PHYSICAL PROPERTIES OF WEAK Mg II ABSORBERS AT z ~ 2

RYAN S. LYNCH² AND JANE C. CHARLTON³

Received 2006 August 22; accepted 2007 May 12

ABSTRACT

We present the results of photoionization modeling of nine weak Mg ii (W_r < 0.3 Å) quasar absorption-line systems with redshifts 1.4 < z < 2.4 obtained with the Ultraviolet and Visual Echelle Spectrograph on the Very Large Telescope. These systems have been chosen because they provide access to a regime of redshift space that previous weak Mg ii studies have not looked at. The densities, metallicities, Doppler parameters, and column densities of these systems are compared to those of other weak Mg ii systems at lower redshift. There is no significant statistical variation in the properties of the absorbers over the redshift range 0.4 < z < 2.4. The number density per unit redshift is known to decrease for weak Mg ii absorbers between z ~ 1 and 2 by a greater amount than predicted from cosmological effects and changes in the extragalactic ionizing background alone. We suggest that, because the physical properties of the absorber population are not seen to change significantly across this range, the evolution in dN/dz is due to a decrease in the activity that gives rise to weak Mg ii absorption, and not due to a change in the processes that form weak Mg ii absorbers. The presence of separate, but aligned (in velocity) low- and high-density clouds in all single-cloud weak Mg ii absorbers provides an important diagnostic of their geometry. We discuss possible origins in dwarf galaxies and in extragalactic analogs to high-velocity clouds.

Subject headings: intergalactic medium — quasars: absorption lines

Online material: color figures

1. INTRODUCTION

Weak Mg ii absorbers are defined to be those with rest-frame equivalent widths W_r < 0.3 Å. They represent a different population than strong Mg ii absorbers (Rigby et al. 2002; Nestor et al. 2005). Strong Mg ii absorbers are known to be associated with luminous galaxies [within ~38 h^{-1}(L/L^*)^{0.15} kpc; Bergeron & Boissé 1991; Bergeron et al. 1992; Le Brun et al. 1993; Steidel et al. 1994, 1997; Steidel 1995], while weak Mg ii absorbers are not typically seen within a 50 h^{-1} kpc impact parameter of a luminous galaxy (Rigby et al. 2002; but see Churchill et al. 2005 for some exceptions). The exact environment(s) and process/processes that give rise to weak Mg ii absorbers are not yet known, but they may arise in dwarf galaxy environments, in the cosmic web surrounding galaxies, and/or in high-velocity clouds. Weak Mg ii absorbers generally correspond to sub-Lyman limit systems [15.8 < log N(H_i) < 16.8 (cm^{-2}); Churchill et al. 1999, 2000; Rigby et al. 2002], and they have metallicities of at least 10% solar and as high as solar or even supersolar (Rigby et al. 2002; Charlton et al. 2003; Simcoe et al. 2006). In addition, the Fe ii/Mg ii ratio of some absorbers does not allow for α-enhancement; thus Type Ia supernovae must contribute as well as Type II. Because Type Ia supernovae cannot eject metals to large distances, metals must be produced in situ.

The number statistics and kinematics of single-cloud weak Mg ii absorbers lend themselves best to a flattened geometry and suggest that the absorbers may be produced by higher density regions in the cosmic web (Milutinović et al. 2006). Mg ii absorption typically arises in a high-density region ~1–100 pc thick, which is often surrounded by a lower density region that gives rise to high-ionization C iv absorption centered at the same velocity as the Mg ii (Charlton et al. 2003; Simcoe et al. 2006). Additional low-density regions producing C iv absorption, which are detected at different velocities than Mg ii, often exist.

While most weak Mg ii absorbers can be fit by a single Voigt profile component, about one-third have multiple components (Churchill et al. 2000; Lynch et al. 2006). Some of these multiple-cloud weak Mg ii absorbers are weaker versions of strong Mg ii absorbers with similar kinematics, as if they arise in the outskirts or in sparse regions of luminous galaxies. Others, which tend to have more kinematically compact profiles, have been hypothesized to arise in dwarf galaxies (Zonak et al. 2004; Ding et al. 2005; Masiero et al. 2005).

When exploring the nature of weak Mg ii absorbers, two methods are often used, statistical surveys and photoionization modeling of individual systems. Narayanan et al. (2007), Churchill et al. (1999), and Lynch et al. (2006) conducted surveys of systems with equivalent widths in the range 0.02 Å < W_r < 0.3 Å, which, when combined, span the redshift range 0 < z < 2.4. These surveys obtained number densities of absorbers per unit redshift (dN/dz): dN/dz = 1.00 ± 0.20 (0 < z < 0.3; Narayanan et al. 2007), dN/dz = 1.74 ± 0.10 (0.4 < z < 1.4; Churchill et al. 1999), and dN/dz = 1.06 ± 0.12 (1.4 < z < 2.4; Lynch et al. 2006). Apparently, the population of weak Mg ii absorbers peaks at z ~ 1 over the range 0 < z < 2.4. Furthermore, the density of absorbers at z ~ 2 is significantly lower than expected if the change in dN/dz was due only to cosmological effects and to the changing extragalactic background radiation (Lynch et al. 2006). This indicates either that the same process creates weak Mg ii absorbers across this redshift range, but was less active at z ~ 2 than at z ~ 1, or that the physical mechanisms responsible for creating the absorbers change across redshift and are more efficient at z ~ 1 than at z ~ 2. It should be noted that this trend in dN/dz is consistent with the star formation history in dwarf galaxies (Gabasch et al. 2004; Kauffmann et al. 2004), which may suggest that weak Mg ii absorbers are related to this activity.

