ABSTRACT

We present an investigation of Mg II absorbers characterized as single-cloud "weak systems" [defined by \( W_j(\lambda 2796) < 0.3 \) Å] at \( z \approx 1 \). We measured column densities and Doppler parameters for Mg II and Fe II in 15 systems found in High Resolution Echelle Spectrometer/Keck spectra at 6.6 km s\(^{-1}\). Using these quantities and C IV, Ly\(\alpha\), and Lyman limit absorption observed with the Faint Object Spectrograph on the Hubble Space Telescope (resolution \( \sim 230 \) km s\(^{-1}\)), we applied photoionization models to each system to constrain metallicities, densities, ionization conditions, and sizes. We find the following:

1. Single-cloud weak systems are optically thin in neutral hydrogen and may have their origins in a population of objects distinct from the optically thick strong Mg II absorbers, which are associated with bright galaxies.

2. Weak systems account for somewhere between 25% and 100% of the \( z < 1 \) Ly\(\alpha\) forest clouds in the range \( 10^{15.8} \) cm\(^{-2}\) \( \leq N(\text{H}^I) \leq 10^{16.8} \) cm\(^{-2}\).

3. At least seven of the 15 systems have two or more ionization phases of gas (multiphase medium). The first is the low-ionization, kinematically simple Mg II phase and the second is a high-ionization C IV phase, which is usually either kinematically broadened or composed of multiple clouds spread over several tens of kilometers per second. This higher ionization phase gives rise to the majority of the Ly\(\alpha\) absorption strength (equivalent width), although it often accounts for a minor fraction of a system’s \( N(\text{H}^I) \).

4. We identify a subset of weak Mg II absorbers, those with \( \log \left[ N(\text{Fe} ^{II})/N(\text{Mg} ^{II}) \right] > -0.3 \), which we term "iron-rich." Although there are only three of these objects in our sample, their properties are the best constrained because of their relatively strong Fe II detections and the sensitivity of the \( N(\text{Fe} ^{II})/N(\text{Mg} ^{II}) \) ratio. These clouds are not \( \alpha \)-group–enhanced and are constrained to have sizes of \( \sim 10 \) pc. At that size, to produce the observed redshift path density, they would need to outnumber \( L^* \) galaxies by approximately 6 orders of magnitude. The clouds with undetected iron do not have well-constrained sizes; we cannot infer whether they are enhanced in their \( \alpha \)-process elements.

We discuss these results and the implications that the weak Mg II systems with detected iron absorption require enrichment from Type Ia supernovae. Furthermore, we address how star clusters or supernova remnants in dwarf galaxies might give rise to absorbers with the inferred properties. This would imply far larger numbers of such objects than are presently known, even locally. We compare the weak systems to the weak kinematic subsystems in strong Mg II absorbers and to Galactic high-velocity clouds. Although weak systems could be high-velocity clouds in small galaxy groups, their neutral hydrogen column densities are insufficient for them to be direct analogues of the Galactic high-velocity clouds.

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

1. INTRODUCTION

Absorption lines from intervening galaxies in quasar (QSO) spectra provide a wealth of information about the physical conditions of gas in these galaxies. Since QSO absorption-line spectroscopy offers unmatched sensitivity to high redshifts and low column densities, the technique can be used to follow the gas phase in galaxies over cosmic time, from primordial galaxies to the local universe.

The resonant Mg II \( \lambda 2796 \), 2803 doublet has been used extensively to find low-ionization QSO absorption systems (see, e.g., Lanzetta, Turnshek, & Wolfe 1987; Steidel & Sargent 1992). At \( z \sim 1 \), Mg II absorbers with rest-frame equivalent widths \( W_j(\lambda 2796) \) greater than 0.3 Å are optically thick in neutral hydrogen; they are observed to give rise to Lyman limit breaks (Churchill et al. 2000b). Furthermore, these "strong" systems almost always arise within 40 h\(^{-1}\) kpc of bright \( (L \geq 0.05 \) \( L^* \)) normal galaxies (Bergeron & Boisse 1991; Bergeron, Cristiani, & Shaver 1992; Le Brun et al. 1993; Steidel, Dickinson, & Persson 1994; Steidel 1995; Steidel et al. 1997). The gas kinematics are consistent with
material in the disks and extended halos of galaxies (Lanzetta & Bowen 1992; Petitjean & Bergeron 1990; Churchill, Steidel, & Vogt 1996; Charlton & Churchill 1998; Churchill & Vogt 2001).

The discovery of weak systems [those with $W_r(\lambda 2796) < 0.3 \, \AA$] in High Resolution Echelle Spectrometer (HIRES)/Keck spectra (Churchill et al. 1999b; hereafter Paper I) necessitates a revision in the standard picture. Weak systems comprise $\sim 65\%$ of Mg II–absorbing objects by number, yet only four of 19 whose fields have been imaged have a $\gtrsim 0.05 L^*$ galaxy candidate within $\pm 50 \, h^{-1}$ kpc (C. Steidel, private communication).\footnote{More precisely, fields were searched within $10^\circ$ of the quasar, which corresponds to $\sim 50 \, h^{-1}$ kpc at $z \sim 1$.} The large redshift path number density of weak systems relative to that of Lyman limit systems (LLSs) statistically indicates that, unlike strong absorbers, the majority of weak systems arise in optically thin neutral hydrogen (sub–Lyman limit) environments (see Fig. 5 of Paper I). This has been observationally confirmed by Churchill et al. (2000b). Furthermore, the majority of weak systems are single clouds, often unresolved in HIRES/Keck spectra (resolution $6.6 \, km \, s^{-1}$), in striking contrast to the complex kinematics of strong Mg II absorbers (Petitjean & Bergeron 1990; Churchill & Vogt 2001). This evidence suggests that a substantial fraction of the weak Mg II systems selects a population of objects distinct from the bright, normal galaxies that are selected by the strong Mg II absorbers.

This begs the question: what are these single-cloud objects that outnumber Mg II–absorbing galaxies yet often have no obvious luminous counterparts? A first strategy for addressing this question, adopted in this paper, is to constrain the column densities, metallicities, ionization conditions, and sizes of single-cloud weak systems. Setting useful constraints on these physical conditions requires not just low-ionization species but also neutral hydrogen and medium- to high-ionization species. At $z \sim 1$, the Lyman series and the C II, C IV, and Si IV transitions fall in the near-UV. These transitions were observed with the low-resolution Faint Object Spectrograph (FOS) on board the Hubble Space Telescope (HST). Churchill & Charlton (1999) have demonstrated that photoionization modeling using both high-resolution optical spectra and low-resolution UV spectra can yield meaningful constraints on the physical conditions of Mg II absorbers. We have adapted their approach to study weak systems.

In § 2 we describe the optical and UV spectra used in this study and discuss sample selection to motivate our focus on single-cloud weak Mg II systems. In § 2.5 we describe our methods for CLOUDY (Ferland 1996) photoionization modeling to obtain constraints on cloud metallicities, ionization conditions, and sizes. The resulting constraints for the 15 single-cloud weak Mg II systems are presented in § 3 and summarized in § 4. In § 5 we consider what types of astrophysical environments could be consistent with the properties of the weak single-cloud Mg II absorbers. In § 6 we speculate about the evolution of weak Mg II systems and suggest future investigations.

2. DATA AND SAMPLE

2.1. The HIRES Spectra

Weak systems were charted in a survey of 26 QSO spectra (Paper I) obtained with HIRES (Vogt et al. 1994) on the Keck I telescope. A total of 30 systems were found, with 22 of them being new discoveries. The survey covered the redshift interval $0.4 \leq z \leq 1.4$ and was unbiased for $W_r(\lambda 2796) < 0.3 \, \AA$. The spectral resolution was $R = 45,000$ (FWHM = $6.6 \, km \, s^{-1}$) with a typical signal-to-noise ratio of $S/N \simeq 30$ per 3 pixel resolution element. The survey was 80% complete for a 5 $\sigma$ equivalent width detection threshold of $W_r(\lambda 2796) = 0.02 \, \AA$. We restrict our study to those systems with this limiting equivalent width in the continuum at the $\lambda 2796$ transition. Simulations reveal that Voigt profile fits to HIRES data become increasingly less certain below this limit (Churchill 1997; Churchill & Vogt 2001). This equivalent width cutoff removes from this sample three systems from Paper I: S9, S11, and S22.

Data reduction, line identification, and Mg II doublet identification have been described in Paper I. In Figure 1 we display all the detected transitions (Mg II, Fe II, and Mg I) associated with the 16 weak single-cloud Mg II absorbers found in regions of the HIRES spectra that satisfy our equivalent width selection criterion.

2.2. Physically Motivated Sample

The adopted equivalent width demarcation at $W_r(\lambda 2796) = 0.3 \, \AA$ between weak and strong Mg II absorbers is an artifact of observational sensitivity (see, e.g., Steidel & Sargent 1992). However, there are at least two physical conditions that set weak systems apart from strong systems. First, almost all weak systems are optically thin to neutral hydrogen. This was shown statistically in Paper I and observationally in Churchill et al. (2000b). By contrast, strong Mg II absorbers are Lyman limit systems and thus by definition are optically thick in neutral hydrogen.

Second, the weak systems are often single clouds with very small velocity widths (unresolved in the HIRES spectra). For the sample of 30 weak systems presented in Paper I, the number of clouds per weak system ranges from 1 to 7. Figure 2 shows the frequency distribution of the number of clouds per system for both the strong systems and weak systems. The number of clouds per strong absorption system follows a Poissonian distribution with a median of seven clouds (see Table 7 of Churchill & Vogt 2001). In contrast, the distribution for weak systems is non-Poissonian, with a spike at one cloud per absorber; i.e., there are many single-cloud weak systems. This suggests that these Mg II absorbers represent a distinct population of objects. To produce many more single-cloud absorbers than multiple-cloud absorbers, weak systems should have a small covering factor or a preferred large-scale geometry such that a line of sight is unlikely to intersect multiple clouds.

In this paper we study the single-cloud systems. This selection criterion together with the equivalent width cutoff described in § 2.1 yield 16 single-cloud systems from the sample of 30 systems of Paper I.

2.3. The FOS Spectra

For 13 of the 16 single-cloud systems, archival FOS/HST spectra were available. The resolution of these spectra was $\sim 230 \, km \, s^{-1}$ FWHM with four diodes per resolution element. For PKS 0454 + 039 and PKS 0823 - 223, which contain three single-cloud weak systems, the spectra were retrieved from the archive and reduced in collaboration with S. Kirhakos, B. Jannuzi, and D. Schneider (Churchill et al. 2000b) using the techniques and software of the HST QSO Absorption Line Key Project (Schneider et al. 1993).
The remaining six QSOs were observed and published by the Key Project (Bahcall et al. 1993, 1996; Jannuzi et al. 1998) and have kindly been made available for this work. Further details of the FOS/HST observations and the analysis were presented in Churchill et al. (2000b). In general, for the single-cloud weak systems discussed here, the useful FOS transitions were C IV, Lyα, and the Lyman limit since they are strong features commonly covered in the...
we have adopted those system numbers. Table 1 lists the equivalent widths and limits for C iv and Lyz, taken from Churchill et al. (2000b). In Figure 3, spectra covering Mg II, Fe II, C iv, Lyz, and the Lyman limit are displayed for each system to show, in a single view, the full sample including blends, nondetections, and noncoverage. Additional transitions observed in the FOS data but not plotted in Figure 3 can be found in Churchill et al. (2000b).

