solar abundance. The inferred $[\text{Fe/H}]$ is even greater for the H II abundance pattern model. The neutral hydrogen column density is slightly higher, in the range $16.0 \leq \log N(\text{H}\ I) \leq 16.5\,\text{cm}^{-2}$ (also consistent with the lack of a Lyman limit). The range of $b_{\text{turb}}/b_{\text{tot}}$ is $0.75 \leq f \leq 0.97$, which corresponds to the kinetic temperatures $3300 \geq T \geq 450\,\text{K}$. There is an inversion in the cooling curve at $T \sim 2000\,\text{K}$, which implies that this absorber cannot be stable across the full range of allowed temperatures. It must either be a few thousand degrees or several hundred degrees. The density and metallicity are $n_\text{d} \sim 0.1\,\text{cm}^{-3}$ and $[Z/Z_\odot] \sim 0.7$, a metallicity enhancement of 5 to 40 times over the typical values seen in Galactic H II regions (Baldwin et al. 1991; Rubin et al. 1991; Osterbrock et al. 1992). To date, no other intervening QSO absorption system with such a high metallicity has been reported.

### 6.3. Why the Stellar/Galaxy Scenarios Fail

In what follows, we discuss the difficulties with the stellar/galactic scenarios. The constraints were a trade-off between the number of stars, or their number density, and the stellar population. The former is constrained by astrophysics, assuming a nonextreme stellar environment, and by the imaging data. The latter is constrained by the absorption-line data, which have limited the UV ionizing flux to late-type stars and/or early-type galaxies.

First, consider the case in which the stellar/galactic flux contributes to the UVB intensity. In order for a stellar/galactic contribution to modify the properties of a UVB model cloud, the stellar/galactic flux must exceed the UVB at $\geq 1\,\text{ryd}$, particularly in the regions $1 \leq hv \leq 1.2\,\text{ryd}$ (from the H I edge up to and including the Fe II ionization potential). As outlined in Appendix B, if the stellar population is dominated by A0 III and A0 V stars, this requires $\sim 10^{12}$ stars confined to a region of space $\sim 1\,\text{kpc}$ in radius. This implies a stellar number density $n_\star \geq 500$ stars pc$^{-3}$. 

![Fig. 7.—The $z = 0.9315$ absorber properties. See legend for Fig. 6.](image-url)
which is 5 orders of magnitude greater than the density of A0 V stars in the solar neighborhood (Allen 1981). The required number density increases dramatically for later spectral types. If, on the other hand, the stars are dominated by early-type B0 V (BO I, III) stars, then ~10,000 (1000) stars would be required in a volume of radius 1 kpc. For the main-sequence stars, this corresponds to a number density about 100 times greater than that of the solar neighborhood (Allen 1981). Only O stars can provide the UV flux necessary to match the UVB at 1 rypad and have a number density of stars consistent with that of a typical galaxy environment. However, early-type stars give rise to high-ionization absorption properties, especially C III, C IV, and Si IV, so that the model cloud conditions are not consistent with the data.

The 12 Gyr $[Z/Z_\odot] = -0.7$ Worthey (1994) model is characterized by a steep continuum slope with $\Delta \log v_f \sim -5$ from 1 to 1.2 ryd. This continuum shape is a smooth continuation of the H I edge, so that this galaxy model had to have $v_f \geq 10^8$ times that of the UVB at 5500 A before affecting the model cloud properties. Based upon the arguments presented in Appendix B, for the expected distribution of main-sequence and giant stars in these galaxies (Worthey 1994), the stellar number densities would be extreme. $N_* \geq 10^3$ stars pc$^{-3}$, or $\sim 10^{-2}$ stars within a kpc. Even under these extreme conditions, the 12 Gyr Worthey models yielded $[\text{Fe/H}] \geq -1$.

The 8 Gyr Worthey model with metallicity $[Z/Z_\odot] = -2$ is characterized by a continuum with a smaller H I edge of $\Delta \log v_f \sim -2$ at 1 rypad and a power law with $\sim \nu^{-1}$ out to $\sim 1.5$ ryd (this is steep but not nearly as steep as the 12 Gyr model). The flux must be elevated to $v_f \geq 10^4$ times that of the UVB at 5500 A before affecting the model cloud properties. As the flux, $v_f(0.17)$, is increased above $\sim 10^4$ ergs cm$^{-2}$ s$^{-1}$, the ratio $N(\text{H I})/N(\text{H II})$ very quickly changes from unity to $\sim 10^{-5}$; the model cloud becomes highly ionized, and the limits on C III and/or C IV are exceeded (depending upon the specific absorber). To adopt the idea that the 8 Gyr Worthey galaxy is contributing to the ionization conditions, we would be forced to accept a very narrow range of acceptable $v_f(0.17)$ arising from the galaxy. This range implies the absorbers would be embedded in the galaxy itself (zero-impact parameter), with an extremely unrealistic number of stars. Such a scenario is ruled out.

The exponential SFR spectrum of Bruzual & Charlot (1993) has a continuum shape at 1–3 rypad that is similar to the Haardt & Madau (1996) UVB from the incident flux. This would require environments that are more extreme than those presented above, or that are shielded from the UVB but not from the stellar flux. Is it possible that dust extinction could be playing a role? For a dust absorption/scattering cross section of $\sigma(1 \text{ rypad}) \sim 10^{-22}$ cm$^{-2}$ (Mathis, Rumpl, & Nordsieck 1977), the total hydrogen column density [$N(\text{H I}) + N(\text{H II}) + 2N(\text{H}_2)$] required for $f_{\text{dust}} \sim 3$ at 1 rypad is $\log N \sim 22.5$ cm$^{-2}$. Given the upper limits on $N(\text{H I})$ for the absorbers, this implies highly ionized gas with $N(\text{H II})/N_{\text{H}_2}(\text{H}) \geq 10^{-5}$. In all our model clouds, the fraction of molecular hydrogen never increased above $f(\text{H}_2) \leq 10^{-6}$.

In principle, one could imagine an environment in which the absorbing gas is embedded in a late-type dwarf galaxy that itself is enshrouded in dust. This scenario provides the steep continuum above 1 rypad while not requiring the spectrum intensity to be elevated above the UVB. For some models it was possible to achieve $\log N(\text{H II}) \sim 22.5$ cm$^{-2}$, but even with no competition from the UVB, these shielded models required high $v_f(0.17)$. Again, as outlined in Appendix B, this implies unrealistic stellar densities. It is not simply a matter of the continuum slope, but also the intensity that dictates the cloud ionization conditions. Interestingly, these models produced very low metallicities, with $[Z/Z_\odot] \sim -3$. All of the above stellar/galaxy models represent our failed attempt to locate a place in parameter space consistent with low-metallicity clouds.

