HIGH-RESOLUTION STIS/HUBBLE SPACE TELESCOPE AND HIRES/KECK SPECTRA OF THREE WEAK Mg ii ABSORBERS TOWARD PG 1634+706

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ABSTRACT

High-resolution optical (HIRES/Keck) and UV (STIS/Hubble Space Telescope) spectra, covering a large range of chemical transitions, are analyzed for three single-cloud weak Mg ii absorption systems along the line of sight toward the quasar PG 1634+706. Weak Mg ii absorption lines in quasar spectra trace metal-enriched environments that are rarely closely associated with the most luminous galaxies (>0.05L*). The two weak Mg ii systems at z = 0.81 and 0.90 are constrained to have at least solar metallicity, while the metallicity of the z = 0.65 system is not as well constrained, but is consistent with more than 1/10 solar. These weak Mg ii clouds are likely to be local pockets of high metallicity in a lower metallicity environment. All three systems have two phases of gas, a higher density region that produces narrower absorption lines for low-ionization transitions, such as Mg ii, and a lower density region that produces broader absorption lines for high-ionization transitions, such as C iv. The C iv profile for one system (at z = 0.81) can be fitted with a single broad component (b ~ 10 km s^{-1}), but those for the other two systems require one or two additional offset high-ionization clouds. Two possible physical pictures for the phase structure are discussed: one with a low-ionization, denser phase embedded in a lower density surrounding medium and the other with the denser clumps surrounding more highly ionized gas.

Subject headings: galaxies: evolution — galaxies: halos — quasars: absorption lines

1 INTRODUCTION

Weak Mg ii absorbers, those with W_r(2796) < 0.3 Å, constitute 65% of the total Mg ii absorber population (Churchill et al. 1999) at z ~ 1. They account for a fair fraction of the N(H i) ~ 10^{16} cm^{-2} Lyman forest (Rigby, Charlton, & Churchill 2002). Unlike strong Mg ii absorbers (which almost always are associated with a greater than 0.05L* galaxy; Bergeron & Boisse 1991; Steidel, Dickinson, & Persson 1994; Steidel 1995), weak Mg ii absorbers can usually not be associated with a greater than 0.05L* galaxy within impact parameter ~50 h^{-1} kpc of the QSO (Rigby et al. 2002; C. Steidel 2002, private communication). This lack of an association with bright galaxies suggests that weak Mg ii absorbers may be a physically different population from strong Mg ii absorbers.

Studying the physical conditions of weak Mg ii absorbers (e.g., metallicity, ionization conditions, total column density, and size) is useful for two reasons. (1) Physical conditions provide clues as to the nature of these absorbers, whose physical origin is not known. (2) Weak Mg ii clouds provide an opportunity to study metal-enriched environments over a range of redshifts. They trace metal production in either intergalactic space or dwarf or low surface brightness galaxies.

A study of weak Mg ii absorbers at z ~ 1 requires spectra in both the optical and the UV, in order that the several key low- and high-ionization transitions (especially Mg ii, Fe ii, and C iv), as well as the Lyman series, are covered. Using the Keck/High-Resolution Echelle Spectrograph (HIRES; Vogt et al. 1994) at high resolution (R = 45,000) and the Faint Object Spectrograph (FOS)/Hubble Space Telescope (HST) at low resolution (R = 1300), Rigby et al. (2002) applied photoionization models to 15 single-cloud weak Mg ii absorbers. They argued that many multiple-cloud weak absorbers (which comprise 35% of the weak absorbers) are likely to be part of the same population as the strong absorbers, but that single-cloud weak systems are likely to be a different population.

At least half of the weak, single-cloud systems of Rigby et al. (2002) require a second phase of gas in order to reproduce the C iv absorption and/or to fit the Lyα profile without exceeding the H i column density derived from the Lyman limit break. While the Mg ii clouds typically have Doppler parameters of 2–6 km s^{-1}, the second phase must have a larger effective Doppler parameter (~10–30 km s^{-1}). With only the low-resolution UV data available to Rigby et al. (2002), it was not clear if this implies a single broad component or multiple, blended clouds. Also, in the systems for which the second phase is not required (such as when only a limit for C iv can be derived), it was not clear if the phase is just less extreme in its properties or if it is absent.
By comparing the Mg ii column densities to the Lyα profiles, Rigby et al. (2002) inferred that weak, single-cloud Mg ii absorbers have metallicities of at least 1/10 solar in the phase of gas in which the Mg ii absorption arises. The sizes and densities of most of the weak, single-cloud systems were unconstrained; however, three of them had $N$(Mg ii) $\sim N$(Fe ii), which implies low ionization conditions, relatively high densities, $n_{\text{HI}} = 0.1 \text{ cm}^{-3}$, and small sizes, $\sim 10 \text{ pc}$. Those systems with limits on Fe ii may be part of a “continuum” of single-cloud weak Mg ii absorbers, with some having Fe ii just below the detection threshold, implying a continuous distribution of ionization conditions. Alternatively, some of the systems without detected Fe ii could be part of a different population, with ionization conditions, metallicities, and/or environments distinctly different from systems with detected Fe ii.

In 2000 May and June, high-resolution UV spectra ($R = 30,000$) of the $z = 1.335$ quasar PG 1634+706 became public in the $HST$ archive. We have high-resolution optical (HIRES/Keck) spectra of this same quasar. For the first time, weak Mg ii absorbers can be studied through simultaneous high-resolution coverage of numerous transitions. This allows more direct inferences of the physical properties of the gas, such as metallicity and phase structure. In particular, it should enable a determination of the nature of the second, broad phase required for some absorbers by the large relative strength of C iv absorption in lower resolution data. Is this higher ionization, broad phase centered on the Mg ii cloud, or is it offset? Is it produced by multiple clouds or by a single, smooth structure? Are systems for which C iv was not detected at low resolution fundamentally different, or do they merely have a weaker second phase? The kinematics and physical properties of the second phase and its relationship to the Mg ii cloud phase are important diagnostics of the type of structure responsible for the weak Mg ii absorption.

In anticipation of the release of the high-resolution STIS/$HST$ spectra, we previously pursued an in-depth study of four Mg ii absorbers along the PG 1634+706 line of sight (Charlton et al. 2000), using the available low-resolution FOS/$HST$ spectra and the HIRES/Keck spectra. Since only the brightest quasars can, in the near future, feasibly be studied at high resolution in the UV, we aimed to compare inferences drawn on the basis of low-resolution spectra to those that would be obtained once the higher resolution spectra were released. Confirmation of our conclusions would lend credibility to larger statistical studies that rely on a combination of high- and low-resolution spectra (Rigby et al. 2002; Churchill et al. 2000b).

The present paper focuses on three single-cloud weak Mg ii absorbers along the PG 1634+706 line of sight. Two of these absorbers, at $z = 0.8182$ and 0.9056, were detected in the HIRES/Keck spectra at the sensitivity of our original weak Mg ii survey (5 $\sigma$ for Mg ii $\lambda 2796$; Churchill et al. 1999). These two systems are dramatically different from each other in that the $z = 0.8182$ system has a stringent limit on C iv $[W'_c(1548) < 0.07 \text{ A at } 3 \sigma]$, while the $z = 0.9056$ absorber has C iv detected at $W'_c(1548) = 0.18 \text{ A}$. In the latter system, the C iv arises not in the Mg ii cloud phase, but in a second phase of gas. This provides an excellent opportunity to both study a system with very weak C iv and address the nature of the second phase. The metallicity could not be derived for the $z = 0.8182$ system because the FOS/$HST$ spectrum did not cover any of the Lyman transitions; however, the new STIS/$HST$ spectra can address metallicity for this system. Models of the $z = 0.9056$ absorber did, however, imply a supersolar metallicity and/or a depleted or $\alpha$-enhanced abundance pattern. This conclusion is reassessed in this paper. Also, as we describe in § 2, we have now identified a third single-cloud weak Mg ii system at $z = 0.6534$ that was just below the detection threshold of our previous study. That system was not modeled in Charlton et al. (2000), but is considered in the present paper.