2.4. Column Densities

For the HIRES spectra, the column densities and Doppler parameters were obtained using MINFIT, a χ² minimization Voigt profile fitter (Churchill 1997; Churchill & Vogt 2001; C. W. Churchill, S. S. Vogt, & J. C. Charlton 2002 in preparation). The column densities and Doppler parameters of the fits to Mg II and Fe II are listed in Table 1, as are 3σ upper limits on the Fe II column density for cases in which no Fe II transitions were detected. The latter were obtained from the 3σ equivalent width limit for Fe II λ2600, assuming a Doppler parameter equal to that obtained for Mg II in the same system.

The column density ratio \( N(\text{Fe II})/N(\text{Mg II}) \) is critically important to the photionization modeling; as discussed in §2.5.1, this ratio constrains the ionization parameter. Therefore, it is important to appreciate the systematic errors when \( N(\text{Mg II}) \) and \( N(\text{Fe II}) \) are comparable in strength. Simulations reveal that a 5σ equivalent width detection limit of 0.02 Å in HIRES spectra gives a 99% completeness limit of \( \log N(\text{Mg II}) = 11.9 \text{ cm}^{-2} \) and \( \log N(\text{Fe II}) = 12.4 \text{ cm}^{-2} \) (Churchill 1997; C. W. Churchill et al. 2002 in preparation). Above these column densities MINFIT accurately models the column densities. For \( \log N(\text{Fe II}) < 12.4 \text{ cm}^{-2} \), MINFIT statistically overestimates \( \log N(\text{Fe II}) \) by up to ~0.3 dex (Fig. 4.8 of Churchill 1997) because of a bias toward “false detections” in “favorable” noise patterns. Mg II Doppler parameters were well recovered in the simulations, with an rms scatter of ~1 km s⁻¹ for all column densities above the sensitivity cutoff. Fe II Doppler parameters were poorly recovered when the column density was near or below the sensitivity cutoff (Churchill 1997).

For an Fe II detection at the 3σ level in the lowest S/N spectrum in our sample, the detection limit (99% completeness) for the ratio \( N(\text{Fe II})/N(\text{Mg II}) \) would be

\[
\log \left[ \frac{N(\text{Fe II})}{N(\text{Mg II})} \right] = 12.2 - \log N(\text{Mg II}),
\]

Therefore, with increasing \( N(\text{Mg II}) \), the upper limit on \( N(\text{Fe II})/N(\text{Mg II}) \) decreases, i.e., becomes more stringent. We show this relation in Figure 4 as a diagonal line. The value of \( \log [N(\text{Fe II})/N(\text{Mg II})] \) for each of the single-cloud weak systems is plotted, with detections represented as solid circles and upper limits as downward-pointing arrows. Note that since the plotted \( N(\text{Fe II})/N(\text{Mg II}) \) detection limit

5 Weak systems in Paper I were numbered in increasing redshift order; we have adopted those system numbers.

6 Limits were insensitive to the assumed Doppler parameter because Fe II was on the linear part of the curve of growth.
line was computed from the noisiest spectrum in our sample, the data points are often lower than the limit and thus are more constraining of the Fe II–Mg II ratio than the line indicates.

Since there is an apparent gap in the distribution of \( \log \left[ N(\text{Fe} \ II)/N(\text{Mg} \ II) \right] \), we somewhat arbitrarily define systems with detectable Fe II and \( \log \left[ N(\text{Fe} \ II)/N(\text{Mg} \ II) \right] > -0.3 \) (systems S7, S13, and S18) as “iron-rich” weak systems.

Since all three so-called iron-rich systems lie above the worst-case sensitivity line and all other systems fall below it, there may be a selection effect at work— are the highest \( N(\text{Mg} \ II) \) systems identified as iron-rich systems simply because their Fe II is easier to detect? We argue that this is not the case. To illustrate, we consider the five systems with \( N(\text{Mg} \ II) \) between that of S18 and S7 (two iron-rich systems.) If these five systems had \( \log \left[ N(\text{Fe} \ II)/N(\text{Mg} \ II) \right] \sim 0 \), as is true for the iron-rich systems, then Figure 4 makes clear that they should have detected Fe II. Only one of the five systems does (S28), and since it has \( \log \left[ N(\text{Fe} \ II)/N(\text{Mg} \ II) \right] \sim -0.6 \), it is not deemed iron-rich. The limits on \( \log \left[ N(\text{Fe} \ II)/N(\text{Mg} \ II) \right] \) for the other four systems are also well below 0, by more than half a dex. Thus, it seems that while we have insufficient information to address whether the distribution of \( N(\text{Fe} \ II)/N(\text{Mg} \ II) \) is continuous or bimodal, the iron-rich systems do appear to have significantly higher \( N(\text{Fe} \ II)/N(\text{Mg} \ II) \) ratios than do the other systems. As § 2.5.1 will show, this difference in column density ratios indicates variations in ionization and/or abundance pattern between the iron-rich systems and the other systems.

2.5. Photoionization Modeling

We assume that the single-cloud, weak systems are in photoionization equilibrium, and we constrain their properties with the photoionization code CLOUDY, Version 90.4 (Ferland 1996). The clouds are modeled as constant density, plane-parallel slabs and are matched to the Mg II and Fe II column densities measured from the HIRES spectra. Using each model's output column densities for ions of interest, we synthesized FOS/HST spectra, which we directly compared to the observed C IV and Lyα profiles and to the spectral region covering the Lyman limit break. This procedure constrains both the ionization conditions and gas phase metallicities. Further discussion of the modeling technique was presented by Churchill & Charlton (1999) and by Charlton et al. (2000b).

We begin each analysis with the assumption that the Mg II, Fe II, Lyα, and C IV arise in a single isothermal structure, described by a single metallicity and ionization parameter. The data often show that this assumption is violated, in which case we model two phases, each having its own metallicity, temperature, and ionization parameter. Further details are presented below.

Clouds were assumed to be ionized by a Haardt & Madau background spectrum (Haardt & Madau 1996). For cloud redshifts below \( z = 0.75 \), we used a spectrum shape and normalization at \( z = 0.5 \), and for redshifts above \( z = 0.75 \), we used the shape and normalization at \( z = 1.0 \). For all models, we assumed a solar abundance pattern. In § 2.5.5, we discuss possible abundance pattern variations and the effect of alternative spectral shapes.

2.5.1. Applying Constraints to the Mg II Cloud

As Figure 5 illustrates, when the assumption of photoionization equilibrium holds, the \( N(\text{Fe} \ II)/N(\text{Mg} \ II) \) and \( N(C \ IV)/N(\text{Mg} \ II) \) ratios are uniquely determined by the ionization parameter, which is defined as \( U = n_e/n_H \), where \( n_e \) and \( n_H \) are the number density of photons capable of ionizing hydrogen and the total hydrogen number density, respectively. Therefore, \( \log U = \log n_e - \log n_H \), where \( n_e \) is set by the background spectrum. For the Haardt & Madau (1996) spectrum, \( \log n_e = -5.6 \) at \( z = 0.5 \) and \( \log n_e = -5.2 \) at \( z = 1.0 \).

When \( N(\text{Mg} \ II) \) and \( N(\text{Fe} \ II) \) were both measured, they were used to constrain the optimized mode of CLOUDY at a set metallicity to yield \( U \) and \( N(H I) \) by varying both \( N(H I) \) and \( n_H \). Models were run for a range of metallicities \(-2.5 \leq Z \leq 0 \) in increments of 0.5 dex.

When only an upper limit on \( N(\text{Fe} \ II) \) was measured, we

| ID | \( z_{em} \) | QSO | \( N(\text{Mg} \ II) \) (cm\(^{-2}\)) | \( b(\text{Mg} \ II) \) (km s\(^{-1}\)) | \( N(\text{Fe} \ II) \) (cm\(^{-2}\)) | \( b(\text{Fe} \ II) \) (km s\(^{-1}\)) | \( W(C \ IV) \) (Å) | \( W(Ly\alpha) \) (Å) |
|----|--------|------|-------------------------------|-----------------|-------------------------------|-----------------|----------------|----------------|
| S1 | 0.4564 | 1421+331 | 13.07 ± 0.06 | 7.65 ± 0.61 | ... | ... | ... | ... |
| S2 | 0.5215 | 1354+193 | 11.91 ± 0.05 | 4.88 ± 0.90 | <11.98 | ... | <0.24 | 1.08 ± 0.08 |
| S6 | 0.5915 | 0002+051 | 12.63 ± 0.01 | 6.78 ± 0.22 | <11.97 | ... | <0.23* | ... |
| S7 | 0.6428 | 0454+036 | 12.74 ± 0.02 | 5.79 ± 0.25 | 12.60 ± 0.05 | 5.31 ± 0.88 | 0.38 ± 0.03 | 0.70 ± 0.05 |
| S8 | 0.7055 | 0823+223 | 12.40 ± 0.02 | 13.30 ± 0.62 | <11.78 | ... | <0.18 | ... |
| S12 | 0.8182 | 1634+706 | 12.04 ± 0.03 | 2.06 ± 0.41 | <11.84 | ... | <0.07 | ... |
| S13 | 0.8433 | 1421+331 | 13.10 ± 0.10 | 3.15 ± 0.23 | 13.47 ± 0.07 | 2.34 ± 0.18 | ... | ... |
| S15 | 0.8665 | 0002+051 | 11.89 ± 0.04 | 2.65 ± 0.82 | <11.94 | ... | <0.11* | 0.81 ± 0.10 |
| S16 | 0.8955 | 1241+174 | 11.73 ± 0.06 | 7.51 ± 1.44 | <11.58 | ... | <0.10 | 0.45 ± 0.05 |
| S17 | 0.9056 | 1634+706 | 12.47 ± 0.01 | 2.77 ± 0.10 | <11.60 | ... | 0.18 ± 0.02 | 0.49 ± 0.03 |
| S18 | 0.9315 | 0454+036 | 12.29 ± 0.08 | 1.52 ± 0.19 | 12.24 ± 0.08 | 2.28 ± 1.46 | <0.62 | 0.31 ± 0.07 |
| S19 | 0.9343 | 1206+456 | 12.05 ± 0.02 | 7.52 ± 0.52 | <11.48 | ... | 0.25 ± 0.05 | 0.47 ± 0.07 |
| S20 | 0.9560 | 0002+051 | 12.15 ± 0.02 | 7.54 ± 0.58 | <11.58 | ... | 0.52 ± 0.04 | 0.85 ± 0.07 |
| S24 | 1.1278 | 1213-003 | 12.11 ± 0.05 | 1.94 ± 0.44 | <11.96 | ... | ... | ... |
| S25 | 1.2113 | 0958+551 | 12.41 ± 0.03 | 3.34 ± 0.34 | <11.67 | ... | ... | <0.92 |
| S28 | 1.2724 | 0958+551 | 12.57 ± 0.02 | 3.92 ± 0.21 | 11.99 ± 0.22 | 1.19 ± 1.30 | 0.44 ± 0.03 | 0.75 ± 0.15 |

* C IV \( \lambda 1550 \) equivalent width.
Fig. 3—“Data matrix” for the single-cloud weak Mg II systems. For each absorber, the Mg II λ2796 transition is shown in the top subpanel. In the respective lower subpanels are presented the spectral regions where the Fe II λ2600 (or λ2383) transition, the C IV doublet, the Lyα transition, and the Lyman limit break are expected. Ticks above the spectra give the locations where features are expected. The full velocity window of the subpanels with Mg II and Fe II is 100 km s\(^{-1}\) and for the FOS data is 5000 km s\(^{-1}\). “No-Cov” indicates that the spectral region was not observed, and “Bad-Data” indicates that S/N in the spectral region was too low for a useful measurement. “D” indicates a clean detection at the 3 \(\sigma\) or greater significance level. “L” denotes no detection, but only an upper limit on the equivalent width. “Bl” indicates poor constraints due to blending with other features. Transitions not plotted can be found in Churchill et al. (2000a).
detected Fe II on Fe II shift the grid down. In order that S18 does not have a significant Lyman limit, higher metallicity would shift the grid to the right; on a CLOUDY grid for metallicity $Z$ detection limit for Fe II pattern is required to produce the high intervals.)

created a grid of CLOUDY models over $\log U$ (from $-2$ to $-5$ in 0.1 dex intervals) and $Z$ (from 0 to $-2.5$ in 0.5 dex intervals) $N$(Mg II) provided the constraint, and $N$(H I) was the parameter for which CLOUDY solved. We rejected ionization parameters whose models, over the whole metallicity range, yielded $N$(Fe II) that was greater than the 3 $\sigma$ limits listed in Table 1. This set lower limits on the ionization parameter.