7. DISCUSSION

Based upon the success rate of finding two Mg II absorbers out of 28 Ly$\alpha$ absorbers along the PKS 0454+039 line of sight, we must conclude that the two absorbers are unique in some manner with respect to the Ly$\alpha$ forest at large. We note, as mentioned in § 4, that not a great deal can be quantified about the range of metallicities in the Ly$\alpha$ forest at $z \leq 1$ based upon our upper limits on the Mg II column densities. However, if our assumption of $b \sim 30$ km s$^{-1}$ is not applicable, as found for the two Mg II absorbers, then our quoted estimates in the range of metallicities would be quite wrong. In fact, given that the upper limits on the metallicity are supersolar for the $W_f(\text{Ly} \alpha) \leq 0.3$ A absorbers, and that it is not expected that many of the absorbers are supersolar, we are led to suggest that either the $b$ parameters of the $W_f(\text{Ly} \alpha) \leq 0.3$ A absorbers are significantly smaller than $30$ km s$^{-1}$ or the objects do not have a Gaussian velocity distribution (simple curve of growth techniques are not applicable). It could be that the uniqueness of the two Mg II absorbers is that they are dynamically settled and have a small velocity dispersion.

Other possibilities for the uniqueness of the Mg II absorbers, as are follows.

1. Their ionization conditions are different.—If the chemical enrichment histories of these absorbers are typical of Ly$\alpha$ forest clouds, then it might be inferred that their ionization conditions are governed by a local UV flux rather than the UVB. However, our models lead us to conclude that there is nothing “special” about the photoionization conditions of these clouds; they are best described as being photoionized by the UVB. There is no evidence to suggest that these clouds are collisionally ionized.

2. Their chemical conditions are different.—If the ionization source is no different than that ionizing the other 26 Ly$\alpha$ systems we searched, then we are led to infer somewhat unique chemical enrichment histories for these two
absorbers. If these absorbers are IGM/Ly\alpha clouds, in that they are not associated with galaxies, then the low-metallicity results of SC96 at higher redshift do not support the notion that these two absorbers have undergone typical IGM chemical enrichment. In other words, these two absorbers are not consistent with the picture in which the IGM was enriched at high redshift by a single burst of Population III stars that left the Ly\alpha forest $z$-group enhanced\(^7\) with $[\text{Fe/H}] \leq -2$. Thus, these absorbers could constitute a metal-rich minority of the IGM/Ly\alpha population (less than $\sim 10\%$). It then becomes a question of understanding what environments and evolutionary histories give rise to high metal content in some Ly\alpha clouds. It is already known that at least some fraction of the Ly\alpha forest at $z < 1$ are associated with galaxies (Le Brun et al. 1996; Lanzetta et al. 1995; Bowen et al. 1996).

3. Both their ionization and chemical conditions are different.—Inferring the chemical content of ionized absorbers requires ionization corrections that are uncertain. In the case of photoionization, the inferred conditions of the clouds are very sensitive to both the intensity and shape of the ionizing continuum. We have explored this interplay between the chemical content of the clouds and the properties of the UV ionizing flux and have concluded with some certainty that the ionizing field for the two absorbers is constrained to have slope and intensity consistent with the UVB. This is tantamount to saying that it is only the chemical conditions that are inferred to be unique in the two absorbers.

Overall, it is difficult to understand these absorbers in terms of the classic picture of Ly\alpha forest clouds. One problem is that their inferred H I column densities are higher than “typical” forest clouds. A second is their high $[\text{Fe/H}]$ and iron-group enhanced abundance pattern. Since the metal abundance patterns of these absorbers are not $z$-group enhanced, it is implied that their environments have been influenced by Type Ia SNe yields (Lauroesch et al. 1996; Timmes, Lauroesch, & Truran 1995; however, see Gibson et al. 1997). It could be that these absorbers are associated with galaxies. However, based upon imaging and spectroscopic studies, there are no candidate high surface brightness (HSB) objects in the PKS 0454 + 039 field.

The extended luminous objects identified in the WFPC2 images (Fig. 4 of LBBD) and ground-based image (Fig. 3 of Steidel et al. 1995), have now had their redshifts spectroscopically measured using LRIS on the Keck I telescope. None of them have redshifts that match the two Mg II absorbers (C. Steidel 1997, private communication). Object 5 in LBBD has been confirmed by Steidel and collaborators to be the strong Mg II absorbing galaxy at $z = 1.1536$. At impacts greater than $120 h^{-1}_7$, there are three galaxies with $0.605 \leq z \leq 0.610$ (not presented in published images). Thus, to a limiting of magnitude of $K \sim 20.5$, the limit of the Steidel et al. (1993) image, there are no luminous candidates within $\sim 30\arcmin$ of the QSO.

Based upon the residuals following the point-spread function subtraction of the QSO in both the WFPC and the ground-based images, there is no evidence for luminous objects directly in front of the QSO (“zero-impact” absorbers). However, dwarf galaxies of roughly $\leq 0.01 L^*$ at zero impact cannot be ruled out. In general, it seems unlikely that two absorbing galaxies, separated by such a large redshift interval, would be aligned with the QSO on the sky. According to the work of Bowen et al. (1997), dwarf spheroid galaxies similar to Leo I are not massive enough to have halos that can contribute significantly to the metal-line absorption cross section of QSO absorbers seen at high redshift. But the situation is not so clear overall, given the recent discovery by BBLD of the saturated Mg II doublet associated with $z = 0.072$ dwarf galaxy at impact parameter $2.7 h^{-1}_{75} \text{kpc}$. The emission-line properties of this dwarf (Steidel, Dickinson, & Bowen 1993) suggest that star formation in these objects may directly govern their gas cross section. If so, perhaps active star-forming dwarf galaxies could contribute to the overall metal-line absorption cross section (cf. York et al. 1986; Yanny & York 1992). Naively, one would then expect that the abundance pattern arising from a bursting dwarf would be $z$-group enhanced. Also, it is likely that UV ionizing flux from the newly formed O and B stars would contribute to the ionization conditions in the absorbers, which is not what we find.

If we are to assume that these two absorbers are associated with galaxies of some type, and if we accept the lack of evidence for HSB candidates in the PKS 0454 + 039 field, then we must explore the idea that low surface brightness (LSB) galaxies (cf. Bothun et al. 1997) could be giving rise to the absorbing gas. Particularly, we are lead to consider the class of galaxies called “giant LSB galaxies” (Sprayberry et al. 1993, 1995).