We begin in § 2 by presenting, for the three single-cloud weak Mg ii systems toward PG 1634+706, high-resolution profiles of all relevant transitions covered by STIS/$HST$ or HIRES/Keck spectra. In § 3, we discuss our strategy to infer the physical conditions of these systems by applying CLOUDY photoionization models. We also consider the possibility that collisional ionization dominates. The results inferred for the phase structure, ionization parameters/densities, metallicities, kinematics, and abundance patterns of the three systems are presented in § 4. In § 5, the effect of relaxing assumptions of abundance pattern and the shape of the ionizing spectrum are considered. The three weak Mg ii systems are compared in § 6. In that discussion, we particularly focus on the nature of the second phase and compare the results to those obtained on the basis of just the lower resolution FOS/$HST$ spectrum. Finally, we summarize our conclusions in § 7.

2. OBSERVATIONS OF THE THREE WEAK Mg ii ABSORBERS TOWARD PG 1634+706

We briefly describe the observations with HIRES/Keck, STIS/$HST$, and FOS/$HST$ of PG 1634+706 and then present the three single-cloud weak Mg ii absorbers along this line of sight at $z = 0.8181$, 0.9056, and 0.6534. A WFC2/$HST$ image of the quasar field exists (program 6740, S. Oliver, PI), but the quasar is quite bright, so it is not possible to perform adequate point-spread function (PSF) subtraction in order to detect galaxies close to the line of sight. Also, without redshifts of candidate galaxies in the field, we could not separate out the identities of the three weak and two strong Mg ii absorbers.

2.1. HIRES/Keck

The HIRES/Keck observations covered 3723–6186 Å at $R = 45,000$ (FWHM $\sim 6.6 \text{ km s}^{-1}$; 3 pixels per resolution element). Mg ii, Mg i, and Fe ii transitions are covered for the three systems, but in all cases only Mg ii is detected (at $\gtrsim 3 \sigma$). Equivalent widths and limits are listed in Table 1. The spectra were obtained on 1995 July 4 and 5, and the combined spectrum has a signal-to-noise ratio (S/N) of $\sim 50$ over most of the wavelength range that gradually falls toward the lowest wavelengths. The most stringent limits on Fe ii come from the reddest of the Fe ii transitions, at 2600 Å. The reduction of the spectrum, continuum fits, line identification, and procedure for Voigt profile fitting were described in Churchill & Vogt (2001).

2.2. STIS/$HST$

The STIS/$HST$ observations provided useful coverage from 1880 to 3118 Å at $R = 30,000$ (FWHM $\sim 10 \text{ km s}^{-1}$; 2 pixels per resolution element). Two sets of echelle spectra were obtained with two different tilts of the E230M grating,
using the $0.2 \times 0.2$ slit. The first, with a central wavelength of 2269 Å, was obtained by Burles et al. in 1999 May and June (proposal ID 7292). The total exposure time was 29,000 s. The second, with central wavelength 2707 Å, was obtained by Jannuzi et al. in 1999 June (proposal ID 8312), with a total exposure time 26,425 s. The two spectra overlap in the region 2275–2708 Å. We co-added the spectra, weighted by the exposure times, and also combined multiple-order coverage in the same spectrum. However, we also considered the differences between the two realizations as an indication of systematic errors (due to continuum fitting, correlated noise, and unknown factors) when comparing model profiles to the data. Reductions were done with the standard STIS pipeline and continuum fits using the "sft" task in IRAF.\footnote{IRAF is distributed by the National Optical Astronomy Observatory, which is operated by AURA, Inc., under contract to the NSF.}

2.3. The Three Weak Single-Cloud Mg II Systems

Based on our original analysis of the HIRES/Keck spectrum, there were two single-cloud weak Mg II systems along the PG 1634+706 line of sight, at $z = 0.8181$ and 0.9056. After analyzing the STIS/HST spectra, another, slightly weaker Mg II system was found in the HIRES/Keck spectra, just below the threshold of our previous survey (Churchill et al. 1999). First, the STIS spectra were searched for C IV doublets. Only one C IV doublet was found with equivalent width comparable to those associated with the two known Mg II absorption systems. The new system, at $z = 0.6534$, also had detected Ly$\alpha$, a Si IV doublet, C IV, and Si IV in the STIS spectrum. Based on the equivalent width of Si IV we expected that Mg II should be detected in the HIRES/Keck spectrum. We then searched that location in the HIRES spectrum and found the Mg II doublet. The $\lambda 2796$ transition was detected at the 6.8 $\sigma$ level and the $\lambda 2803$ transition at the 2.9 $\sigma$ level. (Our previous survey had a 3 $\sigma$ detection threshold for the $\lambda 2803$ transition.)

Figure 1 presents detected transitions and limits of interest in constraining the conditions in the $z = 0.8181$ system. Figure 2 displays the same for the $z = 0.9056$ system and Figure 3 for the $z = 0.6534$ system. Table 1 lists the equivalent widths for detected transitions and selected equivalent width limits (3 $\sigma$) for the three systems. We fitted each transition with the minimum number of Voigt profile components consistent with the errors (Churchill 1997; Churchill, Vogt, & Charlton 2003). In all three systems, the Mg II and the other low- and intermediate-ionization transitions could be fitted with one component. However, the C IV profiles required two components for the $z = 0.9056$ system and three for the $z = 0.6534$ system. For selected transitions, column densities and Doppler parameters of the Voigt profile fits, performed separately for each transition, are given in Table 2. For the $z = 0.6534$ system, numbers are estimated only for Mg II and C IV because fits are ambiguous as a result of blending.

There is no flux detected from PG 1634+706 shortward of a Lyman limit break at $\sim 1830$ Å, which is due to a strong Mg II absorber at $z = 0.9902$ (Charlton et al. 2000; Ding et al. 2003a). Also, a partial Lyman limit break at $\sim 1890$ Å reduces the flux to about 30% of the original continuum level because of a multiple-cloud weak Mg II absorber at $z = 1.0414$ (Charlton et al. 2000; Zonak et al. 2002).

Although O VI for the $z = 0.8181$ system is covered in an

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### TABLE 1

| Transition | $z = 0.8181$ | $z = 0.9056$ | $z = 0.6534$ |
|------------|-------------|-------------|-------------|
| Ly$\alpha$ | 0.220 ± 0.010 | 0.349 ± 0.008 | 0.665 ± 0.022 |
| Ly$\beta$  | 0.160 ± 0.010 | 0.206 ± 0.022 | -           |
| Mg II $\lambda 2853$ | <0.004 | <0.002 | <0.010 |
| Mg II $\lambda 2796$ | 0.030 ± 0.005 | 0.034 ± 0.002 | 0.031 ± 0.006 |
| Mg II $\lambda 2803$ | 0.018 ± 0.006 | 0.024 ± 0.003 | 0.007 ± 0.003 |
| Fe II $\lambda 2600$ | <0.008 | <0.003 | <0.022 |
| Si II $\lambda 1813$ | ... | 0.015 ± 0.005 | <0.028 |
| Si II $\lambda 1600$ | 0.020 ± 0.004 | <0.061 | 0.021 ± 0.007 |
| C II $\lambda 1335$ | 0.017 ± 0.002 | 0.31 ± 0.01 | 0.045 ± 0.005 |
| N II $\lambda 1084$ | <0.028 | 0.063 ± 0.016 | ... |
| Si II $\lambda 1207$ | 0.045 ± 0.007 | 0.952 ± 0.006 | ... |
| Si IV $\lambda 1394$ | 0.019 ± 0.003 | ... | 0.123 ± 0.006 |
| Si IV $\lambda 1403$ | 0.019 ± 0.003 | 0.026 ± 0.003 | 0.071 ± 0.006 |
| N IV $\lambda 1089$ | ... | 0.084 ± 0.018 | ... |
| C IV $\lambda 1548$ | 0.079 ± 0.003 | 0.196 ± 0.007 | 0.355 ± 0.025 |
| C IV $\lambda 1551$ | 0.060 ± 0.003 | 0.154 ± 0.004 | 0.305 ± 0.008 |
| N V $\lambda 1239$ | <0.004 | 0.061 ± 0.004 | 0.048 ± 0.014 |
| N V $\lambda 1243$ | ... | 0.027 ± 0.006 | <0.054 |
| O VI $\lambda 1032$ | <0.076 | ... | ... |

Note.—Limits are at a 3 $\sigma$ level. A blank entry indicates that the transition was not covered, or that it was so severely blended with a stronger transition that the limit is not useful.