---

¹ Based on public data obtained from the ESO archive of observations from the UVES spectrograph at the Very Large Telescope (VLT), Paranal, Chile, ESO Program ID 166.A-0106. HE 2217–2818 was observed during UVES commissioning.
² Department of Astronomy, P.O. Box 400325, University of Virginia, Charlottesville, VA 22904; rslv@virginia.edu.
³ Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802; chalton@astro.psu.edu.
Photoionization models facilitate the exploration of the physical properties of the absorption system, such as ionization parameter, density, temperature, abundance pattern, and size. By understanding these properties for absorbers at different redshifts, we can gain insight into what processes create them. If different processes are responsible for the formation of these absorbers at different epochs, then the physical properties of the absorbers are likely to evolve. If no statistical difference in the physical properties is observed, this would suggest that the same mechanism is responsible for creating weak Mg ii absorbers at different epochs. To this end, we have produced photoionization models of the nine 1.4 < z < 2.4 systems found by Lynch et al. (2006) using the code Cloudy (Ferland et al. 1998) and compared our results to those of systems at lower redshift (Ribgy et al. 2002; Charlton et al. 2003; Zonak et al. 2004; Ding et al. 2005; Masiiero et al. 2005). Our methodology for modeling the systems is the subject of § 2. In § 3 we report the results of our models for each individual system. In § 4 we discuss our results and their implications for the population of weak Mg ii absorbers and conclude in § 5.

### 2. MODELING METHODOLOGY

The nine systems selected for modeling were taken from Lynch et al. (2006) and were identified by detecting a weak Mg ii λ2796, 2803 doublet in the redshift range 1.4 < z < 2.4. The systems were chosen because they lie in a region of redshift space (1.4 < z < 2.4) that previous weak Mg ii studies have not looked at. In order to be accepted as a true detection, the Mg ii λλ2796, 2803 had to be detected at least a 5 σ significance level in Mg ii λ2796. For a detailed discussion of the data reduction procedure, see Kim et al. (2004), and for a discussion of the survey method, see Lynch et al. (2006). Once an absorption system was identified, the Doppler parameter and column density of the Mg ii λλ2796, 2803 doublet were measured from a Voigt profile fit to the doublet using Minfit (Churchill et al. 2003). This code finds the minimum number of components required for an adequate fit to the observed absorption of Mg ii.

The measured Mg ii column density was used as a direct constraint for the photoionization code Cloudy 94.00 last described by Ferland et al. (1998; i.e., the photoionization models were optimized on the column density of Mg ii). For each cloud (separate Voigt profile component) a grid was constructed for which the metallicity \((\log Z/Z_\odot)\) and ionization parameter \((\log U = \log n_e/n_r)\) were changed in incremental values, typically in steps of 0.5 dex. A solar abundance pattern was assumed unless otherwise noted. A Haardt & Madau ionizing background of quasars plus star-forming galaxies with a photon escape fraction of 0.1 for \(z < 3\) was used at the redshift of each system (Haardt & Madau 1996, 2001). This radiation was assumed to be incident on a plane-parallel slab. Cloudy calculated column densities for all detected transitions and an equilibrium temperature for the cloud. This temperature was used, along with the measured Doppler parameter of Mg ii, to calculate the turbulent/bulk motion contribution to the total Doppler parameter, \(b_{\text{turb}} = b_{\text{tot}} - 2kT/m_{\text{Mg}}\). This \(b_{\text{turb}}\) was then applied to calculate the expected \(b_{\text{tot}}\) for every other element, again using the equilibrium temperature given by Cloudy. The model column densities and Doppler parameters of all clouds were used to generate a synthetic spectrum that was convolved with the instrumental profile appropriate for the Ultraviolet and Visual Echelle Spectrograph (UVES), \(R = 45,000\). These were compared to the data by using \(\chi^2\) indicators combined with profile inspection in order to refine the metallicity and ionization parameter values of the model. At times, it was necessary to adjust the abundance pattern of the model in order to achieve an adequate agreement.

### TABLE 1

| QSO          | \(v_{\text{abs}}/v_{\text{velocity}}\) (km s\(^{-1}\)) | \(U\) (log) | \(Z/\text{Z}_\odot\) (log) |
|--------------|---------------------------------|-------------|-----------------|
| HE 2347–4342 | 1.405362 Mg ii phase: –3.0 to –2.5, C iv phase: ≥–1.8 | Lyα not covered |
| Q0002–422    | 1.446496 Mg ii phase: –3.5 to –3.0, C iv phase: –1.8 to –1.3 | Lyα not covered |
| Q0122–380    | 1.450109 Mg ii phase: –4.0 to –2.5, C iv phase: –1.8 to –1.7 | Lyα not covered |
| HE 2217–2818 | 1.555845 Mg ii phase: –4.0, C iv phase: –2.5 to –2.0 | ≥–1.4       |
| HE 0001–2340 | 1.651462 Mg ii phase: –4.0 to –3.5, C iv phase: –1.7 to –1.5 | ≥–1.5       |
| HE 0151–4326 | 1.708494 Mg ii phase: –4.0, C iv phase: ≥–2.3 | ≥–1.5       |
| HE 2347–4342 | 1.796237 Mg ii phase: –4.0, C iv phase: ≥(–2.0 to –1.0 | ≥–1.0       |
| Q0453–423    | 1.858380 Mg ii phase: –4.0, C iv phase: –2.8 | ≥–2.0       |
| HE 0940–1050 | 2.174546 Mg ii phase: –3.7 to –2.5, C iv phase: –2.0 to –1.0 | ≥–2.0       |

* A more detailed description of these systems can be found in §§ 3.5 and 3.7.

### TABLE 2

| QSO          | \(v_{\text{abs}}/v_{\text{velocity}}\) (km s\(^{-1}\)) | \(N_{\text{Mg ii}}\) (cm\(^{-2}\)) | \(b\) (km s\(^{-1}\)) |
|--------------|---------------------------------|----------------|----------------|
| HE 2347–4342 | 1.405362                         | 11.87 ± 0.01   | 7.42 ± 0.06    |
| Q0002–422    | 1.446496                         | 12.09 ± 0.01   | 6.00 ± 0.06    |
| Q0122–380    | 1.450109                         | 12.36 ± 0.01   | 6.22 ± 0.06    |
| Cloud 1      | –18.0                            | 11.68 ± 0.08   | 5.11 ± 0.95    |
| Cloud 2      | –3.9                             | 11.59 ± 0.11   | 8.65 ± 2.52    |
| Cloud 3      | 40.4                             | 11.76 ± 0.03   | 10.90 ± 0.89   |
| HE 2217–2818 | 1.555845                         | 12.06 ± 0.01   | 7.37 ± 0.03    |
| Cloud 1      | –79.7                            | 11.38 ± 0.01   | 6.40 ± 0.02    |
| Cloud 2      | –49.2                            | 12.56 ± 0.01   | 2.69 ± 0.02    |
| Cloud 3      | –30.9                            | 11.82 ± 0.01   | 1.51 ± 0.06    |
| Cloud 4      | –14.7                            | 12.02 ± 0.01   | 8.05 ± 0.10    |
| Cloud 5      | 4.9                              | 12.62 ± 0.01   | 5.09 ± 0.02    |
| Cloud 6      | 37.4                             | 12.16 ± 0.01   | 7.37 ± 0.03    |
| HE 0001–2340 | 1.651462                         | 12.56 ± 0.01   | 2.89 ± 0.03    |
| HE 0151–4326 | 1.708494                         | 11.86 ± 0.01   | 3.90 ± 0.14    |
| HE 2347–4342 | 1.796237                         | 13.26 ± 0.02   | 4.20 ± 0.07    |
| Q0453–423    | 1.858380                         | 13.26 ± 0.02   | 4.20 ± 0.07    |