Great progress in our knowledge of LSB galaxies, their number density, sizes, metallicities, and luminosity function in the local universe has been made over the past few years (de Blok 1997; Quillen & Pickering 1997; Dalcanton et al. 1997; Sprayberry et al. 1997; de Jong 1996; Sprayberry et al. 1995; McGaugh 1994). Dalcanton et al. (1997) find that LSB galaxies have a space density of at least $n = 0.03$ galaxies $h^{-3}_{75} \text{Mpc}$ and outnumber comparable HSB galaxies by factors of $\sim 2$ or more. LSB galaxies are a nonnegligible component of the local universe baryonic mass. Sprayberry et al. (1995) find that LSB giants have larger disk scale lengths than HSB galaxies of comparable total luminosity. In the cases of F568-6 and UGC 6614, the luminous spiral arms extend to $80 h^{-1}_{75} \text{kpc}$ and $50 h^{-1}_{75} \text{kpc}$, respectively (Quillen & Pickering 1997). The extent of the H I disks for the general population of LSB galaxies is seen to be roughly 2.5 times that of their $D_{25}$, the diameters of their $\mu_b = 25$ mag arcsec$^{-2}$ isophotes (van der Hulst et al. 1993). If this scaling holds for F568-6, then it may have an H I disk of $\sim 200 h^{-1}_7 \text{kpc}$. In the case of the LSB galaxy 1226 + 0105, the H I disk may extend more than 4 times its $D_{25}$ (Sprayberry et al. 1995).

Whatever structures give rise to these two absorbers, the H I gas must have a velocity dispersion of no more than $\sim 30 \text{ km s}^{-1}$, as dictated by the inferred upper limit on the $b$ parameter of the $z = 0.6428$ cloud. The constraint is even as low as $\sim 15 \text{ km s}^{-1}$ based upon the $z = 0.9315$ cloud. The best values of the cloud $b$ parameters are $\sim 12 \text{ km s}^{-1}$ and $\sim 9 \text{ km s}^{-1}$, respectively. These $b$ parameters fall below the lower cutoffs in the overall Ly\alpha forest $b$ distribution (Kim et al. 1997; Lu et al. 1996; Hu et al. 1995). Again, this suggests that these absorber possibly arise in a minority subclass of the overall Ly\alpha cloud population. In their study of the giant H I disks of F568-6 and UGC 6614, Quillen & Pickering

\(^7\) Depending upon the Population III IMF, some pockets of the IGM may have experienced slow metallicity buildup due to late-type stars. However, we find this scenario to be no different in name than if the process took place in “galaxies.”
(1997) found that the H I showed small velocity dispersions of 10–30 km s$^{-1}$ and 10–20 km s$^{-1}$, respectively, as compared to 60–90 km s$^{-1}$ measured for local HSB spirals (Vogel, Kulkarni, & Scoville 1988; Canzian, Allen, & Tilanus 1993). These dispersions were measured among the spiral arms; it could be that the extended outer disks are even more quiescent. Even so, these values are consistent with the allowed ranges of the two absorbers. If a subpopulation of the Ly$\alpha$ forest is arising in LSB galaxies, they may be characterized by having $b$ parameters scattered about the low end of the distribution.

The metallicities of several LSB galaxies have been measured using H II regions. LSB galaxies with relatively smaller disk scale lengths are found to have $[Z/Z_{\odot}] \leq -0.3$, and are therefore metal poor (McGaugh 1994). However, McGaugh found near-solar and supersolar metallicities for UGC 5709 and F568-6, respectively. These two galaxies have large disk scale lengths and classify as giant LSB galaxies. Pickering & Impey (1995; C. Impey 1997, private communication) have also found other giant LSB galaxies with metallicities that scatter around solar. These giant galaxies are found to have stellar surface densities at least on the same order as their gas densities, which leads Pickering and Impey to suggest that these galaxies have been forming stars slowly.

We find these facts to be quite interesting in light of the two high-metallicity Mg II systems we have found. It is well established that Mg II absorption with $W_\lambda \geq 0.3$ Å selects the population of HSB galaxies (Churchill, Steidel, & Vogt 1996; Steidel 1995; Steidel, Dickinson, & Persson 1994; Bergeron & Boissé 1991). These galaxies appear to be “normal” in their morphologies and to have luminosities greater than $\sim 0.05 L^{*}$. By comparison, the total luminosities of giant LSB galaxies scatter about $L^{*}$ (cf. Sprayberry et al. 1995). Although LSB galaxies have low-luminosity densities, their disks are proportionally larger, giving them total luminosities on a par with HSB galaxies. Thus, it seems reasonable that LSB galaxies could be part of a more general Mg II absorption selected galaxy population, where the LSB galaxies are selected by the smaller Mg II equivalent widths.

In a recent survey to a limiting rest-frame equivalent width of 0.02 Å, Churchill et al. (1998a) found that Mg II absorbers with $W_{\lambda}(12796) \leq 0.3$ Å (hereafter called “weak Mg II absorbers”) account for $\sim 65\%$ of all Mg II absorbers (also see Churchill 1998). Nothing is yet known about the type of luminous object they select; none have luminous candidates to $\leq 0.06 L^{*}$ (assuming the Freeman 1970 surface brightness) in the survey of Mg II absorbers by Steidel et al. (1994; C. Steidel 1997, private communication). These systems also exhibit Fe II absorption; for the sample, $\langle \log N(\text{Fe II})/N(\text{Mg II}) \rangle = -0.3 \pm 0.4$ (i.e., they may have $\langle \text{Fe/Hi} \rangle \geq -1$). Without information on their H I absorption, we can only speculate that some fraction of the weak Mg II systems have ionization and chemical conditions similar to the two absorbers studied in this work.

If weak Mg II absorbers are selecting out a “missing” part of the Mg II absorption selected galaxy population, LSB galaxies are a logical candidate for this missing portion, particularly the class of giant LSB galaxies, or “Malin-cousins,” as designated by Sprayberry et al. (1993, 1995). These galaxies are disk galaxies, and these disks are observed to have a lower neutral H I surface density than HSB galaxies (Bothun et al. 1997). As a result, the giant LSB galaxy disks have relatively quiescent stellar evolution. In fact, the general population of LSB galaxies show a trend of increasing red color with increasing disk scale length (Sprayberry et al. 1995). Quillen & Pickering (1998) report extremely red colors ($R - H = 2.2 \text{ and } B - H = 3.5 - 4.2$) for the two giant LSB galaxies UGC 6614 and F568-6, which suggest that they have a dominating old component in their stellar populations. These galaxies provide the precise type of environment in which there has been ample time for iron-group enhancement and metallicity build up in the gas phase of their disks. Further, the quiescent nature of their disks leads us to suggest that we should not expect to see the complex velocity structures seen in the majority of the stronger Mg II absorption profiles (Churchill 1997; Churchill et al. 1998b). Indeed, the low H I surface density of these galaxy disks should result in weaker Mg II absorption because there is less of the neutral hydrogen shielding required for Mg II to survive. Also, the quiescent nature of the interaction between the gas and stars in these galaxies suggests that the gas is not being stirred up, which would generate erratic gas kinematics. It may be that such processes facilitate the generation of a high-ionization layer around the disk, as seen in the Galaxy (cf. Savage & Sembach 1996). The small $b$ parameters inferred for the H I and the apparent lack of C IV absorption in the two weak absorbers are consistent with a quiescent disk.