### TABLE 2

| Transition | $z = 0.8181$ System | $z = 0.9056$ System | $z = 0.6534$ System |
|------------|---------------------|---------------------|---------------------|
| Mg II ............ | 12.04 ± 0.03 | 2.1 ± 0.4 | 0 |
| C IV ............. | 13.55 ± 0.05 | 6.6 ± 1.8 | 0 |
| Si II ............ | 12.42 ± 0.10 | 6.5 ± 3.0 | 0 |
| Si IV ............ | 12.47 ± 0.07 | 12.9 ± 2.7 | 0 |
| C IV ............. | 13.53 ± 0.02 | 10.4 ± 0.5 | 0 |

Note.—Velocities are offsets from the Mg II cloud. For the resonant doublet transitions, the Voigt profile fits were generally constrained by both members; however, Si IV for the $z = 0.9056$ system was measured from just the 1403 Å transition. Unique Voigt profile fits could not be obtained for the $z = 0.6534$ system because of blending. The three-cloud fit given for C IV provides an adequate fit to the doublet, assuming that one component is centered on the Mg II cloud.
3. MODEL TECHNIQUES

Several descriptions of the basic technique used for modeling were given in previous papers (Churchill & Charlton 1999; Charlton et al. 2000; Rigby et al. 2002). For those efforts, only Mg II, Mg I, and Fe II were covered at high resolution, and all other transitions were observed with FOS/HST only at $R = 1300$. Even with the availability of numerous transitions at high resolution, the modeling technique used in the present paper is very similar to those previous efforts. We begin with the phase of gas that produces the dominant Mg II absorption, the “low-ionization” phase. Then we add in other phases of gas as needed to reproduce the observed absorption profiles for all transitions.

For each single-cloud Mg II absorber we begin with the column density, $N$(Mg II), and the Doppler parameter, $b$(Mg II), derived from a Voigt profile fit to the Mg II doublet. CLOUDY photoionization models (ver. 94.00; Ferland 1996) were applied to determine column densities of the various transitions that would result from the same phase of gas that produces this Mg II, assuming a slab geometry. The parameters for these models are the metallicity $Z$ (expressed in units of the solar value), the abundance pattern (initially assumed to be solar), and the ionization parameter, $\log U$. The ionization parameter is defined as the ratio of ionizing photons to the number density of hydrogen in the absorbing gas, $n_H$. We assume that the ionizing spectrum is of the form specified by Haardt & Madau (1996) for $z = 1$. The normalization of the Haardt-Madau background at $z = 1$ is fixed so that $\log n_H = -5.2 - \log U$. The assumption that stellar sources do not make a substantial contribution is likely to be valid, since weak Mg II absorbers typically do not have a nearby high-luminosity galaxy, such as a starburst. The effects of alternative spectral shapes are discussed in § 5.2.

Fig. 1.—Detected transitions and constraining limits presented in velocity space for the weak, single-cloud Mg II system with velocity centroid at $z = 0.818157$. The data are at $R = 45,000$ from HIRES/Keck for the Mg II, Mg I, and Fe II transitions. All other transitions are taken from the STIS/HST spectra, at resolution $R = 30,000$. The sigma spectrum is indicated as a solid curve just above the dotted line crossing each plot at zero flux. Some transitions that were covered in the spectrum are not displayed because of severe blending with stronger transitions. The position of the lower row of ticks, displayed above all of the transitions (at zero velocity), was determined based on a simultaneous Voigt profile fit to the Mg II doublet. The upper row of ticks shows velocities of the additional components that were required to fit C IV. An example of a model (summarized in Table 4) that provided an adequate fit to the data is superposed on the data as a solid curve. The dotted and dashed curves represent model contributions of the low- (Mg II) and high- (C IV) ionization phases, respectively.

$R = 10, 300$ STIS G230M spectrum of PG 1634+706, this reduced flux and crowding with Lyman series lines from the $z = 0.9902$ system prevent us from deriving a useful constraint. We therefore have not used the G230M spectrum as a constraint in the analysis.
The Doppler parameters of other elements are derived from $b(Mg \, \text{H})$, using the temperature output from CLOUDY to derive the thermal and turbulent contributions for each element. For each choice of parameters, the CLOUDY output column densities and Doppler parameters are used to synthesize noiseless spectra, convolving with the instrumental profile characteristic of STIS/E230M. The synthetic model spectra are compared with the observed profiles to identify permitted regions of the parameter space. The model column densities and Doppler parameters for permitted models are within 1 $\sigma$ of the values measured from the data.

From the three systems studied in this paper, Fe $\, \text{H} \lambda 2600$ is covered but not detected. For $\log U > -4.0$, the ratio $N(Mg \, \text{H})/N(Fe \, \text{H})$ is strongly dependent on the ionization parameter in the optically thin regime (see Rigby et al. 2002), and the Fe $\, \text{H}$ limit can be used to place a lower limit on $\log U$ of the low-ionization phase. To obtain an upper limit on the ionization parameter of this phase, Si $\, \text{IV}$ and C $\, \text{IV}$ provide constraints. For optically thin gas, the

![Fig. 2. Velocity-aligned plot for the system at $z = 0.905554$, displayed as in Fig. 1](image-url)
constraints on log $U$ do not depend significantly on the metallicity. The metallicity is constrained by fitting the Ly$\alpha$ and any higher Lyman series lines that are covered for the system. Low metallicities will overproduce the Ly$\alpha$ in the wings. High metallicities will underproduce the Ly$\alpha$ but cannot be excluded, since the additional H i absorption can arise in a different phase. We assumed a solar abundance pattern, but note that there is a simple trade-off between metallicity and the abundance of the metal-line transition that is compared to the hydrogen, discussed further in $\S$ 5.1.

In general, once the basic constraints on log $U$ are derived, we consider whether a single-cloud model can fully reproduce profiles of all of the observed transitions. In all three of the systems modeled in this paper, we conclude that the C iv absorption cannot be fully produced in the same phase as the Mg ii absorption. For the range of permitted values of log $U$ for the low-ionization phase, we constrain the properties of the high-ionization phase that is required to fit the C iv profile. First, we consider whether a single, relatively broad component is sufficient. If the C iv profile is asymmetric (as in the $z = 0.6534$ system), then it is clear that more than one component is needed. A Voigt profile fit to the C iv serves as a starting point for deriving the number of clouds needed in the high-ionization phase, their $N(\text{C iv})$ and their $b(\text{C iv})$. Results from these fits are listed in Table 2. The $b(\text{C iv})$ of these C iv clouds is larger than that of the Mg ii clouds. CLOUDY models of this additional phase are constrained to match the observed C iv clouds, and log $U$ is adjusted to determine what range of values is consistent with other transitions. An upper limit is set so that N v (if covered) are not overproduced. A lower limit is set so that the broader components do not produce observable Mg ii and Si ii. In some cases, the intermediate-ionization transitions, such as Si iii, C ii, and especially Si iv, could not be fully produced in the Mg ii cloud phase. In these cases, an intermediate value of log $U$ is sought for the C iv clouds in order to also account for the remainder of these transitions without overproducing the lower ionization transitions. A lower limit on the metallicity of a C iv cloud can be derived in order that Ly$\alpha$ absorption is not overproduced. More exactly, it is the combination of the Mg ii and C iv clouds.

Fig. 3.—Velocity-aligned plot for the system at $z = 0.653411$, displayed as in Fig. 1
that is constrained not to overproduce Lyα absorption, so there is a trade-off between their metallicity constraints. If all transitions of a certain element (such as Si ii, Si iii, and Si iv) are underproduced relative to other elements, then simple abundance pattern variations (α-enhancement and depletion) are considered.