* A defect in the spectrum, most likely a sky line that was not properly removed, is responsible for this anomalous measurement.
fit to the observed spectrum. The effect of such changes on model parameters is given in the individual system descriptions. We assume a solar abundance pattern unless otherwise stated.

Many of the low-wavelength transitions fell in the Ly$\alpha$ forest and contained significant blends. In this case, a model was taken to be acceptable if it did not overproduce the observed absorption of a given transition. However, when blends were not present, a more exact match was required. In some cases, a range of model parameters produced an adequate fit. In the case of blends, an upper or lower limit was often the only constraint that could be obtained.

In most cases, there was absorption in higher ionization transitions that Cloudy could not reproduce through the low-ionization Mg $\Pi$ phase (i.e., the clouds that were optimized on the Mg $\Pi$ column density). This happened either because the high-ionization absorption was too broad to arise from the low-ionization phase or because the high-ionization absorption was not sufficiently produced for ionization parameters that provided a sufficient fit to low- and intermediate-ionization absorption. In these cases, the Doppler parameters and column densities of the C $\IV$ $\lambda\lambda 1548, 1550$ doublet were measured using Minfit, and Cloudy models were produced, optimizing on C $\IV$. The combined low- and high-ionization phase models were compared to the data. Separate constraints on metallicity and ionization parameter were obtained for the high-ionization clouds, when possible. However, it is common that the low-ionization phase has only a lower limit on metallicity in order not to overproduce Ly$\alpha$ absorption. For higher values of

---

**Fig. 1.** The $z = 1.405362$ system toward HE 2347−4342. Only relevant transitions are displayed here, in velocity space, centered at the redshift corresponding to the optical depth–weighted mean of the Mg $\II$ 2796 profile. The error array is plotted, but in some cases is so small that it is difficult to distinguish from zero flux. This model uses log $U = -3.0$ for the low-ionization phase, log $U = -1.7$ for the high-ionization phase, and log $Z/Z_\odot = 0.0$ for both phases. The positions of model clouds from the low-ionization phase are marked with ticks on the Mg $\II$ panels, while the high-ionization phase clouds are marked with ticks on the C $\IV$ panels. The feature to the right of C $\IV$ 1551 is most likely Ly$\alpha$ absorption in the forest. [See the electronic edition of the Journal for a color version of this figure.]


metallicity, an additional contribution to Lyα from the high-ionization phase would be required. In the event that there was a blend in the expected location of the C iv λλ1548, 1550 doublet, the Si iv λλ1393, 1402 doublet was used instead. If there were blends in the expected locations of both these transitions, no constraint on the high-ionization phase could be obtained (although this was a problem for only the z = 1.708494 system toward HE 0151−4326).

In addition to a Haardt & Madau ionizing background of quasars plus star-forming galaxies with a photon escape fraction of 0.1 for z < 3, the effect of using an ionizing background including only quasars was also explored. In most cases, this change had little effect, and the small effect it did have was only seen in the high-ionization gas. The sole exception is the z = 1.450109 absorber toward Q0122−380, for which the effect of the change of spectral shape is described in § 3.3.

3. PROPERTIES OF INDIVIDUAL SYSTEMS

The results of the photoionization modeling of our nine systems are presented here, and a summary can be found in Table 1.
so there is no constraint on metallicity. In the optically thin regime, our constraints on $\log U$ are insensitive to the assumed metallicity.

3.2. $Q0002-422$, $z = 1.446496$

This is a single-cloud absorber in Mg ii. A second phase is required to reproduce the observed C iv absorption. The ionization parameter is constrained to be $-3.5 \leq \log U \leq -3.0$ for the low-ionization phase and $-1.8 \leq \log U \leq 1.3$ for the high-ionization phase. Lower ionization parameters for the low-phase overproduce O i, and higher values overproduce Si iv. The constraint on the high phase is based on the strength of the Si iv $\lambda\lambda1393, 1402$ doublet. Using $\log n_\gamma = -4.82$, we find $-1.8 \leq \log n_H \leq -1.3$ (cm$^{-3}$) for the Mg ii phase and $-3.5 \leq \log n_H \leq -3.0$ (cm$^{-3}$) for the C iv phase. For an $\alpha$-enhanced model, lower densities would apply. Ly$\alpha$ is not covered due to the low redshift of this system, so there is no constraint on metallicity.

3.3. $Q0122-380$, $z = 1.450109$

This is a multiple-cloud absorber in Mg ii with three resolved components and requires a second phase to reproduce the observed C iv absorption. The ionization parameter is constrained to be $-4.0 \leq \log U \leq -2.5$ for the Mg ii phase across all clouds and $-1.8 \leq \log U \leq -1.7$ for the C iv phase. Higher values of the ionization parameter for the low phase overproduce Al iii, and lower values overproduce O i. A different ionization parameter for the high phase does not reproduce the observed Si iv absorption. Using a number density of photons of $\log n_\gamma = 4.82$, we find $-2.3 \leq \log n_H \leq -0.8$ (cm$^{-3}$) for the Mg ii phase and $-3.2 \leq \log n_H \leq -3.0$ (cm$^{-3}$) for the C iv phase. Ly$\alpha$ is not covered due to the low redshift of this system, so there is no constraint on metallicity.