If weak Mg II absorbers are selecting giant LSB galaxies, then these absorbers provide a potential probe of the number density of these massive galaxies. LSB galaxy disks may grow from isolated 1–2 $\sigma$ peaks in the initial density fluctuation spectrum and may trace low density extended dark matter halos in a relatively unbiased way (Bothun et al. 1997). They also would provide a powerful probe of the chemical enrichment history of LSB galaxies, which appear to evolve at a significantly slower rate and may produce stars via conventional pathways (such as not within molecular clouds; cf. Bothun et al. 1997).

To date, there is not enough known about the number density and gaseous cross sections of the class of giant LSB galaxies to compare their $dn/dz$ directly to that of the weak Mg II systems, or to place meaningful limits on their number evolution if we assume they are selected by weak Mg II absorption (Bothun et al. 1997; C. Impey 1997, private communication). Roughly, the overall population of LSB galaxies appears to follow a trend such that those with larger disk scale lengths are observed to have smaller central surface brightness (Sprayberry et al. 1995). Following this relation, there is a significant gap between Malin 1 and the remaining subpopulation of giant LSB galaxies. Malin 1 has a disk scale length a factor of 30 times greater than that of F568-6 and a central surface brightness a factor of 100 less than F568-6. Does the gap in this parameter space reflect a true break, suggesting that Malin 1 is a rare galaxy type? Or, is the gap an artifact of selection effects? As Sprayberry et al. (1993) point out, it is important to explore this parameter space in order to determine the size
and number density distributions of giant LSB galaxies. If LSB galaxies are considered to be a natural extension of the HSB galaxy luminosity function, and their disk scale lengths and central surface brightnesses exhibit similar behaviors to those found for HSB galaxies, then the region of central surface brightness scale length parameter space giving rise to Malin-type LSB galaxies is continuously populated (S. Linder 1997, private communication).

We can only tentatively suppose that weak Mg II systems with accompanying Fe II absorption may be selecting the class of giant LSB galaxies (Sprayberry et al. 1993) out to \( z \sim 1 \). Impey & Bothun (1989), upon reexamining the selection effects and assumptions that go into the calculations of galaxy cross sections from QSO absorbers, found that LSB galaxies are expected to dominate the absorption cross section. If we assume a non-evolving absorber cross section, \( n_0 \sigma_0 \), we can write the projected radial extent of QSO absorbers as \( R \approx 7.5(N/n_0)^{1/2} h_z^{-1} \) kpc, where we have integrated over the redshift interval 0.42 \( \leq z \leq 1.18 \) and where \( N \) is the number of observed absorbers in the redshift interval. If we are to claim that the two Mg II systems arise from the general population of LSB galaxies, we obtain \( R \sim 60 \) kpc, where we have used the space density, \( n = 0.03 \) galaxies \( h_z^{-3} \), Mpc \(^{-3} \), found by Dalcanton et al. (1997). Supposing that giant LSB galaxies comprise 1\% of the LSB population, the size of the absorbers is inferred to be \( R \sim 200 \) kpc, which compares to the \( H \) I sizes of F568-6, UGC 6614, and UGC 5709 (the "Malin cousins").

The success rate of two weak Mg II absorbers out of 28 Ly \( z \) clouds leads us to tentatively suggest that 5\%-10\% of the so-called Ly \( z \) clouds in the forest at \( \langle z \rangle \sim 0.7 \) will have detectable Mg II absorption to our level of sensitivity. Using the \( dn/dz \) for the Ly \( z \) forest from the Quasar Absorption Line Key Project (Jannuzi et al. 1998), this corresponds to non-evolving population with \( dn/dz \sim 1.5 \)-3. Interestingly, this is not inconsistent with the number density of \( dn/dz \approx 1.74 \) for Mg II absorbers with \( W_c \leq 0.3 \) \AA, as reported by Churchill et al. (1998a). As with the Ly \( z \) absorbers at \( z \leq 1 \), the weak Mg II systems are consistent with a non-evolving population. It could be that our search through the PKS 0454 + 039 forest has picked up the same population of absorbers selected by a fair fraction of the weak Mg II survey, whatever that population may be. Fe II absorption is present in many of these systems, suggesting that many of these absorbers may have chemical and photoionization conditions similar to the two absorbers along the PKS 0454 + 039 sight line (i.e., they may arise in similar environments with similar evolutionary histories).

In contrast to poststarbursting dwarfs, which have not formally been ruled out if they both happen to be tightly aligned on the sky with the QSO, the few giant LSB galaxies known to date have colors consistent with a population of late-type stars (Quillen & Pickering 1998). This is consistent with the inferred ionization conditions of the two absorbers, since early-type stars are ruled out as sources of UV flux. Most giant LSB galaxies have active galactic nuclei (narrow emission lines; Sprayberry et al. 1995; Bothun et al. 1997), and this could very well be the case here. There is a pointlike/stellar object (object 7 in LBBD) with impact parameter \( \sim 45 \) or 60 \( h_z^{-1} \) (assuming \( z = 0.6 \) or \( z = 0.9 \)) that has a one-sided spiral arm like structure. Although many damped Ly \( z \) absorbers are seen to be LSB galaxies and low-luminosity dwarfs (Cohen et al. 1996; Le Brun et al. 1997; Steidel et al. 1997; Meyer & York 1992), this is not a necessary condition for the absorbers to be LSB galaxies; the high-redshift LSB absorbing galaxies studied so far have been selected by their H I absorption and not by their Mg II absorption. Weak Mg II absorption that is accompanied by Fe II absorption of comparable strength may be selecting a well-defined population of luminous objects. These objects probably do not include the damped Ly \( z \) systems, but probably do include sub-Lyman limit systems with high metallicity. This is in contrast to the findings of BBLD, who find that strong Mg II absorption accompanied by strong Fe II absorption selects damped Ly \( z \) systems of low metallicity.