A model was judged to have failed or to be inapplicable for any of the following three reasons: failure to converge on an ionization parameter [usually when $N$(Fe II)/$N$(Mg II) $\approx 1$], the cloud size exceeded the Jeans length and was thus unstable to collapse, and the cloud size exceeded 50 kpc.

2.5.2. Metallicities and Multiple Ionization Phases

Whereas the ionization parameter is constrained by the Mg II and Fe II HIRES data, the metallicity and $N$(H I) are constrained by the Lyz profiles and the presence or absence of the Lyman limit break in the FOS spectra. In the regime where a cloud is optically thin at the Lyman limit, to create more $W_c$(Lyz), given a measured $N$(Mg II), requires lowering the metallicity, which increases $N$(H I), the total hydrogen column density $N_H$, where $N_H = N$(H I) + $N$(H II), and the cloud size.

Because the low-resolution FOS/HST profiles are largely dominated by the instrumental spread function, their column densities and Doppler parameters cannot be directly measured. In order to use the FOS spectra as a constraint, we created synthetic FOS spectra (infinite sampling and S/N) using the kinetic temperature and column densities output by CLOUDY.

First, we assumed a priori that all detected absorption arises in one phase of gas, the same phase that gives rise to Mg II absorption. Using the temperature of the CLOUDY model and the measured $b$(Mg II), we solved for the turbulent component $b_{turb}$ and computed the Doppler parameter for other ions by the relation

$$b_{ion}^2 = 2kT/m_{ion} + b_{turb}^2.$$  \hfill (2)

This inferred Doppler parameter and the column density are used to generate a Voigt profile, which is then convolved with the FOS instrumental spread function to produce a synthesized spectral feature.

To constrain each cloud’s metallicity, we visually compared the synthesized and FOS Lyz profiles for each modeled metallicity. In Figure 6, we illustrate the metallicity fitting procedure. Metallicities of $Z = 0$, $-1$, $-2$, and $-2.5$ are plotted; clearly, $Z = 0$ and $Z = -1$ do not fit the Lyz profile nor are their equivalent widths consistent with

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Ratio of $N$(Fe II) to $N$(Mg II) vs. $N$(Mg II). Clouds with detected Fe II (filled circles) are identified by system number. Limits, depicted as open circles, are obtained from the 3 $\sigma$ equivalent width limits on Fe II 22600. The dotted diagonal line on the plot represents the 3 $\sigma$ detection limit for Fe II in a spectrum with limiting equivalent width $W_c(22600) = 0.02$ Å. The individual system data points are superimposed on a CLOUDY grid for metallicity $Z = -1$ with a solar abundance pattern and using a Haardt-Madau (1996) spectrum at $z = 1$. The solid lines indicate constant $log N$(H I) and dotted lines indicate constant $log U$. Higher metallicity would shift the grid to the right; $\alpha$-enhancement would shift the grid down. In order that S18 does not have a significant Lyman limit break, its metallicity is constrained to be significantly larger than $Z = -1$. High above the permitted grid of values, S13 may be iron-enhanced. It is clear that a solar or slightly iron-enhanced abundance pattern is required to produce the high $N$(Fe II)/$N$(Mg II) ratios.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{Ratio of $N$(Fe II)/$N$(Mg II) and $N$(C IV)/$N$(Mg II), which are uniquely determined functions of the ionization parameter over 3 dex of $\log U$. Since ionization structure is not important for weak Mg II absorbers, the ratios are independent of metallicity. Note that at low values of $\log U$, the Fe II/Mg II ratio flattens and thus provides less constraint.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6.png}
\caption{Illustration of procedure to constrain cloud metallicity from Lyz. Model predictions for metallicities of $Z = 0$, $-1$, $-2$, and $-2.5$ are superimposed on the Lyz profile of S16. Lower metallicities predict more neutral hydrogen for a given observed $N$(Mg II). Clearly, $Z = 0$ and $Z = -1.0$ do not fit the Lyz profile; thus, the metallicity is constrained to be $-2.5 < Z < -1.5$.}
\end{figure}
the measured value, and $Z = -2.5$ slightly overpredicts the Lyα absorption. In this example, assuming that a single phase produces the Lyα absorption, the metallicity is constrained to be in the range $-2.5 < Z < -1$.

For the systems for which the Lyman limit break is known to be absent, an additional metallicity constraint may be imposed. From the Lyα curve of growth, shown in Figure 7, for a given $N(H\ I)$, we can find the $b(H\ I)$ required to observe a given $W'(Ly\alpha)$. The lack of a Lyman limit break provides a direct constraint, log $N(H\ I) < 16.8$ cm$^{-2}$, which then implies a lower limit on $b(H\ I)$. If this $b(H\ I)$ is larger than that implied by thermal scaling of $b(Mg\ II)$ for the cloud, then there is evidence for a second phase of gas. Much of the Lyα equivalent width must arise in this second phase, whose larger Doppler parameter produces the Lyα transition. Curves of equivalent width vs. $H\ I$ column density are given for $Mg\ II$ and $C\ IV$. Single-phase models were rejected when the equivalent widths of the synthesized profiles fell at least $3\,\sigma$ below that measured in the FOS data; a second phase with a larger $b(C\ IV)$ was then required. This second phase should be sufficiently ionized that it does not produce a detectable broad Mg II component. However, its other properties (e.g., its Doppler parameter and metallicity) are not well constrained by the low-resolution FOS spectrum.

The $C\ IV$ $\lambda 1548$, 1550 doublet ratio can also indicate that $C\ IV$ absorption occurs in a broader phase. If all transitions arose in the narrow Mg II phase, the $C\ IV$ doublet would be saturated and unresolved, with a doublet ratio of $\sim 1$. By contrast, a broad phase would produce less saturated lines and a $C\ IV$ doublet ratio closer to the natural value of 2. This argument is not model-dependent but relies only on the spectral resolution of FOS/HST. Unfortunately, the errors in the doublet ratio are large; S17 is the only system for which the doublet ratio can be used to infer that the $C\ IV$ arises in a broader phase than the Mg II.

2.5.4. Inferred Sizes and Masses

The derived cloud size (plane-parallel thickness) is simply $d = N_{H\ II}/n_{H\ II}$, where $N_{H\ II}$ is the total hydrogen column density $N(H\ I) + N(H\ II)$. Assuming a spherical geometry, we can estimate the cloud masses within a geometric factor as

$$M_{cl} \approx 4 \left( \frac{N_{H}}{10^{18} \text{ cm}^{-2}} \right)^{3/2} \left( \frac{10^{-2} \text{ cm}^{-3}}{n_{H}} \right)^{3/2} M_{\odot}.$$  

Because $n_{H} = n_{\gamma}/U$, this equation can also be written in terms of the ionization parameter where $n_{\gamma}$ is slightly redshift-dependent.

2.5.5. Robustness to Assumptions

Much of what can be inferred and/or deduced about the physical and cosmological properties of single-cloud weak systems is directly related to the size and mass measurements from the models. Here we examine the sensitivity of these quantities to our modeling assumptions.

First, we have assumed photoionization equilibrium. Photoionization models have been shown to underestimate the sizes of some Lyα forest clouds by several orders of magnitude (Haehnelt, Rauch, & Steinmetz 1996). In these cases, the gas is not in full thermal equilibrium because of additional heating from shocks, and errors in temperature propagate to large errors in derived size. Such nonequilibrium is found to occur for log $n_{H} \leq -4$ cm$^{-3}$, corresponding to the high-ionization conditions of higher redshift Lyα forest clouds, where recombination timescales can rival a Hubble time. At $z = 1$, such a density corresponds to log $U = -1.4$. As shown in Figure 5, photoionized clouds with $N(Fe\ II) \approx N(Mg\ II)$ are constrained to have log $U \leq -3.5$. Thus, iron-rich weak Mg II systems have densities too high, or equivalently, ionization parameters too low, for their sizes to be underestimated in this manner.

Second, we have assumed that the gas is ionized by a Haardt & Madau (1996) extragalactic UV background spectrum. Since high-luminosity counterparts are apparently rarely associated with weak systems, the most likely stellar contribution to the spectrum would be that from a single star or small group of stars quite near to the cloud. However, the constraints on the stellar types, number of stars, and their distance from the cloud can be quite severe (see, e.g., Appendix B of Churchill & Le Bruun 1998). To explore model sensitivity to the spectral shape, we produced

![Figure 7. Illustration of the constraints placed on the Doppler parameter $b$ of a broad Lyα component from the curve of growth of the Lyα transition. Curves of equivalent width vs. $H\ I$ column density are given for six different values of $b(Ly\alpha)$, ranging from 10 to 100 km s$^{-1}$. The equivalent widths of Lyα are shown as horizontal lines for the five weak $Mg\ II$ absorbers without a detected Lyman limit break. Restricting log $N(H\ I) < 16.8$ cm$^{-2}$ for the measured $W'_(Ly\alpha)$ provides a lower limit on $b(Ly\alpha)$ from this curve of growth. From these considerations, systems S3, S15, and S20 have $b(Ly\alpha) \geq 40$ km s$^{-1}$.

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a CLOUDY grid, similar to that in Figure 5, for a stellar spectrum characteristic of \( T = 30,000 \) K stars. Such a spectrum, although it is too soft to ionize carbon into \( \text{C IV} \), still has \( \text{Fe II}/\text{Mg II} \) that decreases with increasing ionization parameter. Thus, a low-ionization parameter (and high density) is still required for the \( \text{Mg II} \) clouds, especially those with measured \( \text{Fe II} \).

Third, we have assumed a solar abundance pattern with no depletion onto dust grains. Enhancement of \( \alpha \)-process elements relative to iron would shift the CLOUDY grid in Figure 4 down so that a given \( N(\text{Fe II})/N(\text{Mg II}) \) ratio would correspond to a lower ionization parameter and smaller cloud size. By contrast, iron enhancement would make the clouds larger than we infer, but such enhancement is rarely found in astrophysical environments (Edvardsson et al. 1993; McWilliam 1997). Dust depletion would mimic \( \alpha \)-enhancement since iron depletes more readily than magnesium by as much as 0.5 dex (see, e.g., Lauroesch et al. 1996; Savage & Sembach 1996a). Dust would also affect the cooling function in the models. To investigate model sensitivity to this, we ran CLOUDY models for S7 [a high \( N(\text{Fe II})/N(\text{Mg II}) \) system] both with no dust and with varying amounts of dust scaled relative to the interstellar medium (ISM) level (taken from the CLOUDY database). Dust had a negligible effect on cloud sizes for dust abundances up to 10 times the ISM level. At higher levels, the cloud sizes decreased with increasing dust content.