For the high-ionization phase, we consider collisional ionization models as alternatives to CLOUDY photoionization solutions. In this case, an alternative source of heating (e.g., shocks) must be responsible for heating the gas to the assumed higher \( T \). The measured Doppler parameter of the C iv, \( b(C \ iv) \), is used to place an upper limit on the temperature, \( T < b(C \ iv)^2 m(C \ iv)/2k \). For an assumed \( T \) and \( Z \), and with the measured \( N(C \ iv) \), the collisional equilibrium tables of Sutherland & Dopita (1993) were used to determine the column densities of all other covered transitions. The Doppler parameters of these other transitions, \( b_{tr} \), were calculated from \( b_{tr}^2 = 2kT/m_{tr} + b^2_{turb} \), where the turbulent component of the Doppler parameter is given by \( b^2_{turb} = b(C \ iv)^2 - 2kT/m(C \ iv) \). In order to constrain \( T \), synthetic spectra were generated and superposed on the data to facilitate comparison. Also, the model column densities of the various transitions were compared to the measured values.

The Lyα profiles provided a constraint on the metallicity of any collisionally ionized phase. “Wings” on these profiles can be produced by such a phase, which would be characterized by a relatively large \( b \)-parameter. The contribution of a collisionally ionized phase to Lyα is minimized at low \( T \) and high metallicity. A lower limit on \( T \) is therefore set so as not to overproduce Lyα at the highest reasonable metallicity (usually taken to be solar). As for photoionization models, for the high-ionization phase, the lower limit on the metallicity depends on the metallicity of the low-ionization phases, which determines its contribution to Lyα.

| \( z_{abs} \) | \( v \) (km s\(^{-1}\)) | \( \log U \) | \( Z \) (\( Z_\odot \)) | \( b \) (km s\(^{-1}\)) | \( N(H) \) (cm\(^{-2}\)) |
|----------------|----------------|----------------|----------------|----------------------------------------------------------------------|
| 0.8182 .......... | 0              | -6.0 to -4.0   | \( \geq 2 \)   | 10\(^{-6}\) to 10\(^{-4}\) | 2                  | 15.6–15.9              |
| 0.9056 .......... | 0              | -2.2 to -1.8   | \( \geq 1 \)   | 0.05–0.15              | 10                 | 14.4–15.4              |
| 0.6534 .......... | 0              | -3.0 to -2.7   | \( \geq 1 \)   | 0.03–0.1               | 3                  | 15.7                  |
|                 | 0              | -1.8 to -1.5   | \( \geq 1 \)   | 0.4–1                 | 6                  | 14.1–14.4             |
|                 | 15             | -1.9 to -1.8   | \( \geq 1 \)   | 0.4–0.5               | 14                 | 14.4–14.5             |
|                 | 0              | -4.0 to -3.0   | 0.03–1        | 0.0002–1              | 15.1–16.7           |
|                 | 0              | -2.5 to -2.4   | 0.1–1        | 2–4                   | 14.9–16.2           |
|                 | 24             | -2.2 to -2.1   | 0.1–1        | 2–4                   | 14.4–16.2           |
|                 | 54             | -2.2 to -2.0   | 0.1–1        | 2–4                   | 15.0–16.5           |

Note.—This table is intended to be a concise summary of results for the three systems. The models that it presents are consistent with the HIRES/Keck and STIS/HST data; they are indicative but not unique. Abundance patterns were assumed to be solar, but this is not a unique solution, i.e., a different abundance pattern is possible for different choices of the other parameters. Doppler parameters are listed for Mg ii in the case of the low-ionization Mg ii cloud components (first entry for each system) and for C iv for all other components.

4. MODEL RESULTS

First, we describe the model results for the two weak single-cloud Mg ii absorbers detected in the original HIRES/Keck survey (Churchill et al. 1999). Then the results for the newly discovered \( z = 0.6534 \) system are presented. A range of parameters for satisfactory models is summarized in Table 3. Model profiles for an example of an acceptable model are superposed on the data for each of the three systems in Figures 1–3. Parameters for these sample models are listed in Table 4. Results in this section use the simplest set of assumptions that produces models consistent with the data, i.e., a Haardt-Madau spectrum and a solar abundance pattern. The effects of alternate spectra and abundance patterns are discussed in § 5.

4.1. The \( z = 0.8181 \) System

Figure 1 shows detections of Lyα, Mg ii, Si ii, C ii, Si iii, Si iv, and C iv. There are useful limits for Fe ii and N v. An obvious, but important, first result is that C iv is now clearly detected in this system, despite the strong limit from the earlier low-resolution data.

We begin with the Voigt profile fit to the Mg ii doublet and adjust the ionization parameter to fit as many of the other transitions as possible. We find that the Mg ii cloud is constrained to have \( \log U \approx -4.0 \). There is no strict lower limit, because the \( N(Mg \ ii)/N(Fe \ ii) \) versus \( \log U \) curve is flat for \( \log U < -4.0 \). Very small values of \( \log U \) (as low as \( \log U \sim -6.0 \)) are permitted, but cloud sizes would be extremely small. For \( \log U < -6.0 \), C ii is underproduced. To find an upper limit on the ionization parameter, we first determined that for \( \log U = -2.5 \), the model would produce minimum fluxes at the positions of Si iv and C iv that are consistent with the observed profiles. However, the model \( b(Si \ iv) \) and \( b(C \ iv) \) are small compared to the observed values; i.e., the model profiles are narrow compared to the observed profiles. We therefore conclude that the Si iv and C iv are produced in a separate, higher ionization phase and that \( \log U \lesssim -4.0 \) for the Mg ii cloud phase. The contribution of the Mg ii cloud phase to the absorption profiles (negligible for all but the singly ionized transitions) is denoted by a dotted line in Figure 1.

The metallicity of the cloud with detected Mg ii is constrained to be \( \sim 0.3 \) dex greater than solar (for a solar abundance pattern). For lower metallicities, absorption in the wings of the Lyα profile will exceed that observed. Also, unless the metallicity is even higher for the Mg ii cloud, the additional high-ionization phase (required to fit C iv) is constrained not to give rise to significant Lyα absorption. For
TABLE 4

CLOUD PROPERTIES FOR SAMPLE MODELS

| Cloud   | v (km s⁻¹) | Z (Z⊙) | log U | n_H (cm⁻³) | Size (pc) | T (K) | N(Hi) (cm⁻²) | N(H) (cm⁻²) | N(Mg ii) (cm⁻²) | N(Si iv) (cm⁻²) | N(C iv) (cm⁻²) | b(H) (km s⁻¹) | b(Mg) (km s⁻¹) | b(C) (km s⁻¹) |
|---------|------------|--------|-------|------------|-----------|-------|--------------|-------------|-----------------|----------------|---------------|---------------|---------------|---------------|
| Mg ii   | 0          | 2.0    | −4.0  | 0.06       | 0.1       | 4600  | 16.3         | 15.3        | 12.0            | 9.7            | 9.4           | 9             | 2             | 3             |
| C iv 1  | 0          | 2.0    | −2.0  | 0.0006     | 80        | 8000  | 17.2         | 14.1        | 10.7            | 12.3           | 13.5          | 15            | 10            | 10            |
| Mg ii   | 0          | 0.0    | −2.7  | 0.003      | 150       | 9000  | 18.1         | 15.8        | 12.5            | 13.1           | 13.6          | 12            | 3             | 4             |
| C iv 1  | 0          | 0.0    | −1.5  | 0.0002     | 1500      | 14000 | 18.0         | 14.2        | 9.1             | 11.4           | 14.0          | 17            | 4             | 6             |
| C iv 2  | 15         | 0.0    | −1.8  | 0.0004     | 600       | 14000 | 17.9         | 14.4        | 10.2            | 12.2           | 14.0          | 20            | 14            | 14            |

Note. — Column densities are listed in logarithmic units.
log $U = -4.0$ and log $Z = 0.3$, the cloud size would be $\sim 0.1$ pc. For log $U = -6.0$ and log $Z = 0.3$, the cloud size would be only $\sim 150$ AU, and the observed C iv profile would be somewhat underproduced by the model.

Primarily because of the breadth of the C iv profiles, we concluded that a second phase is required to fit the C iv, even in this system, for which the C iv absorption is relatively weak. A Voigt profile fit to the C iv profile yields an adequate fit for a single cloud with $b(C\text{ iv}) \sim 10$ km s$^{-1}$ that is centered on the Mg ii cloud. Details of the fit are listed in Table 2. We consider whether the C iv can be produced by photoionization, by collisional ionization in gas that has been heated above the equilibrium value, or by both.