The weak Mg II absorbers may in fact be selecting LSB galaxies, given that the weak Mg II absorbers found by Churchill et al. (1998a) do not have HSB candidates to \( \leq 0.06L_{\odot} \) (Steidel 1995; C. Steidel 1997, private communication). Very deep imaging and faint object spectroscopy will be required if we are to identify the luminous objects selected by weak Mg II absorption. These objects may represent a significant fraction of the galaxy population of the universe (and therefore dark matter content). Thus, understanding their statistical properties is important for theories of structure formation and galactic evolution.

In the future, a detailed comparison of the relative abundances of \( z \)-group elements (O, Ne, Mg, Si, S, Ca) to Fe-peak elements (Cr, Ni, Fe, Zn) in "Ly \( z \) forest clouds" holds the promise of revealing their various origins and formation epochs. The rate of Type Ia SNe appears to be very low for the first Gyr in the history of a Milky Way-like galaxy (Truran & Burkert 1993; Smcker & Wyse 1992). If the delay is similar for the onset of Type Ia SNe in other galaxies as well, then it could be that [Mg/Fe] abundance ratio tests are confined to low redshifts. As such, it is expected that \( z \)-group enhanced abundance ratios should be almost exclusively seen at \( z > 1.5 \) (Timmes et al. 1995). For \( d_0 = 0.5 \) and \( \Lambda = 0 \), if a galaxy formed at \( z \geq 4 \), then Type Ia SNe may not begin to contribute to its chemical enrichment until \( z = 1.5 \) and may not influence the abundance patterns to a detectable level until \( z \sim 1 \) (1 Gyr later). For \( d_0 = 0.1 \) and \( \Lambda = 0 \), the Fe-group enrichment would likely be seen no earlier than \( z \sim 1.5 \).

8. SUMMARY

We searched for Mg II \( \lambda \lambda 2976, 2803 \) absorption in 28 Ly \( z \) forest absorbers along the PKS 0454 + 039 line of sight. The spectrum studied for the metal-line absorption was an optical HIRES spectrum (Churchill 1997; Churchill et al. 1998b). The Ly \( z \) line list were taken from the UV G190H and the G270H FOS/HST spectra of BBLD. The redshift range was \( 0.4163 \leq z(22796) \leq 1.1871 \). The doublets were identified and confirmed using the techniques described in Schneider et al. (1993) and in Churchill et al. (1998a). We found two Mg II absorbers, one at \( z = 0.6428 \), and one at \( z = 0.9315 \). Both these systems exhibit Fe II absorption. We carefully searched the FOS/HST spectrum for the expected metal-line transitions (cf. Hellsten et al. 1998) that were covered in the forest. There are currently no other high spectral resolution studies of metals in the \( z < 1 \) Ly \( z \) forest, and it also appears that there are no counterparts to these two systems at higher redshifts.

In Figure 1, we present the 5 \( \sigma \) rest-frame observed equivalent width detection limit of the Mg II \( \lambda 22796 \) transition as a function of redshift. The detection limit ranged from 0.007 to 0.020 \AA, except for \( z(22796) \leq 0.4662 \), where it ranged from 0.020 to 0.035 \AA. The 5 \( \sigma \) mean upper limit is log
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\[ N(\text{Mg} \, \text{II}) \sim 11.3 \text{ cm}^{-2} \] for clouds with \( 0.1 \leq N(\text{Ly} \alpha) \leq 1.6 \) Å, which corresponds to neutral hydrogen column densities over the range \( 13.5 \leq \log N(\text{H} \, \text{I}) \leq 18.5 \text{ cm}^{-2} \).

We studied the two discovered absorbers in some detail. Voigt profile fitting was performed to obtain the column densities and Doppler \( b \) parameters of the Mg II and Fe II. Since the Mg II and Fe II are unresolved, we performed Monte Carlo modeling of the Voigt profile fitting in order to best constrain the uncertainties in the Voigt profile parameters (Churchill 1997; this work). We then used CLOUDY (Ferland 1996) to model the ionization and chemical conditions of the two absorbers. CLOUDY was used in its optimize mode, in which the residuals between the model and the measured Mg II and Fe II column densities were minimized. The fixed quantities for each cloud, which constitute the grid parameters, were the UV flux intensity and continuum shape, the metal abundance pattern, and the “observed” neutral hydrogen column density. The optimized output quantities were the total hydrogen density, \( n_\text{H} \), and a scaling factor for the metallicity, \( Z_{\text{scale}} \). We constrained the model clouds using the H I column density and the parameter \( f = b_{\text{turb}}/b_{\text{tot}} \), where \( b_{\text{turb}} \) is the nonthermal contribution to \( b_{\text{tot}} \).

The UV continua considered were a Haardt & Madau (1996) UV background (UVB) spectrum, several Kurucz (1991) Atlas stellar models, late-type galaxy models (Worthey 1994), and a star-forming galaxy model (Bruzual & Charlot 1993). We investigated three abundance patterns: solar, H II depletion, and ISM depletion (the latter being \( x \)-group enhanced). The H II and ISM CLOUDY models included grain physics. The only UV ionizing scenario that yielded model clouds that were consistent both with astrophysical constraints (numbers of stars, etc.) and with constraints imposed by the data was the Haardt & Madau (1996) UVB. We conclude that the absorbers are photoionized by the UVB and not by stellar radiation. Neither absorber is consistent with having an \( x \)-group enhanced abundance pattern.

As described in § 6.1, the \( z = 0.6428 \) absorber may have a near-solar or supersolar [Fe/H]. For the solar abundance pattern, the model cloud has \( 16.3 \leq \log N(\text{H} \, \text{I}) \leq 16.8 \text{ cm}^{-2} \), a \( b_{\text{turb}}/b_{\text{tot}} \) of 0.85 \( \leq f \leq 0.93 \), metallicity \(-0.2 \geq [Z/Z_\odot] \geq -0.7 \), and density \( 0.01 \leq n_\text{H} \leq 0.02 \text{ cm}^{-3} \). For the H II abundance pattern, the absorber has \( 16.7 \leq \log N(\text{H} \, \text{I}) \leq 17.2 \text{ cm}^{-2} \), \( b_{\text{turb}}/b_{\text{tot}} \) in the range \( 0.90 \leq f \leq 0.95 \), metallicity \( +0.4 \geq [Z/Z_\text{H II}] \geq 0.0 \), and density \( n_\text{H} \approx 0.008 \text{ cm}^{-3} \). If this cloud is relatively free of dust depletion, so that the abundance pattern is close to solar, then the cloud has [Fe/H] \( \sim -1 \). If the gas-phase abundance follows that of depleted clouds in our Galaxy, then the cloud could have [Fe/H] \( > 0 \).