For this system, a change of the ionizing spectrum from quasars plus star-forming galaxies to quasars only (see §2) did have a negligible effect. In the quasar-only case, the ionization parameter in the high-ionization phase needed to be increased by 0.3 dex to $\log U \sim 1.5$, and the abundance of aluminum needed to be decreased by 0.5 dex relative to solar.

3.4. $HE 2217-2818$, $z = 1.555845$

This is a multiple-cloud absorber in Mg ii, with six resolved components and requires a second phase to reproduce the observed...
C iv absorption. The ionization parameter is constrained to be
$\log U = -4.0$ for the Mg ii phase and $-2.5 \leq \log U \leq -2.0$ in
the C iv phase. A high-ionization parameter for the low-phase
overproduces Al iii, while a lower ionization parameter under-
produces the observed Fe ii absorption. Other values of the ioniza-
tion parameter for the high phase cannot reproduce the observed
Si iv absorption. Using a number density of photons of $\log n_e = -4.78$, we find $\log n_{\text{H}} \leq -0.8$ (cm$^{-3}$) for the Mg ii phase and
$-2.8 \leq \log n_{\text{H}} \leq -2.3$ (cm$^{-3}$) for the C iv phase. It is likely
that $\alpha$-enhancement is required to explain the observed absorption
of Fe and Al within this range of ionization parameters. The
strength of the Ly$\alpha$ line relative to the low-ionization transitions
implies a metallicity of $\log Z/Z_{\odot} \geq -1.4$.

3.5. HE 0001-2340, $z = 1.651462$

This is a narrow, single-cloud absorber in Mg ii. Two phases
are needed to reproduce the observed C iv absorption. There are
two possibilities for fitting the low-ionization phase. One is
to use $\log U \geq -3.5$ and to decrease the abundances of Si, Al,
and C relative to the solar value. The other possibility is to use
$\log U \leq -4.0$ and to decrease the abundances of Fe, Al, and C
relative to solar. The magnitude of the required adjustment is
only about 0.7 dex for each element. Using a number density of
photons of $\log n_e = -4.8$, we find $\log n_{\text{H}} \leq -1.3$ (cm$^{-3}$)
and $\log n_{\text{H}} \geq -0.8$ (cm$^{-3}$), respectively, for the two values
of the ionization parameter. The higher ionization parameter
decreases the observed Fe absorption, but overproduces the Si
absorption, while the lower ionization parameter decreases the
observed Si absorption, but overproduces the Fe absorption. We
remark that these abundance patterns are consistent with dust
depletion and that this is one possible explanation for the observed
absorption profiles (Welty et al. 2002). The ionization parameter
is constrained to be $-1.7 \leq \log U \leq -1.5$ for the C iv phase
based on the observed Si iv $\lambda\lambda 1393, 1402$ doublet, corresponding
to $-3.25 \leq \log n_{\text{H}} \leq -3.05$ (cm$^{-3}$). The strength of the Ly$\alpha$ line
implies a metallicity of $\log Z/Z_{\odot} \geq -1.5$ for the low-ionization
phase. For the C iv phase, low metallicities ($\log Z/Z_{\odot} = -2.5$ for
the blueward component and $\log Z/Z_{\odot} = -1.7$ for the redward
component) fit the Ly$\alpha$ profile, but higher metallicities and a sepa-
rate Ly$\alpha$ phase are also permitted.

![Fig. 4.—The $z = 1.555845$ system toward HE 2217–2818, displayed as in Fig. 1. Only relevant transitions are displayed here. This model uses $\log U = -4.0$ for the low-ionization phase and $\log U = -2.0$ for the high-ionization phase. Metallicity $\log Z/Z_{\odot} = 1.4$. [See the electronic edition of the Journal for a color version of this figure.]](https://example.com/fig4.png)
3.6. HE 0151–4326, z = 1.708494

This is a single-cloud absorber in Mg ii. Due to blends at the expected locations of the C iv λλ1548, 1550 doublet and the Si iv λλ1393, 1402 doublet, it is not possible to absolutely determine whether a second, high-ionization phase is needed. The ionization parameter for the low-ionization phase is constrained to be log U/C21/C0/4 ≤ 0, which is based on the observed strength of Fe ii absorption. Using a number density of photons of log n/C13/C0/4 ≤ 7.4, we find log n/H/C20/C0/0 ≤ 7 (cm⁻³). For the high-ionization phase, if used, we find an ionization parameter of log U/C20/C0/3 ≤ 2. This corresponds to log n/H/C20/C0/0 ≤ 4. A metallicity of log Z/Z/Solar/C12/C21/C0/1 ≤ 5 is required in order not to overproduce Lyα in the red wing; however, the blue wing of Lyα requires a separate, extremely low metallicity phase to be fit.

3.7. HE 2347–4342, z = 1.796237

This is a very weak, narrow single-cloud absorber in Mg ii, although a very weak second component improves the fit in the blue wing. Due to blends at the expected locations of the C iv λλ1548, 1550 doublet and the Si iv λλ1393, 1402 doublet, there is some ambiguity in our assessment of a second phase. However, because the Si iv and C iv are weak, for some parameter choices it is possible for them to arise in the same phase with the Mg ii. There are two possibilities for modeling the Mg ii phase. First, we can use an ionization parameter of log U ≥ −3.2 to match the observed Fe ii, but decrease the abundance of Si and Al relative to solar. Alternatively, we can match the observed abundance of Si iii by using an ionization parameter −4.0 ≤ log U ≤ −3.2, but decrease the abundance of Si, Al, and Fe. Using a number density of photons of log n/C13/C0/4 ≤ 7.2, we find log n/H/C20/C0/0 ≤ −1.5 (cm⁻³) or −1.5 ≤ log n/H/C20/C0/0 ≤ −0.7 (cm⁻³), respectively. If a second phase is used to fit the high-ionization transitions, the parameters are −2.0 ≤ log U ≤ −1.0, so as not to overproduce Si iv. This corresponds to −2.7 ≤ log n/H/C20/C0/0 ≤ −3.7. The metallicity of the low-ionization phase is constrained to be log Z/Z/Solar/C12/C21/C0/1 ≤ −1.0. However, the observed Lyα absorption cannot be fully matched without using a separate, extremely low metallicity phase, even with the addition of the broader high-ionization phase.