For photoionization models of the high-ionization phase, we optimized on the C iv Voigt profile fit values, and the ionization parameter was constrained by data for other intermediate- and high-ionization transitions. To produce the observed Si iv absorption in this phase, $-2.2 < \log U < -1.8$ is the optimal range. The cloud size would be $\sim 100$ pc, considerably larger than the Mg ii cloud. If log $U < -2.2$, the system would have too much Si iii and Si iv absorption relative to C iv. If log $U > -1.8$, $N$(N v) would be overproduced by the model. The metallicity of the high-ionization phase is constrained by the Ly$\alpha$ profile to be solar or higher. For larger values of the ionization parameter, within the constrained range of $-2.2 < \log U < -1.8$ the lower limit on metallicity would be raised to a supersolar value.

Considering collisional ionization, for $b(C\text{ iv}) = 10.4$ km s$^{-1}$, pure thermal broadening gives an upper limit on the temperature of log $T < 4.90$. Below this limiting temperature, Si iv would be severely overproduced (Sutherland & Dopita 1993) if we optimize on C iv. However, raising the temperature to log $T = 4.93$ [which is just consistent with the Voigt profile fit $b(C\text{ iv})$ within 1 $\sigma$ errors] reproduces the observed $N$(Si iv). The metallicity of this collisionally ionized phase would have to be solar or greater in order that Ly$\alpha$ would not be overproduced. Although it requires fine-tuning of the temperature, a collisionally ionized phase with solar metallicity and log $T = 4.93$ provides an adequate fit to the data.

We conclude that the $z = 0.8181$ system has two phases, both with a metallicity solar or higher. The low-ionization phase, with $b = 2$ km s$^{-1}$, has log $U < -4.0$, while the high-ionization phase, with $b = 10$ km s$^{-1}$, could be photoionized with log $U < -2.0$ or collisionally ionized with log $T = 4.93$. The broader high-ionization phase is centered on the Mg ii cloud and is consistent with a single cloud producing the C iv absorption. Constraints are summarized in Table 3. An acceptable model, including two photoionized phases, is superposed on the data in Figure 1. Column densities of selected transitions produced by this model are given in Table 4.

4.2. The $z = 0.9056$ System

The $z = 0.9056$ system is detected in Ly$\alpha$, Ly$\beta$, Mg ii, Si ii, C ii, N ii, Si iii, Si iv $\lambda 1403$, N iii, and C iv. N v $\lambda 1239$ is not confirmed by a detection of N v $\lambda 1242$, so it is viewed as a tentative detection. O vi is also a likely detection, although O vi $\lambda 1038$ is in a confused region of the spectrum that required an uncertain continuum fit. Limits are available for Mg i and Fe ii $\lambda 2600$ in the HIRES/Keck spectrum. All of these transitions are shown in Figure 2. In this system, the C iv is quite strong and shows an asymmetry in both members of the doublet.

We first optimize on the $N$(Mg ii) and $b$(Mg ii) given by a Voigt profile fit to the Mg ii $\lambda \lambda 2796, 2803$ profiles (see Table 2). Comparing to the other transitions, the ionization parameter for this Mg ii cloud is constrained to be $-3.3 < \log U < -2.7$. A higher value overproduces Si iv $\lambda 1403$ absorption at $v = 0$ km s$^{-1}$, which is well fitted for log $U$ at the upper end of this range and underproduced for log $U < -3.0$. (Si iv $\lambda 1394$ is blended with a stronger transition from another system and cannot be used as a constraint.) A value of $\log U < -3.3$ would result in a model that exceeds the limit on Fe ii $\lambda 2600$. If $-3.3 < \log U < -3.0$, then there would have to be a significant contribution to the Si iv absorption from another phase. Even for the maximum consistent log $U = -2.7$, the C iv absorption is not fully produced in this phase, as shown by the dotted curve in Figure 2.

The cloud giving rise to the Mg ii, with $b$(Mg ii) = 3 km s$^{-1}$, would overproduce Ly$\alpha$ in its blue wing unless it has solar or supersolar metallicity. The metallicity constraint could be slightly relaxed if magnesium is enhanced because of an $\alpha$-enhanced abundance pattern. On the other hand, in the red wing, the observed Ly$\alpha$ is not exceeded by any model with log $Z > -2$. This difference between the metallicity constraints from the red and blue wings of the Ly$\alpha$ profile is a consequence of an asymmetry in the distribution of H i relative to Mg ii. The asymmetry in Ly$\alpha$, along with the need to fully produce the C iv absorption, requires an additional phase of gas.

In addition to the Mg ii cloud, two more clouds are needed in order to fit the C iv profile. From a simultaneous Voigt profile fit of the 1548 and 1550 Å transitions, the first, centered on the velocity of the Mg ii absorption, would have $N$(C iv) $\sim 14.0$ and $b$(C iv) $\sim 6$ km s$^{-1}$. A small amount of the C iv absorption is produced in the same phase as the Mg ii for log $U = -2.7$, so the column density of the C iv cloud would be reduced slightly in that case. The second C iv cloud, offset by 15 km s$^{-1}$ to the red, is fitted with $N$(C iv) $\sim 13.9$ and $b$(C iv) $\sim 14$ km s$^{-1}$.

First, we consider the $b$(C iv) = 6 km s$^{-1}$ C iv cloud centered on the Mg ii profile. It is too narrow (log $T < 4.4$) for the C iv to be produced by collisional ionization. From CLOUDY photoionization models, to simultaneously fit the C iv and the N v absorption, we derive the constraint $-1.8 < \log U < -1.5$ for this high-ionization phase. If so, little Si iv arises in this phase, which implies that Si iv absorption should be produced in the low-ionization phase with the Mg ii. Revisiting the constraints for the Mg ii cloud, we now find the constraint $-3.0 < \log U < -2.7$ for the low-ionization cloud, at the upper end of the previous constrained range discussed above. The metallicity of the high-ionization gas that produces the C iv absorption must be high enough not to overproduce Ly$\alpha$ in its blue wing. In conjunction with a solar metallicity Mg ii cloud phase, this yields a solar metallicity for this $-1.8 < \log U < -1.5$ C iv phase as well.

Next, we consider the $b$(C iv) = 14 km s$^{-1}$ C iv cloud, offset by 15 km s$^{-1}$ from the Mg ii cloud, that fills in the red wing of the C iv profile. The $b$(C iv) = 14 km s$^{-1}$ C iv cloud, at $v = 15$ km s$^{-1}$, can be fitted with a simple, single-cloud photoionization model with $-1.9 < \log U < -1.8$. This ionization parameter produces a consistent fit of the O vi, N v, and C iv without overproducing the Si iv. The Si iii and
Si iv data are very slightly underproduced by the model at this velocity, suggesting that a small (~0.2 dex) abundance pattern enhancement of silicon might be needed. A simple model with the minimum number of phases would call for the asymmetry in the Lyα profile to be produced in this cloud along with the red wing of the C iv. The metallicity is thus constrained to be at the solar value in order to fit the red wing of the Lyα line.

Our philosophy of fitting with the minimum number of phases argues against collisional ionization as the mechanism for producing the observed C iv absorption at \( v \approx 15 \text{ km s}^{-1} \). To be consistent with this philosophy, both C iv and Lyα should arise in the same phase. The limit on log \( T \) for this component with \( b(C\ iv) = 14 \text{ km s}^{-1} \) is consistent with production of C iv absorption by collisional ionization. However, for the maximum permitted \( T \) there would not be enough H i absorption in this model component unless the metallicity was well over supersolar. With the relatively low \( T \) needed to produce this much H i absorption, Si iv absorption would be overproduced.

We conclude that the \( z = 0.9056 \) system must have solar metallicity or higher in its low-ionization phase. The \( b(\text{Mg} \, ii) = 3 \text{ km s}^{-1} \) cloud that produces Mg ii absorption must be of a relatively high ionization state, with \(-3.0 < \log U < -2.7\). The range of derived cloud sizes for this constrained range is \(30–100 \text{ pc} \). Two higher ionization, broader clouds are also required: one, with \( b(C\ iv) \approx 6 \text{ km s}^{-1} \), is centered on the Mg ii cloud, while the other, \( b(C\ iv) \approx 14 \text{ km s}^{-1} \) cloud is offset by \(15 \text{ km s}^{-1} \). Both are consistent with photoionization with log \( U \approx -1.8 \) and have sizes of \(0.4–1 \text{ kpc} \). Ranges of acceptable model parameters are presented in Table 3, and model column densities contributed by the three clouds for an adequate model are listed in Table 4. The predictions for this same model are superposed on the data in Figure 2.