To summarize, the model cloud properties are robust to the modeling assumptions. In particular, the conclusion seems robust that clouds with \( N(\text{Fe II}) \gtrsim N(\text{Mg II}) \) and low \( N(\text{H I}) \) are small. If some unknown effect has led us to underestimate the cloud sizes of the iron-rich clouds by 2-3 orders of magnitude, then the discussion of their origins in § 5.4.1 does not apply, and the discussion in § 5.4.2 for clouds with lower \( N(\text{Fe II})/N(\text{Mg II}) \) would be more suitable.

3. INDIVIDUAL SYSTEM PROPERTIES

For each single-cloud weak system, we first summarize in brackets the coverage and detection status of \( \text{Fe II} \), \( \text{Lyz} \), the Lyman limit, and \( \text{C IV} \). We then explain the constraints these transitions impose. Last, in brackets we summarize the evidence or lack of evidence for multiple phases of gas. Systems are listed in redshift order, with system numbers adopted from Paper I. The constraints for all systems are summarized in Table 2.

3.1. \( S1 (Q1421+331: z_{\text{abs}} = 0.45642) \)

[\( \text{Fe II} \) not covered; no FOS spectra.] Since \( \text{Lyz} \) and the Lyman limit were not covered, the metallicity of this system cannot be constrained. The ionization parameter cannot be constrained because \( \text{Fe II} \) and \( \text{C IV} \) were not covered. We do not include this system in discussions of multiple phases and \( \text{Fe II} \) statistics because of the lack of spectral coverage. [Cannot address multiphase.]

3.2. \( S3 (Q1354+195: z_{\text{abs}} = 0.52149) \)

\([N(\text{Fe II}) \) upper limit; \( \text{W}_{\text{C IV}}(\text{Lyz}) \) measured; no break at Lyman limit; \( \text{W}_{\text{C IV}}(\text{Lyz}) \) upper limit.] To produce the strong \( \text{Lyz} \) detection in this cloud requires \( Z < -2.5 \), assuming that all the \( \text{Lyz} \) absorption arises in the same phase of gas as the detected \( \text{Mg II} \). However, the lack of a Lyman limit break requires \( N(\text{H I}) < 16.8 \text{ cm}^{-2} \), which corresponds to \( Z > -1.5 \) for this cloud. Therefore, S3 possesses a second phase of gas with a larger Doppler parameter than that of the \( \text{Mg II} \) phase, which can produce the observed \( \text{Lyz} \) equivalent width without exceeding the \( \text{H I} \) column density limit imposed by the Lyman limit. \( \text{Fe II} \) and \( \text{C IV} \) limits do not constrain \( U \). [Multiphase required because of \( \text{H I}; \text{C IV} \) does not require or rule out multiphase.]

3.3. \( S6 (Q0002+051: z_{\text{abs}} = 0.59149) \)

\([N(\text{Fe II}) \) upper limit; \( \text{Lyz} \) in spectropolarimetry mode; Lyman limit not covered; \( \text{W}_{\text{C IV}}(\text{Lyz}) \) upper limit.] The \( \text{Lyz} \) spectrum is not usable because it was taken in spectropolarimetry mode (Churchill et al. 2000b). This, combined with the lack of Lyman limit coverage, allows no constraints on metallicity. The \( \text{Fe II} \) limit sets a fairly high lower limit on the ionization parameter: \( \log U > -3.5 \). The \( \text{C IV} \)

| TABLE 2 |
| --- |
| **INFERRRED PROPERTIES OF SINGLE-CLoUD WEAK Mg II ABSORBERS** |

| ID | \( \log Z > (Z_0) \) | \( \log Z < (Z_0) \) | \( \log U > \) | \( \log U < \) | \( \log n > (\text{cm}^{-3}) \) | \( \log n < (\text{cm}^{-3}) \) | \( d > \) (pc) | \( d < \) (pc) |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Clouds with Detected Fe II** |
| S7 | -1.0 | 0.0 | -4.5 | -4.2 | -1.4 | -1.1 | 2 | 8 |
| S13 | ... | ... | -5.0 | -3.0 | -2.5 | -0.8 | 1 | 12 |
| S18 | -1.0 | 0.0 | -4.7 | -3.8 | -1.4 | -0.5 | 2 | 2 |
| S28 | -3.7 | -2.8 | -2.4 | -1.5 | 10 | 16000 |
| **Clouds without Detected Fe II** |
| S1 | ... | ... | ... | ... | ... | ... | ... | ... |
| S3 | -1.5 | ... | ... | ... | ... | ... | ... | ... |
| S6 | -3.5 | ... | ... | ... | ... | ... | ... | ... |
| S8 | -3.6 | -2.4 | -3.2 | -2.0 | -0.7 | -3 \times 10^3 | 1.8 | 3 |
| S12 | -3.6 | ... | ... | ... | ... | ... | ... | ... |
| S15 | -1.0 | -3.6 | ... | ... | ... | ... | ... | ... |
| S16 | -2.5 | -1.0 | -4.8 | -2.0 | -3.2 | -0.4 | 0.3 | 14000 |
| S17 | -2.0 | -3.4 | ... | ... | ... | ... | ... | ... |
| S19 | -1.0 | -3.7 | -1.7 | -3.5 | -1.5 | 10 | 10000 |
| S20 | -1.0 | -3.7 | ... | ... | ... | ... | ... | ... |
| S24 | -4.6 | ... | ... | ... | ... | ... | ... | ... |
| S25 | Blend | Blend | -3.5 | ... | ... | -1.7 | ... | ... |
limit is too poor to restrict the ionization parameter. [Cannot address multiphase.]

3.4. S7 (Q0454 + 039; \( z_{\text{abs}} = 0.64283 \))

\[ \text{[N(Fe II) measured; } W_{\text{II}}(\text{Ly}z) \text{ measured; Lyman limit not covered; } W_{\text{I}}(\text{C IV}) \text{ measured.]} \] If we assume the Lyz arises in the Mg II phase, then to match the Lyz profile requires \(-1 < Z < 0\). (This constraint differs somewhat from Churchill & Le Brun 1998, who used a different version of the FOS/HST spectrum.) Mg II and Fe II constrain the ionization parameter to \(-4.5 < \log U < -3.6\) for the full range of metallicities modeled and to \(-4.5 < \log U < -4.2\) for the metallicity range determined above. The model thicknesses range from 2 pc for \( Z = 0 \) to 8 pc for \( z = 1 \). If the cloud was enhanced in iron, both the size and ionization parameter would increase. The large Fe II/Mg II ratio requires a low-ionization cloud, which cannot produce the observed C IV or Si IV; a second phase of higher ionization gas is required. [Multiphase is not required for H I but is required to explain C IV and Si IV.]

3.5. S8 \((Q0823 - 223; \ z_{\text{abs}} = 0.705472)\)

\[ \text{[N(Fe II) upper limit; Lyz and Lyman limit not covered; } W_{\text{I}}(\text{C IV}) \text{ upper limit.]} \] Neither Lyz nor the Lyman limit were covered, providing no metallicity constraint. The Fe II and C IV limits set lower and upper limits, respectively, on the ionization parameter: \(-3.6 < \log U < -2.4\). In order not to exceed the 3 \( \sigma \) equivalent width, log \( N(\text{C IV}) < 14 \) cm\(^{-2}\). [H I cannot address multiphase; C IV is consistent with a single phase.]

3.6. S12 \((Q1634 + 706; \ z_{\text{abs}} = 0.81816)\)

\[ \text{[N(Fe II) upper limit; } W_{\text{I}}(\text{Ly}z) \text{ poor upper limit; Lyman limit not covered; } W_{\text{I}}(\text{C IV}) \text{ upper limit.]} \] The available Lyz coverage is pre-COSTAR and in spectropolarimetry mode and therefore unusable (Churchill et al. 2000b); accordingly, the metallicity of this system cannot be constrained. The Fe II limit requires \( \log U > -4.4 \). The 3 \( \sigma \) C IV limit, which sets log \( N(\text{C IV}) < 15 \) cm\(^{-2}\), does not restrict \( U \). [H I cannot address multiphase; C IV is consistent with a single phase.]

3.7. S13 \((Q1421 + 331; \ z_{\text{abs}} = 0.84325)\)

\[ \text{[N(Fe II) measured; no FOS spectra.] Without FOS spectra for this quasar, the metallicity cannot be constrained. N(Fe II)/N(Mg II) is greater than unity for this cloud: log N(Fe II) = 13.47 \pm 0.07 \text{ cm}^{-2} \text{ and log N(Mg II) = 13.1 \pm 0.1 \text{ cm}^{-2}. As Figures 4 and 5 demonstrate, this cannot occur for a solar abundance pattern and a Haardt & Madau (1996) ionizing background. The iron fit is particularly robust because five Fe II transitions were detected at relatively high S/N. Unresolved saturation may be present in the Fe II transitions, which would cause the fit to underestimate N(Fe II). If the Mg II doublet does not have unresolved saturation, then it could be that this cloud is iron enhanced since depletion cannot yield this pattern. A model with iron enhanced by 0.5 dex predicts log \( U = -4.3 \) and cloud size from 1 to 12 pc. [Without FOS spectra, multiphase cannot be addressed.]}

3.8. S15 \((Q0002 + 051; \ z_{\text{abs}} = 0.86653)\)

\[ \text{[N(Fe II) upper limit; } W_{\text{I}}(\text{Ly}z) \text{ measured; no break at Lyman limit; } W_{\text{I}}(\text{C IV}) \text{ upper limit.] If the observed Lyz absorption were produced in the Mg II cloud, this would require a cloud metallicity of \(-2.5 < Z < -2.0\), which corresponds to 18 cm\(^{-2}\) < log \( N(\text{H I}) < 20 \) cm\(^{-2}\). However, the small Doppler parameter of the Mg II cloud predicts an unresolved Lyz narrower than observed, and the lack of a break at the Lyman limit requires log \( N(\text{H I}) \leq 16.8 \text{ cm}^{-2} \) and \( Z > -1 \) for all ionization parameters. Hence, much of the Lyz absorption arises not in the Mg II cloud but in a separate phase of gas with a larger Doppler parameter (see Fig. 7). The Fe II limit constrains log \( U > -3.6 \) in the Mg II cloud. Models can be made to meet but not exceed the C IV limit; therefore, it does not constrain the ionization parameter; log \( N(\text{C IV}) < 16.5 \text{ cm}^{-2} \) could exist in the Mg II cloud. [Multiphase is inferred from H I, although C IV does not require a second phase.]