3.8. Q0453–423, z = 1.858380

This is a multiple-cloud absorber in Mg ii, with six resolved components. A second phase is needed to fit Si iii and Si iv λ1403. Although C iv is badly blended, we know that it is relatively weak, classifying this as a C iv–deficient system. The ionization parameter of the low-ionization phase is constrained to be log U = −4.0 in order to produce the observed Fe ii absorption. Using a number density of photons of log n/C13/C0/4 = −4.71, we find log n/H/C20/C0/0 ≤ −0.8 (cm⁻³).
This model does not produce the observed Si \(\text{iii}\) or Si \(\text{iv}\), and it does not produce significant C \(\text{iv}\) absorption. A second phase with \(\log U = -2.8\) can account for the observed Si \(\text{iii}\) and Si \(\text{iv}\), but slightly overproduces Mg \(\text{ii}\), Si \(\text{ii}\), and C \(\text{iv}\). A slight (few tenths of a dex) abundance pattern adjustment of these elements could resolve this discrepancy. The strength of the Ly\(\alpha\) line implies a metallicity of \(\log Z/Z_\odot = 0\) for the low-ionization phase, but additional offset high-ionization components, not constrained by these data, could contribute substantially to the Ly\(\alpha\) absorption. If so, the low-ionization phase could have substantially higher metallicity.

3.9. \textit{HE 0940–1050, z = 2.174546}

This is a single-cloud absorber in Mg \(\text{ii}\). A second phase is required to reproduce the observed C \(\text{iv}\) absorption. The ionization parameter is constrained to be \(-3.7 \leq \log U \leq -2.5\) for the Mg \(\text{ii}\) phase and \(-2.0 \leq \log U \leq -1.0\) for the five clouds in the C \(\text{iv}\) phase. The bluest cloud in the C \(\text{iv}\) phase has the lowest ionization parameter. A higher ionization parameter in the low phase will overproduce high-ionization transitions; however, lower ionization parameters require a reduction in the abundance of aluminum and iron by up to 0.7 dex. The ionization parameter in the high phase is constrained by the observed absorption of Si \(\text{iv}\). Using a number density of photons of \(\log n_\gamma = -4.69\), we find \(\log n_{\text{II}} \leq -2.2\) cm\(^{-3}\) for the Mg \(\text{ii}\) phase and \(-3.7 \leq \log n_{\text{II}} \leq -2.7\) (cm\(^{-3}\)) for the five clouds in the C \(\text{iv}\) phase. The strength of the Ly\(\alpha\) line implies a metallicity of \(\log Z/Z_\odot \geq -2.0\). Another phase is required to match the blue wing of the Ly\(\alpha\) profile.

4. DISCUSSION

We have compared the basic and derived properties of weak Mg \(\text{ii}\) absorbers over the redshift range \(0.4 < z < 2.4\). We include the nine systems at \(1.4 < z < 2.4\) from the survey of Lynch et al. (2006), as well as systems from Rigby et al. (2002), Charlton et al. (2003), Zonak et al. (2004), Ding et al. (2005), and Masiero et al. (2005) with \(z < 1.4\). We consider single- and multiple-cloud weak Mg \(\text{ii}\) absorbers separately, since they are likely to have different origins.

One of the most important basic properties of single-cloud weak Mg \(\text{ii}\) absorbers at \(0.4 < z < 1.4\) is their two-phase structure. Mg \(\text{ii}\) is found to arise in a higher density region, while the strength of the C \(\text{iv}\) absorption requires a separate, lower density region (Rigby et al. 2002). This same two-phase structure is also found in all four single-cloud weak Mg \(\text{ii}\) absorbers at \(1.4 < z < 2.4\) for which it was possible to place a constraint on a second phase. The other two single-cloud weak Mg \(\text{ii}\) absorbers in the \(1.4 < z < 2.4\) sample had blends at the expected location of C \(\text{iv}\) that prevented us from deriving a constraint. For comparison, the weaker extragalactic background radiation (EBR) at \(z \sim 0\) would lead to
broader Mg ii components arising from the high-ionization phase of single-cloud weak Mg ii absorbers and to detectable Mg ii absorption from some structures that at higher redshift produced only high-ionization absorption (Narayanan et al. 2007).

Most $0.4 < z < 1.4$ multiple-cloud weak Mg ii absorbers also require separate phases to explain simultaneously the observed Mg ii and C iv absorption. Our three multiple-cloud weak Mg ii absorbers at $1.4 < z < 2.4$ also required two-phase models. At both redshift regimes, we see examples of C iv–deficient multiple-cloud weak Mg ii absorbers, where a second phase may not be needed (e.g., the $z = 0.5584$ system toward PG 1241+176 [Ding et al. 2005] and the $z = 0.7290$ system toward PG 1248+401 [Masiero et al. 2005]) or is needed, but produces only weak absorption (our $z = 1.796237$ system toward HE 2347−4342).

Thus, there may be a difference between single- and multiple-cloud weak Mg ii absorbers in the fraction that have a second, lower density phase producing relatively significant C iv absorption. Also, there seems to be a significant difference in the nature of...
the second phase in cases where it is required. For single-cloud weak Mg II absorbers, both at $0.4 < z < 1.4$ and at $1.4 < z < 2.4$, there is always a C IV cloud centered on the Mg II (within $\sim 3$ km s$^{-1}$). There may also be additional, offset C IV clouds, which tend to be weaker. The multiple-cloud weak Mg II absorbers do not usually have a direct correspondence between the C IV and the Mg II clouds. In both types of absorbers, we might postulate a sheetlike or shell geometry, with separate layers responsible for the Mg II and C IV absorption. However, in the case of the single-cloud Mg II absorbers, it would appear that the layers are quite quiescent and are moving in unison. This would suggest an origin in an environment that has not experienced recent star formation or turbulence.

Figure 10 shows Mg II column density versus $z$ for single-cloud systems, and Figure 11 shows their Doppler parameter versus $z$. There is no apparent change in these parameters across redshift. The same can be said for Figures 12 and 13, which show column density versus $z$ and Doppler parameter versus $z$ for multiple-cloud systems, respectively. Table 2 also gives this information.