4.3. The \( z = 0.6534 \) System

The C iv profile for this newly discovered system has a complex structure, and the Mg ii is extremely weak and narrow. The C iv profile requires at least a three-component fit. The Lyα is not symmetric about the Mg ii, but it is approximately symmetric about the C iv. These profiles, as well as those of the other detected transitions, Si ii, C ii, Si iv, are displayed in Figure 3, along with the region of the spectrum that provides a limit on Fe ii \( \lambda 2600 \). N v is in a noisy region of the spectrum. If the detected feature is really N v, it is present only in the redward component, at \( \approx 50 \text{ km s}^{-1} \).

We begin by considering the Mg ii cloud. Since the Fe ii \( \lambda 2600 \) spectrum is noisy, the low ionization parameter constraint on log \( U \) is not strong: for \( \log U < -4 \), \( N(\text{Mg} \, ii)/N(\text{Fe} \, ii) \) is relatively constant. However, assuming a solar abundance pattern, log \( U > -4 \) provides a marginally better fit to the Si ii and C ii. If log \( U \approx -2.5 \), then the depth of the Si iv and C iv absorption at \( 0 \text{ km s}^{-1} \) can be reproduced in the Mg ii cloud, but the model profile is too narrow and does not provide a good fit to the data. A separate, higher ionization phase is needed to fit these higher ionization transitions. Considering all transitions, and assuming solar abundance pattern, \(-4 < \log U < -3 \) is favored for the Mg ii cloud.

The metallicity of the Mg ii cloud would be log \( Z = -1.5 \) if all of the Lyα in the red wing were to arise in this cloud. However, it could also be significantly higher if there were Lyα contribution from the C iv clouds. For log \( Z = -1.5 \) and \(-4 < \log U < -3 \), the Mg ii cloud size ranges from 6 pc to \( \sim 1 \text{ kpc} \). Sizes scale with \( Z^{-1} \), so that log \( Z = -1.0 \) clouds would be a factor of \( \sim 3 \) smaller than log \( Z = -1.5 \) clouds.

Consider the case of log \( U = -4.0 \) for the Mg ii cloud. Three more clouds are required to fit C iv. The column densities and Doppler parameters for these three clouds were obtained with a Voigt profile fit. This fit is not unique because clouds cannot be well separated, as a result of blending, so there are no error bars listed in Table 2. The cloud centered on the Mg ii was fitted with log \( N(C\ iv) = 13.7 \) and \( b(C\ iv) = 13 \text{ km s}^{-1} \). The other two clouds, at \( v = 24 \) and \( 54 \text{ km s}^{-1} \), were fitted with log \( N(C\ iv) = 13.9 \) and \( b(C\ iv) = 9 \text{ km s}^{-1} \) and log \( N(C\ iv) = 13.8 \) and \( b(C\ iv) = 14 \text{ km s}^{-1} \), respectively.

For photoionization models, the ionization parameters for these three C iv clouds are constrained by the requirement that they produce the observed Si iv without producing significant lower ionization transitions. The \( b(C\ iv) = 13 \text{ km s}^{-1} \) C iv cloud, centered on the Mg ii cloud, is tightly constrained to have \(-2.5 < \log U < -2.4 \) by the Si iv profiles. The range already takes into account the fact that the Mg ii cloud would make a small contribution to Si iv if its log \( U < -3 \). The lower limit on log \( U \) of the C iv cloud arises in order that the Mg ii is not overproduced in its wings by this relatively broad component. The upper limit applies in order to produce sufficient Si iv absorption.

The \( b(C\ iv) = 9 \text{ km s}^{-1} \) C iv cloud at \( v = 24 \text{ km s}^{-1} \) has \(-2.2 < \log U < -2.1 \), in order to produce the optimal fit to Si iv, C ii, and C iv. For log \( U > -1.7 \), N v is overproduced, and for log \( U < -2.6 \), C ii, Si ii, and Mg ii are overproduced.

For the \( b(C\ iv) = 14 \text{ km s}^{-1} \) C iv cloud at \( v = 54 \text{ km s}^{-1} \), log \( U = -2.2 \) provides an optimal fit to the Si iv and is consistent with C ii and the limit on N v. A value of log \( U = -2.0 \) is only marginally consistent, with the model slightly underproducing the Si iv. The inferred properties of this cloud are independent of the Mg ii cloud, since no Mg ii is detected at this velocity.

As with the Mg ii cloud, the metallicities of the three additional C iv clouds cannot be extremely low. Only log \( Z = -1 \) or higher is consistent with the data. If the red side of the Lyα is to be produced by the \( v = 54 \text{ km s}^{-1} \) C iv cloud, log \( Z = -1.0 \) would apply for this cloud similarly, log \( Z = -1.0 \) for the \( v = 0 \text{ km s}^{-1} \) C iv cloud would match the blue wing of Lyα. In the case of the blue wing, the Lyα could in principle be produced in a log \( Z = -1.5 \) Mg ii cloud, and the metallicity of the C iv cloud could be higher. Constraints on the metallicities of these clouds, relative to the cloud that produced the narrower Mg ii profile, are limited by the lack of coverage of higher order Lyman series lines. However, the data are consistent with log \( Z = -1 \) in the Mg ii cloud and in the three C iv clouds. For this metallicity, the sizes of the three C iv clouds would be \( \sim 2–4 \text{ kpc} \).

We also consider whether collisionally ionized gas can be consistent with the observed profiles of C iv, Si iv, and Lyα. For the \( v = 0 \text{ km s}^{-1} \) C iv cloud, log \( T \geq 4.90 \) does not overproduce Si iv, and log \( T = 4.90 \) is consistent with producing the blue side of the Lyα profile for log \( Z = -1 \). If the metallicity is higher, a higher ionization parameter is needed to fit the Lyα line, but in this case the model Lyα profile shape is not consistent with the data. The \( v = 24 \text{ km s}^{-1} \) cloud is too narrow to be consistent with production of C iv absorption through collisional ionization, assuming the particular
Voigt profile fit that we have adopted. However, because this fit is not unique, there could possibly be a broader cloud component that could be reconciled with collisional ionization. Finally, the $z = 54$ km s$^{-1}$ C iv cloud could be collisionally ionized with log $T = 4.95$ and log $Z = -1$, in which case it would match the red side of the Ly$\alpha$ profile.

In summary, the $z = 0.6534$ system Mg ii profile is quite weak and narrow. However, the C iv profile can be fitted with several components spread in velocity over 50 km s$^{-1}$. The three components are similar to each other, having $b \sim 10$ km s$^{-1}$ and log $U$ ranging from $-2.5$ to $-2.1$ if they are photoionized. Collisional ionization with temperatures of log $T \sim 4.9$ could be consistent with the data, but requires fine-tuning of the temperature and seems less likely. The bluest C iv component has the Mg ii detected at the same velocity, but in a narrower component ($b \sim 4$ km s$^{-1}$) produced in gas with a somewhat lower ionization parameter (log $U \sim -3.5$). The C iv clouds have a metallicity of at least log $Z = -1$ and must be at least a couple of kiloparsecs in size.

5. CAVEATS

5.1. Abundance Pattern Variations

Abundance ratios measured in Galactic stars show a clear range of $0 \leq [\alpha/Fe] \leq 0.5$ (Lauroesch et al. 1996). In our presentation of model results (§ 4), a solar abundance pattern was assumed unless the data required an alternative pattern. However, it should be noted that the inferred metallicity depends directly on the assumed abundance pattern. If, instead of solar, the abundance pattern is $\alpha$-group-enhanced, with $[\alpha/Fe] = +0.5$, the inferred metallicity of a phase constrained by $N$(Mg ii) (an $\alpha$-group element) would proportionally drop by $\sim 0.5$ dex. Constraints on the ionization parameter, log $U$, are also affected by changes in the assumed abundance pattern. For example, if the abundance pattern is $\alpha$-group-enhanced, the ratio $N$(Si iv)/$N$(C iv) would constrain log $U$ to be larger than if the abundance pattern is solar. However, for $[\alpha/Fe] \leq +0.5$, the change in the constraint on log $U$ (and therefore on log $n_e$) is less than 0.3 dex. We have used the relative absorption strengths in several other transitions to determine log $U$, but 0.3 dex is typical of the level of uncertainty due to variations in abundance pattern.