As described in § 6.2, the \( z = 0.9315 \) model cloud appears to have a supersolar gas-phase [Fe/H]. For the solar abundance pattern, the absorber has \( 15.8 \leq \log N(\text{H} \, \text{I}) \leq 16.3 \text{ cm}^{-2} \), a \( b_{\text{turb}}/b_{\text{tot}} \) of 0.62 \( \leq f \leq 0.94 \), metallicity \( +0.7 \geq [Z/Z_\odot] \geq +0.1 \), and density \( 0.2 \leq n_\text{H} \leq 0.4 \text{ cm}^{-3} \). The inferred [Fe/H] is even greater for the H II abundance pattern model. For the H II abundance pattern, the absorber has \( 16.0 \leq \log N(\text{H} \, \text{I}) \leq 16.5 \text{ cm}^{-2} \), \( b_{\text{turb}}/b_{\text{tot}} \) in the range \( 0.75 \leq f \leq 0.97 \), metallicity \( +1.6 \geq [Z/Z_\text{H II}] \geq +0.7 \), and density \( n_\text{H} \approx 0.1 \text{ cm}^{-3} \). This is a metallicity enhancement of 5 to 40 times over the typical values seen in Galactic H II regions (Baldwin et al. 1991; Rubin et al. 1991; Osterbrock et al. 1992). No matter the abundance pattern, this cloud has [Fe/H] \( > 0 \).

In § 7, we discussed the possibility that these two absorbers could arise in giant LSB galaxies. These galaxies are seen to have metallicities that scatter about solar (Pickering & Impey 1995) and large extended disks (Quillen & Pickering 1997). We tentatively suggest that 5% (at most 10%) of \( z \leq 1 \) “Ly forest clouds” \( \geq 0.1 \leq N(\text{Ly} \alpha) \leq 1.6 \) Å will exhibit Mg II absorption to a 5 \( \sigma \) detection limit of 0.02 Å. The subsample of these systems that also exhibit comparable Fe II absorption may have iron-group enhanced metallicities with [Fe/H] \( \geq -1 \) and may be selecting giant LSB galaxies at high redshifts.

This work has been supported in part by the National Science Foundation grant AST 96-17185 at Pennsylvania State University. C. W. C. acknowledges support through the Eberly School of Science Distinguished Postdoctoral Fellowship at Pennsylvania State University. Thanks to P. Boissé for providing the FOS spectrum prior to publication, J. Charlton for assistance with the Voigt profile fitting simulations and CLOUDY modeling, G. Ferland for making CLOUDY a public tool, U. Hellsten for providing the Haardt & Madau input spectra for CLOUDY, S. Linder for generating plots of \( \mu_{\text{p}}(0) \) versus log \( z \) of LSB galaxies for our inspection and for discussions about the observed properties of LSB galaxies, and C. Steidel for sharing unpublished data on the PKS 0454+039 field. It is a pleasure to acknowledge J. Bergeron, M. Bershad, P. Boissé, J. Charlton, R. Davè, U. Hellsten, C. Impey, J. Lauroesch, P. Petitjean, D. Schneider, and M. Shetrone for stimulating discussions and/or comments. Special thanks to S. Vogt for HIRES and for providing the opportunity to use it. We thank C. Impey, the referee, for valuable comments that improved the quality of this manuscript. A special thank you to J. L. Nelson.

APPENDIX A

SEARCHING THE FOS SPECTRUM

It is important to thoroughly check for the presence of absorption from both low- and high-ionization species in the FOS spectrum. Here, we present our search for absorption in the FOS spectrum from both the \( z = 0.6428 \) and \( z = 0.9315 \) systems. We then obtain the limiting column densities (to 3.5 \( \sigma \) using curve of growth analysis, where we have assumed both pure thermal and pure turbulent scaling to the measured Mg II \& Fe II parameters. These limits may be useful for further constraining the chemical and ionization conditions of the absorber, even if the sensitivity level in the FOS spectrum is not very high. The continuum fit has been adopted from the work of BLLD. We have used interactive software of our own that employed the line detection algorithm described in Schneider et al. (1993). Since these transitions are embedded in the Lyz forest, it is very difficult to make identifications at a high confidence level. Selected results are tabulated in Table 3.
A1. THE z = 0.6428 ABSORBER

A 3.5 σ observed equivalent width detection limit corresponds to approximately 0.25 Å. Based upon preliminary CLOUDY models of this system, we have used the line observability index (LOX) of Hellsten et al. (1998) to place limits on those transitions that would most likely be detectable in the spectrum. Roughly in decreasing order of their LOX, the covered transitions include C II λ1548, 1550, Si III λ1206, Si IV λλ1394, 1402, C II λ1335 and λ1036, Si IV λ1063, Si III λ1190, O VI λλ1032, 1038, Si II λ1260, and Si II λ1259.

Both the expected positions of the Si III λ1206 and Si IV λ1063 transitions are coincident with the wings of higher order Lyman series lines from the strong z = 1.1538 Mg II absorption system. There is no detected Si III λ1190, which suggests that the Si IV is likely not present in absorption. Both the Si II λ1260 and Si II λ1259 transition are not detected, nor are the Si II λ1190, 1304, and 1527 transitions. Thus, it appears that Si III, Si II, and Si III are not detected to a 3.5 σ observed limit of 0.25 Å, which corresponds to the upper limits log N \~ 15.4, 15.3, 18.7, and 16.1 cm^{-2}, respectively. Additionally, neither the Al II λ1671 nor the Al III λ1855 transitions are detected, giving limits log N \~ 14.3 and 14.5 cm^{-2}, respectively. The QSO flux is extinct due to the Lyman limit break of the C II doublet. However, the C II doublet is extinct due to the Lyman limit break of the C II doublet. There are no other transitions, including Lyα to Lyβ, the covered transitions include C II doublet. However, the C II doublet. We also obtained (not very useful) upper limits on N II λ1084 and Fe II λ1212, giving log N \~ 16.7 and 17.6 cm^{-2}.

Determining the limits on the C IV and Si IV doublets is less clear. The C IV λ1548 transition, predicted to be observed at 2543.37 Å, lies precisely at the position of a z = 1.0922 Lyα line with observed equivalent width 0.64 Å, as identified by BBLD. There are no other transitions, including Lyβ, that corroborate the Lyα absorber. We have also measured the wavelength and observed equivalent width of the feature and obtain λ_{obs} = 2543.27 ± 0.14 Å and W_{obs} = 0.57 ± 0.09 Å. There is an unresolved 2.5 σ absorption feature 0.51 Å redward (+90 km s^{-1}) of the expected C IV λ1550 transition with λ_{obs} = 2548.11 ± 0.18 Å and W_{obs} = 0.22 ± 0.08 Å. Although the doublet ratio is consistent with physically allowed values, there are at least two reasons to not adopt this feature as the C IV λ1550 line at z = 0.6428. First, the detection falls below a 3.5 σ significance when the continuum fit is adjusted downward by only 0.5 (S/N)^{-1}, where S/N is the signal-to-noise ratio in the continuum of the normalized spectrum. The continuum placement is not obvious to this level of accuracy over the region 2540–2558 Å, which brackets the putative C IV line. Second, the measured λ_{obs} is approximately a 3 σ difference from the predicted λ_{obs}.