3.9. S16 \((Q1241 + 176; \ z_{\text{abs}} = 0.89549)\)

\[ \text{[N(Fe II) upper limit; } W_{\text{I}}(\text{Ly}z) \text{ measured; Lyman limit not covered; } W_{\text{I}}(\text{C IV}) \text{ upper limit.] If the Lyz and Mg II absorption arose in the same phase, then Lyz would be best fitted by \(-2.5 < Z < -1 \) (see Fig. 6). The ionization parameter is constrained as \(-4.8 < \log U < -2.0 \) by Fe II and C IV limits. The upper limit of N(C IV) from the 3 \( \sigma \) equivalent width limit, log \( N(\text{C IV}) < 13.4 \text{ cm}^{-2} \), can be produced in the Mg II phase and thus does not require a second phase. However, if the Lyman limit were covered, its metallicity constraint might conflict with the Lyz-determined metallicity and thus necessitate a second phase. [H I cannot address multiphase; C IV is consistent with a single phase.]

3.10. S17 \((Q1634 + 706; \ z_{\text{abs}} = 0.90555)\)

\[ \text{[N(Fe II) upper limit; } W_{\text{I}}(\text{Ly}z) \text{ measured; Lyman limit not covered; } W_{\text{I}}(\text{C IV}) \text{ measured.]} \] If all detected absorption arose in one phase, then Lyz would best be fitted by \(-2 < Z < -1 \), although these fits do not match the observed wings. However, the small Doppler parameter of the Mg II phase predicts unresolved, saturated C IV profiles with a doublet ratio of 1, which is inconsistent with the observed doublet ratio of 1.4 \pm 0.2. So while the log \( U = -2.0 \) models can reproduce the C IV \( \lambda 1551 \) equivalent width [log \( N(\text{C IV}) \approx 17 \text{ cm}^{-2} \)], they cannot fit both C IV \( \lambda 1548 \) and C IV \( \lambda 1551 \) at once. A second phase of gas, with a larger effective Doppler parameter, is required to give rise to the less saturated C IV profile. The Fe II limit constrains the ionization parameter in the Mg II phase: log \( U > -3.4 \). [H I cannot address multiphase; C IV requires multiphase.]

3.11. S18 \((Q0454 + 039; \ z_{\text{abs}} = 0.93150)\)

\[ \text{[N(Fe II) measured; } W_{\text{I}}(\text{Ly}z) \text{ measured; no break at Lyman limit; } W_{\text{I}}(\text{C IV}) \text{ upper limit.] This system has measured N(Fe II) > N(Mg II), which a solar abundance pattern and Haardt & Madau spectrum cannot produce. However, because only one Fe II transition was observed, the Voigt profile fit may be systematically large because of the noise characteristics of the data (more so than the formal errors would indicate). Models will converge for N(Fe II) at least 1 \( \sigma \) less than measured. We quote constraints for the range of N(Fe II) reduced by 1–2 \( \sigma \). The Lyz profile constrains the metallicity \(-1 < Z < 0 \); the lack of a Lyman limit break

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8 The apparent break in Fig. 3 results entirely from a strong Mg II absorber at \( z = 0.8514 \) (Churchill et al. 2000b).
requires $Z > -1$. (As for S7, the constraint differs somewhat from Churchill & Le Brun 1998 because of the use of a different version of the FOS/HST spectrum.) The $b$($H\,\alpha$) from the curve of growth needed to produce the observed $W_\lambda$(Ly$\alpha$) (see Fig. 7) is consistent with the measured $b$(Mg II). These models also give $-4.7 < \log U < -3.6$ for the full metallicity range modeled ($-2.5 < Z < 0$) and $-4.7 < \log U < -3.8$ for $-1 < Z < 0$. These models have sizes below 2.1 pc. Larger sizes (5–175 pc) would result if iron were enhanced by 0.5 dex. In the “iron-enhanced” scenario, Ly$\alpha$ constrains the metallicity as above, but the Lyman limit break is slightly less restrictive, $Z > -1.2$, and the ionization parameter is higher: $-3.7 < \log U < -3.3$. [H I does not require multiphase; C IV limit is too poor to address multiphase.]

3.12. S19 ($Q1206+456; z_{abs} = 0.93428$)

$N$(Fe II) upper limit; $W_\lambda$(Ly$\alpha$) measured; no break at Lyman limit; $W_\lambda$(C IV) measured.] If all the Ly$\alpha$ absorption arose in the Mg II phase, this constrains the metallicity to be $-2 < Z < -1$. This does not conflict with the constraint that $\log N(H\,\alpha) < 16.8$ cm$^{-2}$, as required by the lack of a Lyman limit break. Thus, a second phase of gas is not required to explain Ly$\alpha$ and the Lyman limit. [The value of $b$($H\,\alpha$)~20 km s$^{-1}$ from the curve of growth in Figure 7 is consistent with $b$(Mg II) = 7.5 km s$^{-1}$ for the model temperature.] The Fe II limit requires $\log U > -3.7$. The C IV detection can be produced in the Mg II cloud if $\log U = -1.7$; however, this slightly underproduces Ly$\alpha$ and requires an unreasonably large (80 kpc) cloud. Thus, multiphase ionization structure is required. [H I does not require multiphase; multiphase is required to explain C IV.]

3.13. S20 ($Q0002+051; z_{abs} = 0.95603$)

$W_\lambda$(Ly$\beta$) measured; no break at Lyman limit; $W_\lambda$(C IV) measured.] If all the Ly$\beta$ and Mg II absorption arose in the same phase, then the Ly$\alpha$ profile would require $Z < -2.0$, which corresponds to $\log N(H\,\alpha) > 17.3$ cm$^{-2}$. Contradicting this is the absence of a Lyman limit break, which requires $Z \geq -1$. Thus, a second phase with a larger Doppler parameter is needed to create the Ly$\alpha$ absorption (see Fig. 7). The Fe II limit constrains the Mg II phase to $\log U > -3.7$. The C IV absorption cannot arise in the Mg II cloud, even for $\log U = -2.0$, the highest ionization parameter for which CLOUDY can generate the observed $N$(Mg II). Thus, the C IV also requires a second phase with large Doppler parameter, which is more highly ionized than the Mg II phase. [Multiphase is required to explain H I and C IV.]

3.14. S24 ($Q1213-003; z_{abs} = 1.12770$)

$N$(Fe II) upper limit; no FOS data.] No HST spectra were available for this quasar, so the metallicity of this system cannot be constrained. We doubt the veracity of the 3.5$\sigma$ Fe II detection since two equally strong lines are detected within 120 km s$^{-1}$ of the putative Fe II $\lambda 2383$. Were the Fe II detection real, it would predict $-5.2 < \log U < -3.9$ over the metallicity range $-2.5 < Z < 0$. Using the Fe II as a limit, we constrain $\log U > -4.6$. [No FOS data, so multiphase cannot be addressed.]

3.15. S25 ($Q0958+551; z_{abs} = 1.21132$)

$N$(Fe II) upper limit; $W_\lambda$(Ly$\alpha$) upper limit; Lyman limit and C IV not covered.] Ly$\alpha$ is blended with $\lambda 1550$ from a possible C IV doublet at $z = 0.7330$ (Churchill et al. 2000b), and the Lyman limit is not covered, so metallicity cannot be determined. The Fe II limit constrains $\log U > -3.5$. [Multiphase cannot be addressed.]

3.16. S28 ($Q0958+551; z_{abs} = 1.27238$)

$N$(Fe II) measured; $W_\lambda$(Ly$\alpha$) measured; Lyman limit not covered; $W_\lambda$(C IV) measured.] If all the Ly$\alpha$ arose in the Mg II cloud, $-2.5 \leq Z \leq -2.0$ would be required. However, the Ly$\alpha$ profile is unphysically shaped and therefore this constraint is somewhat untrustworthy. Detected Fe II and Mg II require $-3.7 < \log U < -2.8$, which cannot arise in the same phase as the strong detected C IV. Thus, a second, more highly ionized phase is required. [H I cannot address multiphase; C IV requires multiphase.]

4. SUMMARY OF CLOUD PROPERTIES

In §3 we presented constraints on the physical conditions of 15 single-cloud weak Mg II systems. In this section, we summarize the inferred properties of weak Mg II absorbers. The inferred upper and lower limits on the metallicities, ionization parameters, densities, and sizes of the clouds are given in Table 2. As described in point 8 below, for at least seven of the systems, we infer that two phases of gas are required to simultaneously fit the Mg II, Fe II, C IV, Ly$\alpha$, and Lyman series absorption. In Table 2, and except where noted below, the inferred properties are for the low-ionization Mg II phase; the properties of the high-ionization phase are not well constrained because the relevant transitions were covered only at low resolution. Figure 8 presents an overview of the metallicity constraints on the low-ionization phase, while Figure 9 summarizes the constraints on its ionization parameter/density.

The following points characterize the basic measured and inferred statistical properties of the sample of single-cloud weak Mg II absorbers:

1. Single clouds.—Two-thirds of weak Mg II absorbers are single-cloud systems, as contrasted to strong Mg II absorbers, which are consistent with a Poissonian distribution with a median of seven clouds per absorber (see Fig. 2). This suggests that weak Mg II absorbers represent a distinct population of objects, as does their lack of Lyman breaks. To produce predominantly single-cloud systems, weak Mg II absorbers should have a preferred geometry or small covering factor if they arise in extended galaxy halos or galaxy groups such that a line of sight is unlikely to intersect multiple clouds.

2. Doppler parameters.—Most clouds are unresolved at $R = 6.6$ km s$^{-1}$, with Doppler parameters of 2–7 km s$^{-1}$. A few of the Mg II profiles have slightly larger Doppler param-

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9 The apparent break is entirely accounted for by the $z = 0.9276$ system along this same line of sight (Churchill & Charlton 1999).

10 There are actually 16 single-cloud weak Mg II systems in the sample. Unfortunately, no transitions other than Mg II were covered for S1, so photoionization models for this system cannot be constrained. While we include this system in number-of-cloud statistics, we exclude it from other analyses.
components or bulk motions. Parameters and are slightly asymmetric, suggesting blended subcomponents or bulk motions.

3. Metallicities.—As shown by Figure 8, the Mg II phases of weak absorbers have metallicities at least one-tenth solar. In no case is a cloud metallicity constrained to be lower. In fact, in cases where a strong Lyα profile would seem to require low metallicity (assuming a single phase) and lack of a Lyman limit break requires log $N(\text{H} \ i) < 16.8$ cm$^{-2}$ and thus high metallicity. In such cases much of the Lyα equivalent width arises in a broader, more highly ionized, second phase of gas. Thus, the Mg II phases have log $N(\text{H} \ i) \sim 16$ cm$^{-2}$ and have been substantially enriched by metals.

4. Ionization parameters/densities.—Weak Mg II absorbers have a wide range of ionization parameters ($-5 < \log U < -2$) if a solar ratio of $z$/Fe is assumed, as shown in Figure 9. This translates to a range of densities ($-3.5$ cm$^{-2} < \log n_H < 0$ cm$^{-2}$). There is a degeneracy between $z$-process enhancement and ionization parameter.

5. Iron-rich systems.—$N(\text{Fe} \ ii)$ was detected in four of the 15 systems. Detection of iron considerably tightens constraints on ionization conditions (and thus sizes and densities), as can be seen in Table 2. Three systems (S7, S13, and S18) have $N(\text{Fe} \ ii) \approx N(\text{Mg} \ ii)$. We term these iron-rich systems and infer log $U \sim -4.5$ and log $n_H \sim -1$ cm$^{-3}$. If these clouds were $z$-group–enhanced relative to solar, they could not produce the observed high $N(\text{Fe} \ ii)/N(\text{Mg} \ ii)$ ratio, as Figure 4 illustrates. Therefore, we infer that $z$/Fe $< 0$ for these three systems. Also, since Fe depletes more readily than Mg (Savage & Sembach 1996b; Laureosch et al. 1996), these systems do not have significant dust depletion.