5.2. Effects of Spectral Shape

Based on results for other similar absorption-line systems, there is likely to be no bright galaxy associated with these single-cloud weak Mg ii absorbers (Rigby et al. 2002). Therefore, we used the Haardt & Madau (1996) extragalactic background spectrum for $z = 1$ in our detailed models presented above (§ 4). However, because it is not strictly excluded, we do consider here the effect of changing the spectral shape.

Two alternative galaxy spectra, 0.01 and 0.1 Gyr instantaneous starburst models, were superposed on the Haardt-Madau extragalactic background spectrum. Both models, with solar metallicity and a Salpeter initial mass function (IMF) were taken from Bruzual A. & Charlot (1993). The normalizations of the starburst spectra are defined relative to the Haardt-Madau spectrum at 1 ryd, and in all cases the extragalactic and galactic contributions were superposed. The largest reasonable value for the photon flux from even the most extreme starburst galaxy is $10^{54}$ s$^{-1}$, and of the order of 1% of the photons escape (Hurwitz, Jelinsky, & Dixon 1997). Using these numbers, to have a flux 10 times that of Haardt & Madau (1996) at $z = 1$, the absorber would have to be within 6 kpc of the starburst. Within this distance, we would expect stronger absorption than observed in these weak Mg ii absorbers. Therefore, we consider it most likely that the Haardt-Madau spectral shape is the appropriate assumption. Nonetheless, in this section, we briefly examine the consequences of the alternatives. We consider the effect of spectral shape on the metallicity of the low-ionization phase, on whether the C iv absorption can arise from the same phase as the Mg ii absorption, and on the ionization conditions of the high-ionization phase.

The largest effect on the metallicity would be from an ionizing spectrum with a large feature at the Lyman edge, such as the Bruzual-Charlot 0.1 Gyr instantaneous burst model. In this case, the cloud would be more neutral, so that not as much hydrogen would be required to fit the Ly$\alpha$ profile. In such a case, the metallicity would be even higher than we inferred assuming a pure Haardt-Madau spectrum. In general, we found that the starburst spectrum normalization needed to be at least 10 times that of the Haardt & Madau (1996) spectrum in order to detect a difference in the models. Even with a normalization of 25, the difference in the inferred metallicity is less than 0.5 dex. Most importantly, even if the spectrum of ionizing radiation has a substantial Lyman edge, the metallicity of the weak Mg ii clouds would be even higher than the solar value—an even more surprising result.

A 0.1 Gyr instantaneous burst model, if it dominates over the Haardt-Madau spectrum by a factor of 25, can make significantly more C iv relative to Mg ii. However, only the column density can be made consistent with the observed C iv profiles in the three systems studied here. The Doppler parameters of these lines are still too large for them to be produced in the same phase as the Mg ii.

A spectrum with a sharp He i edge will have the largest effect on the inferred log $U$ of a photoionized high-ionization phase. A 0.01 Gyr starburst model is extreme in this respect, yet it takes a normalization of 10 times that of Haardt & Madau (1996) to see even a small change. With a normalization of 25, the Si iv is significantly overproduced relative to C iv for the same log $U$. However, the qualitative result of a relatively low density phase producing the bulk of the C iv is unchanged. For example, for the $z = 0.8181$ system, log $U$ must be increased from $-1.5$ to $-1.0$ in order that Si iv not be overproduced.

We conclude that at $z = 1$ an extreme starburst spectrum would have to dominate in order to affect the conclusions of our models. Even if such conditions prevailed, the conclusions would be qualitatively unchanged. The constraints would only change by $\sim 0.5$ dex in parameter spaces ranging over a few orders of magnitude.

6. DISCUSSION

This study of the multiple phases of gas and the physical conditions of the three weak Mg ii systems along the PG 1634+706 line of sight indicates a heterogeneous population of objects selected by a weak Mg ii doublet. Figure 4 is a comparison between the three systems showing the range of C iv equivalent widths and kinematic structures, ranging
from a profile consistent with a single cloud for the \( z = 0.8181 \) system to the stronger asymmetric profile for the \( z = 0.9056 \) system to the multiple-component profile for the \( z = 0.6534 \) system. The Ly\( \alpha \)/C\( \text{II} \) profile strength does not systematically increase in proportion with the Mg \( \text{II} \) absorption. It could, however, be increasing with the kinematic spread of the C\( \text{IV} \).

Table 3 gives a summary of the range of "acceptable models" for each of the three systems, while Table 4 gives more detailed information about a sample model that is within the acceptable range. That typical model was also superposed on the data in Figures 1–3.

6.1. Comparisons of the Three Systems

The \( z = 0.8181 \) and \( 0.9056 \) systems provide contrasting examples of a weak Mg \( \text{II} \) absorber that clearly requires a...
separate broad phase to fit a strong C iv profile and one with much weaker C iv not even detected in the previous low-resolution FOS spectrum (Churchill et al. 2000a). For both systems, in the present study we find that a separate, broader phase (\(b \sim 10\) and 6 km s\(^{-1}\), respectively), with an ionization parameter \(\log U \sim -2\), is needed to fit the observed C iv STIS profile. This phase is centered at the same velocity as the phase that gives rise to the weak Mg ii absorption. However, in the \(z = 0.9056\) system there is an asymmetry to the C iv profile that indicates an additional offset component, 13 km s\(^{-1}\) redward of the Mg ii cloud and the first C iv broad phase. The C iv profile can be fitted with a two-cloud model, although it is also possible that there is a more complex distribution of material, spread over a range of velocities, that gives rise to such an asymmetric profile shape. A general point is suggested by the comparison of the \(z = 0.8181\) and 0.9056 systems. The strong C iv absorption that is observed in many weak Mg ii absorbers (Rigby et al. 2002) could be due to the presence of separate clouds that are of higher ionization and do not give rise to detectable Mg ii absorption. The same would apply to the stronger Ly\(\alpha\) absorption apparent in some weak Mg ii absorbers.

The \(z = 0.6534\) system is a more extreme example, in which three separate components are clearly apparent in the C iv profile. A narrow weak Mg ii absorber is centered on one of the higher ionization C iv clouds. The separate C iv components at 24 and 54 km s\(^{-1}\) are quite distinct from the C iv centered on the Mg ii cloud. Like the higher ionization components of the other two systems, these two offset clouds have ionization parameters \(\log U \sim -2\). The Ly\(\alpha\) profile is consistent with being centered around the three C iv components, but not around the Mg ii cloud. The fact that Ly\(\alpha\) absorption is strongest in this system suggests that the spread in velocity of absorbing gas along the line of sight is an important factor in determining the equivalent width of Ly\(\alpha\) absorption.

The metallicities of the \(z = 0.8181\) and 0.9056 systems are constrained to be at least solar. The \(z = 0.6534\) system is likely to have a metallicity of at least 1/10 solar. These relatively high metallicities appear to be common for weak Mg ii absorbers. Rigby et al. (2002) inferred a high metallicity for several systems based on low-resolution FOS data, and in no case did they find that a metallicity less than 1/10 solar was required.

6.2. Comparison to Model Results Based on Low-Resolution Data

For the \(z = 0.8181\) and 0.9056 systems, we can compare the results from this study, incorporating high-resolution STIS data, to those of our previous models, based on the lower resolution FOS data (Charlton et al. 2000).

For the \(z = 0.8181\) system, Ly\(\alpha\) was not covered in the earlier FOS spectrum, so no constraints on metallicity were available. The C iv was not detected in the FOS spectrum, but we showed that it might be detected in the higher resolution STIS spectrum from either a Mg ii cloud with a high ionization parameter or a broader, separate phase. No specific predictions could be made as to which possibility was more likely. Now, with the high-resolution STIS spectrum coverage of C iv we are able to place specific constraints, as was outlined in § 4.1.