Figure 14 shows $n_H$ versus $z$ for systems with a single absorption component in Mg II. There is a large spread in the derived properties for the low-redshift absorbers, but no systematic trend is apparent across redshift. In most cases, only upper limits could be obtained for the density. However, limits for $n_H$ of the high-redshift systems are consistent with those of the low-redshift systems. To verify that there is no significant evolution, we applied the Spearman-Kendall nonparametric rank correlation tests, which take into account the upper limits in the data (Isobe et al. 1986; Lavalle et al. 1992). The Spearman and Kendall tests showed, respectively, 62% and 85% chances that a correlation is not present.

Figure 15 shows $n_H$ versus $z$ for multiple-cloud absorbers. Although our sample size is small, again there is no obvious change in the properties of the absorbers across redshift. Figure 16 shows $Z/Z_\odot$ versus $z$ for single-cloud absorbers. Metallicity constraints could not be obtained for all absorbers because there was not always coverage of the Ly$\alpha$ line. Taking into account the limits, we cannot see a significant change in the properties with redshift. The Spearman-Kendall tests yielded a large probability.
that there is no correlation. However, it is worth noting that we do not yet know of a $z > 1.4$ absorber with a high (close to solar) metallicity. There are a few solar or higher metallicity absorbers (25% of the sample) at $z < 1.4$. Figure 17 shows log $Z/Z_\odot$ versus $z$ for multiple-cloud absorbers. Once again, we suffer from a small sample size, but the metallicities of the high-redshift systems are consistent with those of the low-redshift systems.

First, we consider the possible implications of our results for the multiple-cloud absorbers. This class can be broadly grouped into two categories. First, there are those multiple-cloud absorbers that are kinematically spread and are likely almost strong Mg $\text{II}$ absorbers for which the line of sight simply does not pass through dense regions of gas. Second, there are those multiple-cloud absorbers that are kinematically compact and are likely dwarf galaxies or are associated with dwarf galaxies (Zonak et al. 2004; Ding et al. 2005; Masiero et al. 2005). The $z = 1.450109$ system toward Q0122–380 is an example of a kinematically compact absorber. The metallicity of this system is constrained to be $-1.0 \leq \log Z/Z_\odot \leq 0.0$. The $z = 1.555845$ system towards HE 2217–2818 and the $z = 1.858380$ system toward Q0453–423 are examples of kinematically spread absorbers. The metallicities of these two systems are constrained to be $\log Z/Z_\odot \geq -1.1$ and $\log Z/Z_\odot \geq -2.0$. Because the metallicities of our systems are not well constrained, we cannot draw any definite conclusions about the environments in which each type of system arises.

The redshift path density of single-cloud weak Mg $\text{II}$ absorbers is observed to decrease between $z \sim 1$ and 2 (Churchill et al. 1999; Lynch et al. 2006). Some of this evolution is due to the changing EBR, which varies in the range $-4.83 < \log n_e < -4.71$ (cm$^{-3}$) for $1.4 < z < 2.4$, respectively. The effect of the changing EBR is to lead to more low-ionization Mg $\text{II}$ gas at lower redshift. In addition, cosmological effects will lead to a decrease in the density of weak Mg $\text{II}$ absorbers at lower redshift. When these two competing effects are taken together, they cannot fully account for the lower $dN/dz$ at $z \sim 2$. The range of physical conditions that were found in this study (column density, Doppler parameter, density, and metallicity) for systems at redshift $1.4 < z < 2.4$ do not show a statistical variation from systems at redshift $0.4 < z < 1.4$. The ranges are large, constraints

---

**Fig. 9.** The $z = 2.174546$ system toward HE 0940–1050, displayed as in Fig. 1. Only relevant transitions are displayed here. This model uses $\log U = -3.7$ for the low-ionization phase and $\log U = -2.0$ for the high-ionization phase. Metallicity is $\log Z/Z_\odot = -2.0$. [See the electronic edition of the Journal for a color version of this figure.]
are derived using different transitions at different redshifts, and our samples are small, leading to dilution of any trends. However, at face value our result is consistent with the idea that the evolution in the weak Mg \textsc{ii} absorber population from \( z \approx 2 \) to 1 is due to an increase in the efficiency of the mechanisms that create weak Mg \textsc{ii} absorbers, and not due to a change in the actual mechanisms. For example, if a collapse process gave rise to weak Mg \textsc{ii}–absorbing structures, then, to first order, one would expect a constant range of densities across redshift. Since we see such a constant range, the observed evolution in \( \frac{dn}{dz} \) would then be attributed to a change in the number of structures undergoing such a collapse as a function of redshift.

We now turn our attention to the effects of a changing metallicity. As metallicity generally increases with decreasing redshift, we would expect that, at low redshift, lower total hydrogen column density absorbers could give rise to weak Mg \textsc{ii} absorption.

This would lead to a rise in the number of weak Mg \textsc{ii} absorbers. In our data set, although there is no statistically significant trend, an increase in metallicity with decreasing redshift is still consistent with the data. Because we have a relatively small data set and only have limits in most cases, we cannot draw a firm conclusion about the change in metallicity across redshift. Thus, it is possible that the increase in weak Mg \textsc{ii} absorbers at lower redshift is at least in part due to a systematic increase in metallicity. This may be a fruitful avenue for future study. To improve metallicity constraints, we would need access to lower Lyman series lines. The narrow, low-ionization components have a dominant contribution to these Lyman series lines, while the Ly\( \alpha \) absorption can have contributions from broader components (Churchill et al. 1999; see their Fig. 4).

In summary, through our modeling we have found that the properties of single-cloud weak Mg \textsc{ii} absorbers at \( 1.4 < z < 2.4 \)
are similar to those of single-cloud weak Mg ii absorbers at \( 0.4 < z < 1.4 \). These properties include the existence of two phases, the gas densities, the Doppler parameters, the relatively high metallicities, and the presence of offset C iv components. It is striking that the dominant C iv component, although produced in a different phase, is centered at the same velocity as the Mg ii cloud. Using the facts that almost all C iv absorbers are found within \( \sim 100 \) kpc of luminous galaxies and that half of C iv absorbers have weak Mg ii absorption, Milutinović et al. (2006) argued that weak Mg ii absorbers are likely to arise \( \sim 50–100 \) kpc from luminous galaxies.