6. Systems with Fe II limits.—For most of the clouds without detected Fe ii, we infer log $U > -4$ and log $n_H < -1.5$ cm$^{-3}$. As Figure 4 shows, six are constrained to have $N(\text{Fe} \ ii)$ at least 0.5 dex below $N(\text{Mg} \ ii)$ and thus are significantly different (either more highly ionized and less dense or $z$-group–enhanced) than the iron-rich clouds. For five of the clouds [with small $N(\text{Mg} \ ii)$] the upper limits on $N(\text{Fe} \ ii)/N(\text{Mg} \ ii)$ are not restrictive.

7. Cloud sizes.—Together, the $N_H$ constraint (equivalent to a metallicity constraint) and the density constraint (equivalent to an ionization parameter constraint) allow estimation of the cloud thicknesses $N_H/n_H$. These constraints are given in Table 2. Iron enhancement would increase cloud sizes. For the three iron-rich clouds (see point 5 above), low $N_H$ (high metallicity) and high density (low ionization) indicate that the clouds are small, ∼10 pc. For those systems with only limits on $N(\text{Fe} \ ii)$, densities are not sufficiently constrained to infer sizes. These clouds may be as small as the iron-rich clouds or as large as would be feasible for a cloud with the observed $b(\text{Mg} \ ii)$ of several kilometers per second (perhaps several kiloparsecs).

8. Multiple phases.—Seven of the 15 systems require two phases of gas: the low-ionization, narrow Mg II phase (which is present by definition in all systems and which may or may not have detectable Fe ii) and a second “broader” phase that gives rise to most of the C iv and Lyα absorption. This second phase should be rather highly ionized because broad Mg II absorption is not seen. The high-ionization phase is required in three systems by Lyα and the Lyman limit and in five systems by strong C iv. For S20, it is required by both the Lyα/Lyman limit and C iv.

Of the four systems with detected Fe ii, S7 and S28 have strong C iv, which indicates multiphase conditions, S13 has no C iv spectral coverage, and S18 has poor C iv limits. Only in S18 were Lyα and the Lyman limit both covered, and they do not indicate a second phase.

For systems with $N(\text{Fe} \ ii)$ upper limits, three systems (S17, S19, and S20) have C iv absorption that requires two phases, three systems (S12, S15, and S16) have C iv 3 σ
upper limits more stringent than the detections, and the remaining six have poor limits or no C iv coverage. In S3, S15, and S20, Lyα and the Lyman limit indicate multiphase conditions. For all these systems, absorption from the second phase varies considerably in strength, indicating that in some cases a second phase may be absent, or at least very weak. The Lyα and C iv profiles are of insufficient resolution to significantly constrain the properties of the higher ionization phase.

9. Relationships between properties.—Column density of Mg ii, Doppler parameter of Mg ii, metallicity, ionization parameter, and the presence of a second phase are not found to be correlated properties in this small sample.

5. DISCUSSION

5.1. High-Metallicity Lyα Forest Clouds

Numerical simulations and observations have suggested that the higher column density, $z < 1$ Lyα forest clouds arise within a few hundred kiloparsecs of galaxies (Davé et al. 1999; Cen et al. 1998; Ortiz-Gil et al. 1999). By stacking the spectra of 15 quasars, Barlow & Tytler (1998) detected the spectra of 15 quasars, Barlow & Tytler (1998) detected

\[ [C/\text{H}]_{II} \]

that in some cases a second phase may be absent, or at least very weak. The Lyα and C iv profiles are of insufficient resolution to significantly constrain the properties of the higher ionization phase.

In Paper I, we showed that ~7% of the Lyα forest systems with $W_{\text{Ly}}(\text{Lyα}) \geq 0.1$ Å are weak Mg ii systems; we have now shown that weak systems comprise a substantial fraction, \textit{perhaps most}, of the $z < 1$ Lyα forest with $\log N(\text{H} \, i) \sim 16$ cm$^{-2}$.

5.2. Space Density of Weak Mg ii Clouds

Using the sizes derived from CLOUDY and the observed redshift number densities, we can estimate the space density of weak systems in the universe. From this we then can deduce the relative numbers of weak systems compared to galaxies (i.e., strong Mg ii absorbers) regardless of how they are distributed in the universe.

In general, the space density of absorbers is given by

\[ n(z) = \frac{dN}{dz} = \frac{H_0 c}{\pi R_s^2 C_f} (1 + \frac{q_0 z}{1 + z})^{1/2}, \]  

where $R_s$ is the characteristic radius of the absorber and $C_f$ is the covering fraction, such that $\pi R_s^2 C_f$ is the effective cross section of an absorber. We consider the Mg ii phase only since the high-ionization phase is poorly constrained. Since $n$ is dependent on the square of the characteristic radius of the absorber, we consider the iron-rich systems separately because their sizes are well constrained.\(^{11}\) The systems with no measured $N(\text{Fe} \, ii)$ have $dN/dz = 0.75 \pm 0.05$ over the same redshift range, and their sizes are relatively unconstrained.

Using $q_0 = 1/3$, $z = 1$, and $C_f = 1$, we find $n = 1.3 \times 10^4 h/1 \text{ pc}/R_s^2$ Mpc$^{-3}$ for the iron-rich clouds. For $R_s \sim 10$ pc, $n = 1.3 \times 10^5 h$ Mpc$^{-3}$ (the linear dependence on $h$ arises because our sizes are derived independent of cosmological model). For the clouds without detected iron, we find $n = 56 h(1 \text{ kpc}/R_s^2)$ Mpc$^{-3}$. A lower limit can be estimated by assuming that the clouds are not Jeans unstable and are less than 50 kpc in size. This yields $n > 0.02 h$ Mpc$^{-3}$. Recall that $n \propto C_f^{-1}$, so a smaller covering factor would result in a higher space density.

For comparison, strong absorbers have $dN/dz = 0.91 \pm 0.1$ (Steidel & Sargent 1992), $R_s \approx 40 h^{-1}$ kpc, and unity $C_f$ at $\langle z \rangle = 0.9$, yielding $n = 0.04 h^3$ Mpc$^{-3}$ (Steidel et al. 1994), which is consistent with the space density of galaxies at this redshift (Lilly et al. 1995). The ratio of the space density of weak Mg ii absorbers to the space density of strong Mg ii absorbers (bright galaxies) is a simple comparison of the relative numbers of these populations in the universe, independent of where they arise or how they cluster. Therefore, although we quote the result as a number of weak Mg ii absorbers per $L^*$ galaxy, this

\(^{11}\) It is not clear if iron-rich weak systems are a separate population of absorbers; as Fig. 4 shows, we cannot tell whether weak systems are bimodally or continuously distributed in $N(\text{Fe} \, ii)/N(\text{Mg} \, ii)$ and thus in ionization condition and/or x/Fe enhancement. For the systems with lowest $W_j$, even $N(\text{Fe} \, ii) \approx N(\text{Mg} \, ii)$ would place Fe ii below our detection threshold. Accordingly, the derived space density of iron-rich systems should be taken as a lower limit.
does not imply that weak Mg II absorbers are clustered around or associated with bright galaxies. For the cloud size estimates of the previous paragraph, the lower limits on the ratio of space densities of weak Mg II systems to galaxies are $\approx 3 \times 10^6 \, h^{-2}$ and 0.5 $h^{-2}$ for iron-rich clouds and clouds without detected iron, respectively. Again, recall that $n$ for the weak systems goes as $C_f^{-1} n r_{\perp}^{-2}$, so a smaller covering factor and smaller sizes result in higher ratios.

The sample of three iron-rich systems is small, but since space density depends only linearly on $dN/dz$ (eq. [4]), for an unbiased survey, this uncertainty does not change the qualitative result; more important is the robustness of their inferred size (see § 2.5.5). This is an astonishing result: iron-enriched single-cloud weak systems outnumber bright galaxies by at least a million to one.

5.3. Relationship to Galaxies and Covering Factor

As calculated above, the redshift number densities of all single-cloud weak systems are $\approx 1$, which is comparable to that of the strong systems associated with bright galaxies. Taken at face value, one could argue that almost all weak systems, although significantly more numerous than galaxies, are nonetheless associated with galaxies. In fact, strong Mg II absorbers commonly have weak clouds with $W_\lambda(\lambda 2796) \approx 0.1$ Å at intermediate to high velocities, i.e., 40–400 km s$^{-1}$ from the absorption systematic velocity zero point (Churchill & Vogt 2001). We present a direct comparison of these properties in Figure 10, which shows that the ranges of Mg II column densities, Doppler parameters, ionization conditions, and $N$(Fe II)/$N$(Mg II) are similar.

Thirteen of the single-cloud weak systems in our sample are in QSO fields that have been imaged in efforts to identify the galaxies hosting strong Mg II absorption. We cite a few examples to illustrate that there is growing evidence against the association between bright galaxies and single-cloud weak systems (also see Paper I).

Of the iron-rich systems, two (S7 and S18) are seen in absorption against Q0454+39, whose field has been well studied (Steidel, Dickinson, & Bowen 1993; Le Brun et al. 1997; Churchill & Le Brun 1998). No candidate galaxies are seen at the weak system redshifts within $\sim 10^\circ$ of the QSO, down to $\sim 0.01 L_k^B$ (Le Brun et al. 1997). The line of sight to Q0002+051 has five Mg II systems, of which three are single-cloud weak systems (Paper I). The strongest (S6), with $W_\lambda(\lambda 2796) = 0.29$ Å, is at the redshift of a bright galaxy, while the two others, S15 and S20, are unmatched with galaxies out to 20 $^\circ$. The line of sight to Q1421+331 has four Mg II systems, of which two are single-cloud weak systems (S1 and S13, the third iron-rich system). There is one bright galaxy in the field with an unconstrained redshift; statistically, it is likely to be associated with one of the two strong Mg II absorbers (Steidel et al. 1994; Steidel 1995). This evidence that weak systems do not commonly select bright galaxies within $\sim 50 \, h^{-1}$ kpc of the absorbing gas does not rule out either dwarf galaxies (or smaller mass objects) or bright galaxies within 100–200 kpc of the QSO. That is, they could arise in low-luminosity, small-mass structures that are either clustered within a few hundred kiloparsecs of bright galaxies or are distributed in small groups of galaxies (analogous to the Local Group). If so, this might lead us to consider whether the intermediate and high-velocity weak Mg II clouds in strong systems do not reside within $\sim 50 \, h^{-1}$ kpc of galaxies but instead are the same objects as the weak systems; that is, the weak clouds in strong systems sampled by the lines of sight that select bright, Mg II–absorbing galaxies could, in principle, be interloping weak systems that arise throughout the group environment. However, as we will show, there are problems with this scenario.

If the single-cloud weak Mg II absorbers and the kinematic outliers of strong systems are the same population (with the same spatial distribution and covering factor), then they should have similar redshift number densities. This should be true regardless of whether they are clustered within 100–200 kpc of galaxies or distributed throughout groups. If they are not the same population of objects, then their relative redshift number densities give the ratio of their absorption cross sections,

$$\frac{dN/dz}_w = \sigma_w = \left(\frac{C_f n r_{\perp}^2}{\bar{n}_w}\right)^{\frac{1}{2}},$$

where the terms are the same as described in equation (4) and $w$ and $o$ denote the weak and strong systems, respectively.