For the \(z = 0.9056\) system the main conclusions of our previous study, based on the FOS spectrum (Charlton et al. 2000), were that the C iv is present in a separate broader phase and that the metallicity of the Mg ii cloud is solar or higher. These conclusions are confirmed by the present study. The detailed properties of the broader phase were more difficult to determine based on low-resolution spectra. We suggested that the broad phase has \(b \sim 20\) km s\(^{-1}\) because the doublet ratio of the C iv was large compared to observations, if \(b = 10\) km s\(^{-1}\) was assumed. The high-resolution STIS spectrum shows that the C iv profile is asymmetric, so that it must be composed of at least two separate “clouds,” the broadest having \(b \sim 14\) km s\(^{-1}\). The wings of the Ly\(\alpha\) profile in the low-resolution spectrum were apparently due to FOS fixed pattern noise rather than to an extremely broad phase, since these features are not apparent in the high-resolution STIS spectrum.

From this very limited comparison, we tentatively conclude that it should be possible to draw inferences about the presence of a separate C iv phase based on a combination of high- and low-resolution spectra, i.e., drawing on the existing FOS database. Also, our conclusion of solar metallicity for the \(z = 0.9056\) system was confirmed by modeling of the high-resolution STIS profile of Ly\(\alpha\). This is important, since modeling of FOS data was used to infer that many weak Mg ii absorbers have close to solar metallicity (Rigby et al. 2002).

6.3. Relationships Between Phases

To understand the nature of these systems, we seek to infer the spatial distribution of absorbing material and the relationship to star-forming objects. All three single-cloud weak Mg ii absorbers have two phases that produce a narrower (2–4 km s\(^{-1}\)) and a broader (6–13 km s\(^{-1}\)) absorption component centered at the same velocity. The narrower component is of lower ionization than the broader component. For a fixed Haardt-Madau spectrum intensity, this implies a higher density (~0.01–0.1 cm\(^{-3}\)) for the narrower component and also a smaller size, ~0.1–100 pc. The broader component would arise in a higher ionization/lower density phase (~0.001 cm\(^{-3}\)) with a larger size (~0.1–2 kpc).

Two simple scenarios could be consistent with the inferred properties of the narrow and broad components. (1) The first would have the lower ionization region embedded within the higher ionization region, and the higher ionization region would present a larger cross section. We would then expect many systems to be observed for lines of sight that pass through only the higher ionization region of such structures. These “C iv–only systems” might typically have lower C iv column densities than two-phase weak Mg ii systems. They would be produced at a larger impact parameter in the structure, at which the path length would be shorter and the gas densities would be lower. (2) In the second scenario, the lower ionization components could be produced by parts of a shell structure surrounding a lower density, higher ionization region. The covering factors for the low-ionization shell fragments would be limited (\(\leq 1\)) by the lack of observation of many two-cloud weak Mg ii systems. However, with such a small covering factor, we would again expect a large incidence of C iv–only systems, which in this scenario would tend to have similar C iv phases to those of two-phase weak Mg ii systems.
We searched the PG 1634+706 spectra and found no C iv—only systems with C iv comparable in strength even to that of the $z = 0.8181$ weak Mg ii absorber. However, we have identified several weaker candidate C iv doublets at more than 5 $\sigma$, confirmed by a line detected at the expected position of Ly$\alpha$. Many other lines of sight need to be systematically surveyed, but there clearly will be limits on the geometry and covering factors of the two phases of gas.

An alternative to the idea of embedded phases is to have separate clouds along the line of sight with different densities and sizes. This is consistent with the presence of an offset cloud in the $z = 0.9056$ system and the spread of three clouds over 50 km s$^{-1}$ in the $z = 0.6534$ system. These separate clouds could exist as condensations in larger structures with velocity dispersions of tens of kilometers per second, e.g., dwarf galaxies. However, if the phases were all completely separate from each other, then it would be hard to explain the close alignment in velocity of the lower ionization cloud with one of the higher ionization clouds.

The metallicities of these absorbing structures present a clue as to their place of origin. We do not expect that they are in the vicinity of luminous galaxies ($>0.05L^*$ galaxies are not found within impact parameters of $\approx 50$ $h^{-1}$ kpc from the quasar). Although no useful image is available for the PG 1634+706 field in particular, other single-cloud weak Mg ii absorbers are rarely found near such luminous galaxies (C. Steidel 2002, private communication; Rigby et al. 2002). Dwarf galaxies have metallicities significantly lower than solar, which would appear inconsistent with solar metallicities for single-cloud weak Mg ii absorbers. However, it is possible that the weak Mg ii absorbers are concentrations of higher metallicity within lower metallicity structures.

Most strong Mg ii absorbers [$W$(Mg ii) $> 0.3$ Å] also require a phase in addition to the Mg ii clouds, in order to produce the observed C iv absorption. These absorbers are associated with $\sim L^*$ galaxies (Bergeron & Boissé 1991; Steidel et al. 1994; Steidel 1995), and the high-ionization phase is inferred to have an “effective Doppler parameter,” or velocity spread, of $\sim 50$ km s$^{-1}$ (Churchill et al. 2000b). At high resolution some of the C iv profiles will separate into multiple components, while others may be due to a more uniform distribution of gas (Ding et al. 2003a, 2003b; Zonak et al. 2002). The C iv phase of some strong Mg ii absorbers is reminiscent of what would be expected for a corona such as that observed in C iv and O vi absorption around the Milky Way disk. The single-cloud weak Mg ii absorbers, although they do have a second phase, do not appear to be related to such a corona.

7. CONCLUSIONS

The combination of STIS/HST and HIRES/Keck high-resolution spectra, covering multiple chemical transitions, provided the first opportunity to collect direct information on the metallicities and phase structure of weak Mg ii absorbers. There are three weak Mg ii absorbers, at $z = 0.8181$, 0.9056, and 0.6534, along the line of sight toward the quasar PG 1634+706. All three of these absorbers have a second, higher ionization phase, giving rise to the C iv absorption. The broad phase in one case is consistent with a single cloud, and in the other two cases requires one or two additional clouds separated in velocity space from the one aligned with the Mg ii absorption.

Two of the weak Mg ii absorbers are constrained to have solar or greater-than-solar metallicity and the other one to have a metallicity greater than 1/30 solar. Thus, in general, weak Mg ii absorbers are not weak because of a low metallicity (confirming the result of Rigby et al. 2002). As introduced in §1, it is also possible that they have weak Mg ii absorption because they are more highly ionized than their strong counterparts, or because their total column densities are smaller. The likely answer is that there is some combination of these two effects, perhaps leading to different populations of weak absorbers arising in different environments. The ionization parameters of the absorbers studied here are higher than those inferred for many of the clouds in strong Mg ii absorbers for which Fe ii is also detected. (Fe ii is a tracer of low-ionization conditions; Churchill et al. 1999; Rigby et al. 2002.) However, there is also a population of weak Mg ii absorbers with strong Fe ii lines, amounting to about one-third of the weak Mg ii absorber population (Rigby et al. 2002). Detailed study of the phase structure of this subgroup awaits spectra of additional quasar lines of sight with C iv, Ly$\alpha$, and other transitions covered at high resolution.

Weak Mg ii absorbers are potentially of general importance because they provide a sensitive probe of particular types of star-forming environments. In principle, this population of objects can be used to track the chemical and ionization history of the universe in regions that are not in luminous galaxies, which can be studied by other methods. For example, do they exist with solar metallicity to high redshifts; i.e., are there selected environments with extreme enrichment even at early times? Answering this question will require a large systematic study of many weak Mg ii systems over a range of redshifts. Such a study could address whether there is always C iv absorption centered in velocity on a Mg ii cloud. It could tabulate the distribution of C iv clouds in velocity space and address whether a large C iv equivalent width is typically due to the presence of multiple clouds along the line of sight. Spectral coverage of N v and O vi will also provide better constraints on the ionization conditions of the high-ionization phase. Finally, it is highly desirable to search the quasar fields for faint galaxies that could be related to these weak Mg ii absorbers.

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