Of course, the fundamental goal of our study is to identify single-cloud weak Mg ii absorbers with a specific environment and physical process. The lack of evolution in their properties suggests a common mechanism working over time. The various possibilities include shells or supernova remnants in dwarf galaxies, high-velocity clouds, and shells of enriched material surrounding galaxies in the cosmic web. These possibilities have in common the feature that the high- and low-ionization gas could be separated, but moving at the same velocity, consistent with the arguments of Milutinović et al. (2006).

Lynch et al. (2006) note that the star formation history in dwarf galaxies seems to be consistent with the evolution of the absorber population and suggest that this is a possible process that could give rise to weak Mg ii absorbers. The fact that there is no significant change in the properties of this population across redshift suggest that this scenario is possible. We note that if this idea is correct, then star formation in the regions would have stopped long ago. No UV photons would be left, and so we are justified in using a background spectrum rather than local stellar...
sources. The results of the present study are consistent with the dwarf galaxy hypothesis. The origin of single-cloud weak Mg ii absorbers in the extra-galactic analogs of high-velocity clouds also remains a possibility. The appeal of this scenario is its consistency with the phase structure found in Milky Way high-velocity clouds (Ganguly et al. 2005; Fox et al. 2005), the similar velocities of low- and high-ionization gas in the high-velocity clouds, and the large covering factor of the sky by Milky Way O vi high-velocity clouds (Sembach et al. 2003). If Milky Way high-velocity clouds are produced by cool or warm clouds sweeping through the Galactic corona, a similar phenomenon would be expected to occur around other galaxies, leading to typical impact parameters of ~50–100 kpc for lines of sight that pass through the high-velocity cloud, but not through the luminous galaxy disk. Any distinction between these sheetlike high-velocity cloud structures and portions of the cosmic web clustered near galaxies may just be a matter of semantics. Comparisons between the O vi absorption in single-cloud weak Mg ii absorbers and in Milky Way high-velocity clouds is a useful diagnostic, although challenging because of the location of O vi in the Lyα forest.

5. Conclusion

We used the photoionization code Cloudy to model nine weak Mg ii absorption systems found by Lynch et al. (2006). The Doppler parameter and column density of Mg ii were measured using the Minfit program (Churchill et al. 1999), and these were used as constraints by Cloudy. The ionization parameter and metallicity were then adjusted incrementally in Cloudy for each Mg ii cloud until the simulated absorption profiles matched the observed absorption profiles of other transitions in the spectra. It was usually necessary to include a second, high-ionization phase in order to reproduce the observed absorption in C iv. This was necessary because the C iv profile was too broad and/or too strong to arise solely from the Mg ii phase gas. It was sometimes the case that only an upper or lower limit could be placed on the conditions of the system due to blends at the expected locations of certain transitions. These results were then compared to models of absorbers at 0.4 < z < 1.4 and checked for any evolution across redshift.

1. Six of the nine systems had only a single component of absorption in Mg ii (single cloud), and the remaining three showed multiple components (multiple cloud).

2. A multiphase structure was required in seven of the nine systems. One system had blends at the expected location of C iv and Si iv, and no definite conclusions about a multiphase structure could be reached. In another system, the C iv profile was weak enough that a second phase was not definitely needed, although it was preferred.

3. For single-cloud systems, we find the following constraints on physical properties:

a) For the z = 1.405362 absorber toward HE 2347−4342, 2.3 ≤ log n_H ≤ −1.8 (cm^{-3}) for the low-ionization phase and log n_H ≤ −3.1 (cm^{-3}) for the required high-ionization phase; no metallicity constraint.

b) For the z = 1.446496 absorber toward Q0002−422, −1.8 ≤ log n_H ≤ −1.3 (cm^{-3}) for the low-ionization phase and 3.5 ≤ log n_H ≤ −3.0 (cm^{-3}) for the required high-ionization phase; no metallicity constraint.

c) For the z = 1.651462 absorber toward HE 0001−2340, there are two possibilities for fitting the low-ionization phase: log n_H ≤ −1.3 (cm^{-3}), with decreases in Si, Al, and C relative to solar, or log n_H ≤ −0.8 (cm^{-3}), with decreases in Fe, Al, and C relative to solar; −3.3 ≤ log n_H ≤ −3.1 (cm^{-3}) for the required high-ionization phase; log Z/Z_⊙ ≥ −1.5.

d) For the z = 1.708494 absorber toward HE 0151−4326, log n_H ≤ −0.7 (cm^{-3}) for the low-ionization phase; blends in high-ionization transitions, but high-ionization phase may not be required; log Z/Z_⊙ ≥ −1.5 for the low-ionization phase.

e) For the z = 1.796237 absorber toward HE 2347−4342 there are two possibilities for fitting the low-ionization phase: log n_H ≤ −1.5 (cm^{-3}) or −1.5 ≤ log n_H ≤ −0.7 (cm^{-3}); log Z/Z_⊙ ≥ −1.0 for the low-ionization phase; blends in high-ionization phase; weak C iv could arise in the same phase with Mg ii, but separate phases are also permitted.

f) For the z = 2.174546 absorber toward HE 0940−1050, log n_H ≤ −2.2 (cm^{-3}) for the low-ionization phase and −3.7 ≤ log n_H ≤ −2.7 (cm^{-3}) for the high-ionization phase; log Z/Z_⊙ ≥ −2.0.

4. For multiple-cloud systems, we find the following constraints on physical properties:

a) For the z = 1.450109 absorber toward Q0122−380, −2.3 ≤ log n_H ≤ −0.8 (cm^{-3}) for the low-ionization phase and −3.2 ≤ log n_H ≤ −3.0 (cm^{-3}) for the high-ionization phase; −1.0 ≤ log Z/Z_⊙ ≤ 0.0.

b) For the z = 1.555845 absorber toward HE 2217−2818, log n_H ≤ −0.8 (cm^{-3}) for the low-ionization phase and −2.8 ≤ log n_H ≤ −2.3 (cm^{-3}) for the high-ionization phase; log Z/Z_⊙ ≥ 1.1.

c) For the z = 1.858380 absorber toward Q0453−423, log n_H ≤ −0.8 (cm^{-3}) for the low-ionization phase and log n_H = −1.9 (cm^{-3}) for the high-ionization phase; log Z/Z_⊙ ≥ −2.0.