In strong Mg II absorption systems, the chance of intercepting one or more intermediate or high-velocity, single
weak outliers is roughly 55%; in roughly half of those systems, two or three single weak clouds are observed (Churchill & Vogt 2001). This translates to a redshift number density of \((dN/dz)_h \sim 0.7\), regardless of the spatial relationship between galaxies and the intermediate and high-velocity outliers.

\(L^*\) galaxies cover only a very small fraction of a group; consequently, passing through two strong systems or a strong system and a weak system should be similarly improbable unless weak absorbers cluster strongly around bright galaxies. If the weak \(Mg\ II\) absorbers were clustered within 100–200 kpc of strong \(Mg\ II\) absorbers, a candidate \(L^*\) galaxy would be observed, within 40 \(h^{-1}\) kpc, 5%–10% of the time, which does not violate the observational constraint. However, in this scenario, since the weak absorbers are spread over a fairly large region, their covering factor within that 100–200 kpc radius is also fairly small, and so one would only expect a high-velocity weak outlier in 10%–20% of strong systems. This conflicts with the observed fraction, which is close to 100% (some systems have multiple outliers).

Thus, to explain the kinematic outliers of strong systems, the weak \(Mg\ II\) absorbers would need to be strongly clustered around the strong absorbers. They would be rare at large distances. However, they would also be rare at small distances or else more candidate galaxies for weak \(Mg\ II\) absorbers should have been found within \(\sim 50 h^{-1}\) kpc. This clustering, only at intermediate distances, seems rather contrived. A further complication is that clouds within 100 kpc should merge with the nearby galaxy on timescales of less than \(10^5\) yr.

We therefore conclude that while weak \(Mg\ II\) absorbers and outliers of strong \(Mg\ II\) absorbers are similar in their physical properties, they generally arise in different types of hosts. In the case of the outliers, the host is apparently the bright galaxy responsible for the strong \(Mg\ II\) absorption. The high-velocity clouds around this galaxy could arise from gas tidally stripped from companions or through energetic events that eject gas from the disk (Churchill et al. 1999a). The processes that give rise to the weak \(Mg\ II\) absorbers may be similar but may occur in less massive, less luminous hosts.

5.4. Possible Environments of Weak \(Mg\ II\) Absorption

If we take the inferences presented above as reasonable approximations for the true physical conditions of weak \(Mg\ II\) absorbers, then what are the implications? In what environments does weak \(Mg\ II\) absorption arise?

5.4.1. Iron-rich Clouds

We now consider the environments of the iron-rich weak \(Mg\ II\) absorbers (with \(dN/dz \sim 0.2\)). These absorbers, with comparable column densities of \(Fe\ II\) and \(Mg\ II\), are inferred to be high-metallicity (>0.1 \(Z_\odot\)), small [\(\log N(H I) < 16.8\) cm\(^{-2}\) and size \(\sim 10\) pc] gas clouds, which, if spherical, would outnumber bright galaxies by a factor of \(\sim 10^6\). They seem not to be closely associated with bright galaxies, i.e., within \(\sim 50 h^{-1}\) kpc of \(Z_\odot\) galaxies.

The small inferred gas masses (a few \(M_\odot\)) and small velocity dispersions (\(b \sim 6\) km s\(^{-1}\)) of the \(Mg\ II\) phase in the iron-rich systems suggest objects that would not be stable over astronomical timescales. Either the gas is transient or the clouds are confined by outside gas pressure or stellar and/or dark matter. The \(Mg\ II\) phase would be a conden-

sation inside a larger structure, which may give rise to the higher ionization, larger Doppler parameter phase. However, it is important to note that these two phases would not be in simple pressure equilibrium since they have similar inferred temperatures (if both are photoionized) and different inferred densities.

The high metallicities (\(\geq 0.1\) solar) of weak \(Mg\ II\) absorbers require substantial enrichment. Yet because the gas in the iron-rich systems is not \(\alpha\)-group–enhanced relative to solar, it cannot have been enriched solely by Type II SNe or galactic winds produced by multiple Type II SNe since material processed in this way is observed to be \(\alpha\)-group–enhanced by 0.5 dex (McWilliam 1997; Lauroesch et al. 1996; Tsujimoto & Shigeyama 1998). Therefore, weak \(Mg\ II\) absorbers with high \(Fe\ II\) must have retained enriched gas from Type Ia SNe. In general, retaining high-velocity SNe ejecta requires either a deep potential well or “smothering” of the explosion by gas in the surrounding medium. For weak \(Mg\ II\) absorbers, the lack of Lyman limit breaks and associated bright galaxies within \(\sim 50 h^{-1}\) kpc argues that \(L^*\) galaxy potential wells are not responsible. Accordingly, we consider how Type Ia supernova ejecta might be retained by smaller potential wells.

In the pre–dark matter era, Peebles & Dicke (1968) explored the formation and expected properties of Population III star clusters. We explore the updated general scenario of a dark matter minihalo of \(10^6\)–\(10^8\) \(M_\odot\) with a virial velocity of tens of kilometers per second. Such a minihalo could contain a dwarf galaxy or only a star cluster within it (Rees 2000). When the first massive stars in the cluster exploded as Type II SNe, the resulting superbubble would have driven much of the surrounding gas out into the halo. This process should destroy small halos, which sets a lower limit on the mass of halos that survive. In sufficiently large halos, the superbubble gas should be slowed as it sweeps out into the halo gas. Eventually the shell should slow to the virial speed of the halo and may cool and fragment or mix with the halo gas and disperse. As the product of Type II SNe, this gas should be \(\alpha\)-group–enhanced. Condensations within the superbubble remnant might give rise to detectable Mg II but not Fe II absorption.

After the requisite delay time (\(\sim 1\) Gyr), Type Ia SNe should detonate within the star cluster. Scaling roughly, \(10^5\) \(M_\odot\) in stars should produce one Type Ia supernova per \(10^9\) yr, assuming that the Milky Way SNe rate scales to lower mass structures.

If this Type Ia supernova gas were retained, mixed with already \(\alpha\)-group–enhanced gas, and condensed, such a structure might be observed as an iron-rich, high-metallicity, weak \(Mg\ II\) absorber. In the absence of a large potential well, trapping the debris would require smoothing, either at small radii within a parent star cluster or at larger radii within the surrounding halo. If the Type Ia ejecta were trapped within a star cluster, the observed small \(Mg\ II\) Doppler parameter would represent the low virial speed of the cluster; if the ejecta were trapped within the halo, the small \(b(Mg\ II)\) would indicate a condensation in the supernova shell. Burkert & Ruiz-Lapuente (1997) have also considered the effect of Type Ia SNe on the gas in dwarf spheroidals.

To summarize, the high inferred metallicities and lack of nearby bright galaxies imply that weak \(Mg\ II\) absorption arises in metal-enriched gas inside small dark matter halos. To consider what type of luminous structures could exist
inside the halos (dwarf galaxies or star clusters) and how the absorbing gas is distributed within the halo (concentrated within star clusters or at large in the halo), we must balance the two factors that determine the absorption cross section: the number of parent halos per $L^*$ galaxy and the number of absorbers within these halos. Physically, the latter factor is determined by the generation rate of the absorbing gas and the persistence of the structure.

Equation (5) simply relates absorber sizes and number densities of two populations to the ratio of their redshift number densities. Because the absorption statistics of strong Mg II absorbers are well-established at redshift $0.3 \leq z \leq 2.2$ (Steidel & Sargent 1992) and because $L > 0.1$ $L^*$ galaxies are largely responsible for this strong absorption, it is useful to compare them to weak Mg II absorbers. We can rearrange equation (5) and use $R_s = 40 \ h^{-1}$ kpc, $dN/dz_w = 0.91 \pm 0.1$ for strong systems, $dN/dz_{w'} = 0.18 \pm 0.01$ for iron-rich weak systems, and the unity covering factor $C_p$. Then, $n_w/n_s$ is the ratio of the number of halos containing iron-rich weak absorbers to the number of strong absorbers. The result is that, in each weak absorber halo, weak Mg II absorption covers the same area as a circle with radius $R_w = 17 h^{-1}(n_{wifo}/n_{s})^{-1/2}kpc$.

For the Milky Way, if only the dozen known dwarf satellites contribute to iron-rich weak Mg II absorption, then $R_w = 7$ kpc for $h = 0.7$. Obviously, a very large fraction of each dwarf must give rise to the absorption in this scenario. Simulations generically predict more dark matter halos per poor group than are observed as dwarf galaxies in the Local Group (Klypin et al. 1999; Moore et al. 1999). For a typical $L^*$ galaxy, simulations by Klypin et al. (1999) of poor groups produce about 500 dark matter halos with $v_{circ} > 10$ km s$^{-1}$ per $L^*$ galaxy. Using this for $\eta$ yields $R_w \sim 1$ kpc per small halo for $h = 0.7$. Even with this large population of satellites, a large fraction of each halo would need to give rise to weak Mg II absorption with high $N(Fe II)/N(Mg II)$.

Dwarf galaxies and faint dark matter minihalos might be expected to cluster less strongly than brighter galaxies. If they exist in abundance in voids, then this would raise the number of weak absorber halos per $L^*$ galaxy $n_w/n_s$ and decrease the effective absorption radius per halo $R_w$.

If Population III star clusters exist inside numerous small dark matter halos, gas trapped within the clusters might give rise to weak Mg II absorption. The correspondence between the virial velocity of a globular cluster and the small Doppler parameter of weak Mg II absorbers is suggestive, as is the similarity between globular cluster radii and the inferred sizes of the iron-rich weak Mg II clouds. Two problems of this scenario are that sufficiently small halos should be destroyed by the initial burst of Type II SNe and that rogue star clusters with concentrations similar to that of Milky Way globulars would have been detected in the Local Group. More diffuse clusters might remain below present detection thresholds. The expected concentration is unknown since it is difficult to calculate the expected packaging of the first and second generation of stars to form in the universe (Rees 2000; Abel et al. 1998; Abel, Bryan, & Norman 2000).

Still, unless there are more than a million minihalo hosts of iron-rich weak Mg II absorption for every $L^*$ galaxy in the universe, the absorption cross section per small halo spans more area than the inferred 10 pc size of an iron-rich weak Mg II absorber. Assuming spherical geometries, this would require multiple sites that could give rise to weak Mg II absorption per small halo. In the picture in which enriched gas is trapped within star clusters, this would require multiple star clusters per halo.

Alternatively, the gas could exist not in small, isolated structures but rather in sheets within the halos, which would explain the small sizes inferred for the absorbers and the large cross section for absorption per halo. This would correspond to the general picture discussed in which enriched gas from supernovae, which has fragmented and cooled, is trapped within a halo.

### 5.4.2. Clouds without Detected Fe II

The sizes of the clouds with upper limits on $N(Fe II)$ are not constrained. They could be as small as the iron-rich clouds or much larger, as large as narrow, single-cloud kinematics permit. Like the iron-rich clouds, these clouds with smaller ratios of $N(Fe II)$ to $N(Mg II)$ arise in $Z \geq -1$ environments. However, the clouds without detected Fe II do not require $[\alpha/Fe] \sim 0$; they could be $\alpha$-group–enhanced. So, unlike the iron-rich clouds, clouds without detected Fe II could be wholly externally enriched. Given that they are apparently not closely associated with bright galaxies, two possible origins for their high metallicities are apparent: external enrichment from larger structures or trapping of local SNe ejecta.