The region of the FOS spectrum where the Si IV doublet transitions are predicted to fall (2289.66 and 2304.47 Å, respectively) exhibits what appears to be a low-level flux depression. The only feature identified by BBLD is a broad and asymmetric z = 0.8816 Lyα line. The Si IV λ1393 transition could be a blend in the red wing of this Lyα line; the optimized equivalent width spectrum (following Schneider et al. 1993) shows that there are two minima, suggestive of a two component blend with λ_{obs} = 2286.4 and 2289.5 Å. The latter is consistent with the predicted location of the λ1393 transition. Additionally, the optimized equivalent spectrum has a single minimum at 2304.7 Å, consistent with the predicted location of the λ1402 transition. These minima have \sim 3.5 σ detection significance levels. However, the continuum fit is also somewhat uncertain over this region of the spectrum, so that it is difficult to assess whether the Si IV doublet has actually been observed in absorption. If the Si IV is present, then the C IV is most certainly present.

All things considered, we adopt the position that the C IV doublet has not been detected in the FOS spectrum and assign the 3.5 σ observed equivalent width limit of 0.25 Å to the C IV λ1550 transition, the λ1548 transition being compromised by the z = 1.0922 Lyα line. This gives an upper limit column density of log N \~ 14.7 cm^{-2} for C IV. We also adopt the position that the Si IV doublet has not been detected, which gives the limiting column density log N \~ 15.7 cm^{-2}. However, these are not secure conclusions. If the absorber is multiphased, then our analysis is affected only in the sense that our single-phase cloud model must be valid only for the cooler phase with the higher density. If so, then the estimated H i column density is an upper limit in this phase of the cloud, since some fraction of it must then arise in the hotter, lower density phase.

A2. THE z = 0.9315 ABSORBER

Again, the 3.5 σ observed equivalent width limit of the spectrum is approximately 0.25 Å, and we have used the LOX of Hellsten et al. (1998) to place limits on those transitions that would most likely be detectable in the spectrum. In approximate order of their LOX, the covered transitions include C III λ977, C IV λλ1548,1550, Si III λ1206, Si IV λλ1394, 1403, N III λ990, C II λ1335 and λ1036, Si III λ1190, Si IV λ1063, O VI λλ1032, 1038, and Si II λ1260, among others.

None of these transitions were detected. For the clear non-detections, the corresponding upper limit column densities are log N(C III) \~ 16.3 cm^{-2}, log N(Si IV) \~ 16.1 cm^{-2}, log N(N III) \~ 17.9 cm^{-2}, log N(Si II) \~ 16.2 cm^{-2}, and log N(Si II) \~ 15.6 cm^{-2}. For a few of the transitions, the limits are affected by the presence of other absorption features in the spectrum.

The continuum level fit in the region where the Si IV λ1063 transition is predicted is somewhat uncertain, but if the BBLD fit is adopted, then the not very stringent upper limit is log N(Si IV) \~ 17.9 cm^{-2}. The C IV doublet, if present, would be blended in both transitions. The λ1548 component is coincident with the blue wing of the Fe II λ1608 transition of the z = 0.8598 damped Lyα absorber, and the λ1550 component is coincident with the blue wing of the Mg II λ2796 transition of the z = 0.0714 dwarf galaxy (see Steidel et al. 1993; Le Brun et al. 1997). Thus, we cannot place useful limits on the C IV column density.

The expected position of the Si III λ1206 transition of the Si III λ1206 transition is coincident with a z = 0.8598 O VI λ1038 line from the damped Lyα absorber. Otherwise the limit would be log N(Si III) \~ 15.5 cm^{-2}. The λ1206 transition is the only transition with which limits on Si III could have been placed. There is clearly no absorption feature where the C II λ1036 transition is expected, giving the not very stringent upper limit on C II of log N \~ 16.8 cm^{-2}. The expected position of the O VI λ1038 transition is coincident with a higher order H i line from the strong Mg II absorption system at z = 1.1537. However, a non-stringent upper limit of log N \~ 18.6 cm^{-2} is obtained for O VI via the λ1032 transition, which would arise in a featureless region of the spectrum.

Interestingly, there is a formally significant absorption feature at λ_{obs} = 2168.16 Å with W_{obs} = 0.37 ± 0.09 that is coincident with Fe III λ1122 at z = 0.9315. Assuming a thermal line broadening in a single-phase cloud, this implies the very large
column density of \( \log N \sim 17.8 \text{ cm}^{-2} \). This large of a column density is virtually impossible to reconcile with the Fe II measurement. There are two alternative possible identifications for the putative Fe III line. First, it could be a Ly\( \alpha \) line at \( z = 0.7835 \), although there is no corroborating evidence to support this interpretation. Second, it could be Ly\( \beta \) at \( z = 1.1137 \), which would be supported by the presence of a Ly\( \alpha \) line at \( \lambda_{\text{obs}} = 2569.58 \text{ Å} \). BBLD detected an asymmetric line with an extended blue wing at 2569.85 Å, which they identified as a blend of \( \text{N v} \lambda 1242 \) at \( z = 1.0678 \) (associated with a C IV system) with Si II \( \lambda 1193 \) at \( z = 1.1536 \) (from the strong Mg II system). The \( \text{N v} \) is the weaker transition of the \( \lambda 1238, 1242 \) doublet and the Si II is the stronger transition of the \( \lambda 1190, 1193 \) doublet. The \( \text{N v} \lambda 1238 \) and Si II \( \lambda 1190 \) components of these doublets have been identified by BBLD in two adjacent and unambiguous absorption features, so the blend is corroborated by the doublet counterparts. If both these features have been correctly identified and the 2569.85 Å feature is a blend of the doublets, then there appears to be an inconsistency in that unphysical doublet ratios are required. The equivalent width of the \( \text{N v} \lambda 1238 \)–Si II \( \lambda 1190 \) blend has a lower limit 0.2 Å greater than the measured equivalent width (under the assumption of optically thick Si II and optically thin N v). Also, the identified blend is asymmetric in such a way as to suggest its centroid may in fact be 2569.6 Å (the predicted position of the Ly\( \alpha \) line if the line in question at 2168.16 Å were Ly\( \beta \)). If the blend were actually a Ly\( \alpha \) line, it would place the \( \text{N v} \lambda 1238 \) and/or the Si II \( \lambda 1190 \) identifications in question because the observed Ly\( \alpha \) equivalent width would need to account for at least 50% of the absorption. This particular discussion serves to illustrate the level of ambiguity that arises when line identifications in the Ly\( \alpha \) forest are being considered.