The properties of the absorber population as stated above are not significantly different across the redshift range 0.4 < z < 2.4; i.e., the variation in parameters over the sample of absorbers that produce weak Mg ii absorption is larger than any systematic evolution with redshift. These properties include the presence of two phases to produce Mg ii and C iv absorption and the density of the gas that produces Mg ii absorption. With a limited number of metallicity constraints at high redshift, the data are consistent either with constant metallicity from 0.4 < z < 2.4 or with a metallicity that increases with time. With our increased sample size, one of the most significant results is that the required high-ionization cloud is always centered within 3 km s^{-1} of the single-cloud weak Mg ii absorption.

The lack of evolution in the properties of single-cloud weak Mg ii absorbers implies that the change in the number statistics of absorbers across redshift is due to changes in the rate of relevant processes, and not due to a change in the nature of these processes that give rise to weak Mg ii absorbers. Another possibility for explaining the evolution of the number of weak Mg ii absorbers is a systematic increase in metallicity of the absorbing structures from z ~ 2 to 1. The close correspondence in the velocities of the low- and high-ionization phases suggests a layered structure that could be physically consistent with supernova remnants or winds in dwarf galaxies, or with extragalactic analogs to high-velocity clouds.

The authors wish to thank an anonymous referee for helpful comments and acknowledge the National Science Foundation under grant NSF AST 04-07138 and the REU program and an REU Supplement, as well as NASA under grant NAG5-6399 NNG04GE73G.
REFERENCES

Bergeron, J., & Boissé, P. 1991, A&A, 243, 344
Bergeron, J., Cristiani, S., & Shaver, P. A. 1992, A&A, 257, 417
Charlton, J. C., Ding, J., Zonak, S. G., Churchill, C. W., Bond, N. A., & Rigby, J. R. 2003, ApJ, 589, 111
Churchill, C. W., & Charlton, J. C. 1999, AJ, 118, 59
Churchill, C. W., Kacprzak, G. G., & Steidel, C. C. 2005, in IAU Colloq. 199, Probing Galaxies through Quasar Absorption Lines, ed. P. R. Williams et al. (Cambridge: Cambridge Univ. Press), 24
Churchill, C. W., Mellon, R. R., Charlton, J. C., Jannuzi, B. T., Kirhakos, S., Steidel, C. C., & Schneider, D. P. 2000, ApJ, 543, 577
Churchill, C. W., Rigby, J. R., Charlton, J. C., & Vogt, S. S. 1999, ApJS, 120, 51
Churchill, C. W., Vogt, S. S., & Charlton, J. C. 2003, AJ, 125, 98
Ding, J., Charlton, J. C., & Churchill, C. W. 2005, ApJ, 621, 615
Ferland, G., Korista, K. T., Verner, D. A., Ferguson, J. W., Kingdon, J. B., & Verner, E. M. 1998, PASP, 110, 761
Fox, A. J., Wakker, B. P., Savage, B. D., Tripp, T. M., Sembach, K. R., & Bland-Hawthorn, J. 2005, ApJ, 630, 332
Gabasch, A., et al. 2004, ApJ, 616, L83
Ganguly, R., Sembach, K. R., Tripp, T. M., & Savage, B. D. 2005, ApJS, 157, 251
Haardt, F., & Madau, P. 1996, ApJ, 461, 20
———. 2001, in Recontres de Moriond XXXVI, Clusters of Galaxies and the High Redshift Universe Observed in X-Rays, ed. D. M. Neumann & J. T. T. Van (Paris: ESA), 64
Isobe, T., Feigelson, E. D., & Nelson, P. I. 1986, ApJ, 306, 490
Kauffmann, G., White, S. D. M., Heckman, T. M., Ménard, B., Brinchmann, J., Charlot, S., Tremonti, C., & Brinkmann, J. 2004, MNRAS, 353, 713
Kim, T.-S., Viel, M., Haehnelt, M. G., Carswell, R. F., & Cristiani, S. 2004, MNRAS, 347, 355
Lavalley, M., Isobe, T., & Feigelson, E. 1992, in ASP Conf. Ser. 25, Astronomical Data Analysis Software and Systems I, ed. D. M. Worrall, C. Biemesderger, & J. Barnes (San Francisco: ASP), 245
Le Brun, V., Bergeron, J., Boisse, P., & Christian, C. 1993, A&A, 279, 33
Lynch, R. S., Charlton, J. C., & Kim, T.-S. 2006, ApJ, 640, 81
Masiero, J. R., Charlton, J. C., Ding, J., Churchill, C. W., & Kacprzak, G. 2005, ApJ, 623, 57
Milutinović, N., Rigby, J. R., Masiero, J. R., Lynch, R. S., Palma, C., & Charlton, J. C. 2006, ApJ, 641, 190
Narayanan, A., Charlton, J. C., Masiero, J. R., & Lynch, R. 2007, ApJ, 632, 92
Nestor, D. B., Turnshek, D. A., & Rao, S. M. 2005, ApJ, 628, 637
Rigby, J. R., Charlton, J. C., & Churchill, C. W. 2002, ApJ, 565, 743
Sembach, K. R., et al. 2003, ApJS, 146, 165
Simcoe, R. A., Sargent, W. L. W., Rauch, M., & Becker, G. 2006, ApJ, 637, 648
Steidel, C. C. 1995, in QSO Absorption Lines, ed. G. Meylan (Berlin: Springer), 139
Steidel, C. C., Dickinson, M., Meyer, D. M., Adelberger, K. L., & Sembach, K. R. 1997, ApJ, 480, 568
Steidel, C. C., Dickinson, M., & Persson, S. E. 1994, ApJ, 437, L75
Welty, D. E., Jenkins, E. B., Raymond, J. C., Mallouris, C., & York, D. G. 2002, ApJ, 579, 304
Zonak, S. G., Charlton, J. C., Ding, J., & Churchill, C. W. 2004, ApJ, 606, 196