In the external enrichment scenario, the winds and superbubbles of large galaxies pollute the intragroup gas and the low-mass structures in the group: the low-mass galaxies, tidal debris, and infalling clouds. X-ray observations of poor groups indicate that such gas would have relatively high metallicities ($> 0.1$ solar) (Mulchaey 2000). The level of $\alpha$-enhancement depends on the ability of the galaxy group to retain the early Type II supernova ejecta that may escape into the intergalactic medium (Davis, Mulchaey, & Mushotsky 1999; Finoguenov & Ponman 1999).

In this case, systems with lower Fe II would arise in galaxy groups and might be thought of as low neutral column density (sub–Lyman limit) high-velocity clouds (HVCs). These would not be analogous to HVCs observed locally in 21 cm emission, which have log $N(H I) > 18$ cm$^{-2}$ and may or may not be of extragalactic origin (Blitz et al. 1999; Charlton, Churchill, & Rigby 2000a). Rather, they would be more like the sub–Lyman limit HVCs observed in C IV absorption around the Milky Way, which are likely extragalactic (Sembach et al. 1999). Such C IV HVCs are consistent with a highly ionized single phase, but their Si II and C II detections are also consistent with what would be expected for weak Mg II absorbers.

Because of the degeneracy between high ionization and $\alpha$-enhancement, we do not know whether the clouds without detected Fe II are $\alpha$-group–enhanced. If they are not and instead have solar $\alpha/Fe$, then like the iron-rich clouds, they cannot have been enriched by $\alpha$-group–enhanced external gas. In this case, the argument for the high Fe II clouds applies: in the absence of a large potential well, Type Ia SNe ejecta need to be smothered and trapped by nearby gas. In this scenario, clouds with lower Fe II would be more highly ionized or $\alpha$-group–enhanced versions of the iron-rich clouds.

If the host star cluster is coeval, like a globular cluster, then after the initial burst of Type II SNe, all successive SNe should be Type Ia. If the stars arise in something more like a dwarf galaxy with more continuous or stochastic star formation, then Type II SNe remnants as well as high-
ionization pockets of Type Ia supernova remnants could give rise to lower Fe II systems. Differences in the velocity spread, state of ionization, and absorption strength of the second phase seen in many of the weak Mg II absorbers might reflect differing host environments.

6. EVOLUTIONARY HISTORIES AND FURTHER INVESTIGATIONS

6.1. Weak Mg II Systems at Other Redshifts

How would these $z \sim 1$ weak Mg II absorbers appear at higher redshift? At $z > 1$, the metagalactic ionizing flux was stronger, rates of star formation and galaxy interaction were higher, less material had condensed into galaxies, and less time had transpired for production of Type Ia SNe than at $z = 1$. Thus, clouds with the same total hydrogen column density would have been more highly ionized, $z$-group-enhanced, and lower in metallicity. (We caution that since the star formation history of these systems is unknown, it is difficult to predict metallicity and enhancement evolution.) Higher ionization and lower metallicity would make Mg II absorption weaker, perhaps below detection thresholds. Consequently, sub-Lyman limit weak Mg II absorbers may be rarer or nonexistent at high redshift. Because of increased ionization and possible $z$-group enhancement, Fe II detections for weak Mg II absorbers should become rarer at $z > 1$.

If this population of objects would not be common at high redshift, what kinds of objects would be selected by weak Mg II absorption? Some weak Mg II absorbers at high redshift might still be below the Lyman limit, but the threshold for detecting Mg II should be pushed to higher $N_{\text{HI}}$ by metallicity and ionization effects. Because of the column density distribution function, this would lead to fewer absorbers per unit redshift. However, both cosmological evolution and the fact that small clouds had not yet merged into large structures would have the opposite effect. Regardless of the relative numbers, it is likely that at a sufficiently high redshift, Lyman limit systems would be detected as weak Mg II absorbers. Thus, objects physically associated with weak Mg II absorbers at high redshift may be completely different from those at $z \sim 1$ and may be associated with bright galaxies.

How would the weak Mg II absorbers at $z \sim 1$ have evolved to the modern epoch? Under the less intense metagalactic flux of $z = 0$, detectable Mg II absorption can arise in clouds with less neutral and total hydrogen than at $z \sim 1$. This would make weak Mg II absorbers more common at the present day since they would extend further down into the Ly$\alpha$ forest. However, cosmological expansion and destruction through mergers should have the opposite effect. Such low-ionization clouds should also have higher Fe II then at $z \sim 1$ since there should have been more time for Type Ia SNe to occur. This may not be true for absorbers with recently formed dwarf galaxy hosts.

6.2. Future Investigations

Additional studies at $z \sim 1$ can test some of the inferences of this paper and further constrain the properties of weak Mg II absorbers. Here we briefly discuss four promising avenues: spectroscopy of Mg II absorbers in multiply lensed QSOs, Space Telescope Imaging Spectrograph (STIS) UV spectroscopy, searches for C IV without Mg II, and narrowband imaging.

1. The critical inference that high Fe II clouds have sizes $\sim 10$ pc can be tested by finding weak Mg II systems in the spectra of multiply lensed quasars. The best constraint on absorber sizes thus far was derived from a $z = 3.6$ absorption system in Q1422$+$231, which, because of lensing, is probed by two lines of sight separated by $13 h^{-1}$ pc (Rauch, Sargent, & Barlow 1999). This sub-Lyman limit system has complex absorption spread over 400 km s$^{-1}$, observed in both low- and high-ionization transitions. In the low-ionization transitions (C II $\lambda 1334$ and Si II $\lambda 1260$), column densities vary by a factor of up to 10 between the two lines of sight. In particular, the reddest component was detected in only one of the two sight lines. The inferred density, gas mass, and metallicity of this component are consistent with the inferred values for high Fe II weak Mg II clouds. Based on CLOUDY models, this component would have detectable weak Mg II absorption and $N$(Fe II) $\sim N$(Mg II).

Size constraints have also been determined directly for Mg II absorbers, although at larger spatial scales. Eight weak Mg II absorbers have been observed in the $z = 3.911$ QSO APM 08279$+5255$ in a very high S/N spectrum that combined light from multiple images. (The two brightest images are separated by 0.35.) For three systems at $z = 1.211$, 1.811, and 2.041, Mg II $\lambda 2796$ and $\lambda 2803$ cannot be fitted simultaneously with Voigt profiles, which implies that, because of partial covering of the images, the column densities are significantly different along the two major lines of sight, with separations ranging from 0.5 to 1.5 $h^{-1}$ kpc (Ellison et al. 1999).

2. With low-resolution UV spectra, the properties of the higher ionization phase cannot be well constrained. High-resolution spectra with STIS/HST will soon be available for some of the quasars in this sample. This new data should reveal whether the C IV resolves into multiple components at $R = 30,000$ ($10$ km s$^{-1}$) and whether the high-ionization phase is offset in velocity from the low-ionization phase. If the low-ionization phase is due to ejecta in a larger halo, we might often see a velocity offset of tens of kilometers per second. For the systems for which C IV was not detected with FOS, we can determine whether the high-ionization phase is truly absent. With additional transitions, ionization conditions in the higher ionization phase can also be determined.

3. Sensitive searches for C IV at $z \sim 1$, especially C IV with no corresponding Mg II absorption, would constrain the relative sizes of the C IV and Mg II phases, given the picture that narrow weak Mg II absorption arises in a condensation surrounded by a broader higher ionization phase.

4. It would be very time-consuming to search for galaxy groups at the redshifts of known Mg II absorbers via wide-field imaging and spectroscopy. Narrowband imaging is more feasible (Yanny & York 1992), although small, low-luminosity galaxies directly in front of the QSO would still be missed.

Low-redshift investigations may also be relevant. Weak Mg II absorbers at low redshift should be detected serendipitously in STIS/HST QSO spectra. Because of the small redshift path length for detection of Mg II absorption, few detections are expected. Nevertheless, such detections would help to constrain the evolution of $dN/dz$, and at low redshift, searching for associated luminous structures may be more feasible. Also, deep 21 cm mapping and absorption studies should shed light on how high-velocity and other Lyman limit clouds are distributed around nearby galaxies.
and within nearby groups, further probing the nature of faint, low column density structures in the universe.

7. CONCLUSION

The basic properties of the single-cloud weak Mg II absorbers were outlined in § 4. We conclude the paper by summarizing our discussion of the nature of these absorbers and their relationship to other classes of absorbers and objects.

1. Single-cloud weak Mg II absorbers are of high metallicity (Z \geq -1), and they comprise a large fraction of the log N(H I) \sim 16 \text{ cm}^{-2} \text{ Lyz} forest (see § 5.1).

2. The physical properties of the single-cloud weak Mg II absorbers are similar to those of kinematic outlier clouds in strong Mg II systems. However, most weak absorbers are not observed within \approx 50 h^{-1} \text{ kpc} of L* galaxies. Cross section arguments, outlined in § 5.3, indicate that the single-cloud weak Mg II absorbers and the kinematic outlier clouds in strong Mg II systems cannot be one and the same population of objects (viewed from different orientations). They can, however, have a related process of origin.

3. Three single-cloud weak Mg II absorbers are constrained by their relatively large Fe II column densities to have small physical sizes, less than 10 pc. Their observed dN/dz, compared to that for strong Mg II absorbers, indicates that, if that small, they should outnumber L* galaxies by more than a factor of a million (see § 5.2). These iron-rich single-cloud weak Mg II absorbers do not correspond to any known population of object in the local universe. As we discuss in § 5.4.1, their Fe-to-Mg ratio requires in situ enrichment by Type Ia supernovae. Their sizes and velocity dispersions suggest an origin in star clusters (the elusive Population III?) or in shell fragments from the supernovae. The number of iron-rich Mg II absorbers required is large even compared to the number of low-mass dark matter halos (“failed galaxies”) predicted by dark matter simulations.

4. The physical properties (particularly the sizes) are not as well constrained for the larger subset of single-cloud weak Mg II absorbers without detected Fe II (see § 5.4.2). Unlike the iron-rich population, these could be z-group–enhanced, although their lack of association with bright galaxies requires energetic ejection or an origin in dwarfs. The low-ion subclass could represent lines of sight through sub–Lyman limit regions of high-velocity clouds in galaxy groups. Alternatively, these low-ion single-cloud weak Mg II absorbers could arise in fragments of Type II supernovae or in relatively high-ionization fragments from Type Ia supernovae.

The precise nature of the objects that host single-cloud weak Mg II absorbers is not known. Generally, they select high-metallicity pockets of material in intragroup and/or intergalactic space. The phase structure apparent in many of them suggests condensations within larger potential wells, such as dwarfs, but the large number of absorbers is surprising. Understanding the processes of origin of these mysterious weak Mg II absorbers is likely to teach us about a common, but heretofore unknown, metal-enriched class of object.

Support for this work was provided by the NSF (AST 96-17185) and by NASA (NAG 5-6399). J. R. R. was supported by an NSF REU supplement. We thank Gary Ferland for making CLOUDY available to the astronomical community. We are grateful to more colleagues than we can acknowledge here for stimulating discussions during the course of this work, and we give special thanks to Alan Dressler, Mike Fall, Jim Peebles, Blair Savage, Ken Sembach, Stein Sigurdsson, and Todd Tripp.

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