We adopt the position that the line observed at 2168.16 Å is not the Fe III \( \lambda 1122 \) transition at \( z = 0.9315 \). The strongest argument is that the LOX of the Fe III \( \lambda 1122 \) transition is significantly smaller than that of C III \( \lambda 977 \), which has an ionization potential a bit higher than Fe III and is therefore likely to be present in an environment giving rise to Fe III. If Fe III were present, the C III transition would have likely been easily seen in absorption.

**APPENDIX B**

**COMPUTING THE NUMBER OF STARS**

Assuming no interstellar extinction, stars of all spectral types and luminosity classes produce an observed \( v_f = i f_s = 10^{-4.7 \text{ ergs cm}^{-2} \text{ s}^{-1}} \) at \( \lambda = 5500 \text{ Å} \) when their apparent visual magnitudes are \( V = 0 \) (Allen 1981). Integrating over space out to some finite radius, \( R \), which contains a constant density of stars with a given spectral type, one obtains

\[
\log [v_f(0.17)]_{N_*} = \log N_* - 2 \log R + C_*,
\]

where \( R \) is in kiloparsecs, and \([v_f(0.17)]_{N_*} \) is the total flux from \( N_* \) stars at \( \lambda = 5500 \text{ Å} \) which corresponds to 0.17 ryd. The value of \( C_* \), given by \( 3[v_f(0.17)] + 10 \log d_* - 6 \), is dependent upon the distance, \( d_* \) (pc), at which the given stellar type has apparent visual magnitudes \( V = 0 \). If the stars are not located in a constant density sphere centered on the clouds, but instead are all at some distance \( R \), the only modification to equation (B1) is that each \( C_* \) is reduced by a geometric factor, \( \log 3 \sim 0.5 \).

The \( C_* \) are dependent upon the stellar luminosity class, I, III, and V. For O5, B0, A0, and G0 stars, the \( C_* \) are

\[
C_{O5}(I, V) = (-5.9, \ -5.9), \quad C_{B0}(I, III, V) = (-5.8, \ -6.2, \ -6.6), \quad C_{A0}(I, III, V) = (-5.8, \ -7.9, \ -8.5), \quad C_{G0}(I, III, V) = (-5.8, \ -8.6, \ -10.5).
\]

(B2)

Note that all supergiant stars, luminosity class I, have roughly identical \( C_* \).

We are most interested in the flux intensity at 1–12 ryd, since this is the energy range corresponding to the ionization potentials of the observed transitions. To estimate the number of stars required to elevate the integrated stellar/galactic flux such that it equals the UVB \( v_f \), at \( \sim 1.2 \) ryd, we need to introduce a continuum shape term into equation (B1). We define \( k_* \) to be the ratio of the stellar flux at 0.17 ryd to that at 1.2 ryd, or \( \log [v_f(0.17)]_{N_*} - \log [v_f(1.20)]_{N_*} \). For a given metallicity, Atlas stellar models (Kurucz 1991) show that the \( k_* \) are not sensitive to surface gravity (luminosity class), but only to effective surface temperature (spectral type). Thus, equation (B1) can be written,

\[
\log N_* - 2 \log R = \log k_* + \log [v_f(1.20)]_{\text{UVB}} - C_*,
\]

where \( \log [v_f(1.20)]_{N_*} \) has been replaced by \( \log [v_f(1.20)]_{\text{UVB}} \) (under the assumption of no shielding or extinction of the UVB), which ranges from \( 10^{-5.2} \leq [v_f(1.20)]_{\text{UVB}} \leq 10^{-5.8} \text{ ergs cm}^{-2} \text{ s}^{-1} \) in the redshift range of interest (see Fig. 4).

The spectral shapes, especially continuum breaks, play a significant role in the number of stars that are required to dominate, or match, the UVB flux at \( \sim 1 \) ryd. For O, B, A, and G stars, respectively, the \( k_* \) are roughly 0, 3, 9, and \( \infty \). Thus, for a cloud embedded in a \( R = 1 \) kpc volume of space, the number of luminosity class V stars required to influence the ionization conditions of the model clouds are \( N_* \sim 1, 10^4, 10^5, \) and \( \infty \) stars, respectively. For supergiants, the numbers are \( N_* \sim 1, 10^3, 10^5, \) and \( \infty \) stars, respectively. At redshifts of \( 0.5 \leq z \leq 1.0 \), a single O star could carve out an \( R = 1 \) kpc volume in which it could match or exceed the UVB at 1–12 ryd. However, it would require 1000 B0 I stars, or 10,000 B0 V stars distributed in that same volume. For luminosity class III stars, the numbers are \( N_* \sim 10^4, 10^5, \) and \( \infty \) stars, respectively, where the O type star has been omitted. Because of their sharp H I break, G, K, and M stars would need to have astrophysically unrealistic number densities to contribute to the ionization conditions of the absorbers, regardless of their luminosity class.
It is of interest to know whether the implied stellar number densities are consistent with those of the Galaxy. In terms of the stellar number density per cubic parsec, \( n_* \), equation (B3) is written

\[
\log n_* + \log R = -9.6 + \log k_* + \log [v_f(1.20)]_{UVB} - C_* \text{ stars pc}^{-3},
\]

where \( R \), as above, is in kpc. In a volume with \( R = 1 \) kpc, the required number density of O stars, whether main sequence or supergiant, is \( n_* \sim 10^{-3} \) stars pc\(^{-3}\). For the remaining spectral types, the required stellar density is dependent upon their luminosity class. For an A0 star, the required number densities are \( n_* \sim 1, 100, \) and 100 stars pc\(^{-3}\) for luminosity classes I, III, and V, respectively. In contrast, the observed stellar density of all giants in the solar neighborhood is vanishingly small, and for A0 V stars it is \( 10^{-3} \) stars pc\(^{-3}\) (Allen 1981).

Clearly, under the assumption that the UVB is not shielded by layers of neutral hydrogen or extinguished due to dust, the type of stellar environment that would be required for the stellar flux to dominate over the UVB at \( \sim 1 \) ryd would either need to be uncommonly dense or populated by O stars. Lower metallicity stars have smaller log \( k_* \). Thus, the solar-metallicity stars provide a rough upper limit to the number of required stars. On the other hand, interstellar extinction would have the effect of reducing \( v_f \), at 1.2 ryd for the individual stars, which makes the above estimates a lower limit for solar-metallicity stars.

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