A SURVEY OF ANALOGS TO WEAK Mg II ABSORBERS IN THE PRESENT

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ABSTRACT

We present the results of a survey of the analogs of weak Mg II absorbers [rest-frame equivalent width \( W_r(2796) < 0.3 \) Å] at 0 < z < 0.3. Our sample consisted of 25 HST STIS echelle quasar spectra (\( R = 45,000 \)), which covered Si II \( \lambda 1260 \) and C II \( \lambda 1335 \) over this redshift range. Using those similar transitions as tracers of Mg II facilitates a much larger survey, covering a redshift path length of \( \delta z = 5.3 \) for an equivalent width limit of Mg II corresponding to \( W_r(2796) > 0.02 \) Å, with 30% completeness for the weakest lines. Correcting for incompleteness, we find the number of weak Mg II absorber analogs with 0.02 Å < \( W_r(2796) < 0.3 \) Å to be \( dN/dz = 1.00 \pm 0.20 \) for 0 < z < 0.3. This compares to a value of \( dN/dz = 1.74 \pm 0.10 \) found by Churchill et al. for the higher redshift range, 0.4 < z < 1.4, and is consistent with cosmological evolution of the population. We consider the expected effect on observability of weak Mg II absorbers of the decreasing intensity of the extragalactic background radiation field from z ~ 1 to ~0. Assuming that all the objects that produce absorption at z ~ 1 are stable on a cosmological timescale and that no new objects are created, we would expect \( dN/dz \sim 2-3 \) at z ~ 0. About 30%–50% of this z ~ 0 population would be descendants of the parsec-scale structures that produce single-cloud, weak Mg II absorbers at z ~ 1. The other 50%–70% would be lower density, kiloparsec-scale structures that produce C IV absorption, but not detectable low-ionization absorption, at z ~ 1. We conclude that at least one, and perhaps some fraction of both, of these populations has evolved away since z ~ 1, in order to match the z ~ 0 value of \( dN/dz \) measured in our survey. This would follow naturally for a population of transient structures whose generation is related to star-forming processes, whose rate has decreased since z ~ 1.

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1. INTRODUCTION

Quasar absorption-line systems have been observed at redshifts 0 < z < 6. They provide detailed information about the chemical contents, kinematics, and ionization states of a variety of gaseous structures ranging from galaxies to the diffuse interstellar medium. The population of weak Mg II absorbers [those with rest-frame equivalent width \( W_r(2796) < 0.3 \) Å] provides an opportunity to probe an otherwise elusive part of the network of otherwise invisible galaxies. Regardless of their mechanism or mechanisms of origin, weak Mg II absorbers are likely to be important in a global picture of star formation, galaxy formation, and/or the interplay between galaxies and their surroundings.

Because of the practical consideration of simplicity of optical observations, most of our information about weak Mg II absorbers is for redshifts in the range 0.4 < z < 1.4. Churchill et al. (1999) conducted a comprehensive survey over this range, using the High Resolution Echelle Spectrometer (HIRES; Vogt et al. 1994) on the Keck I telescope. They found a redshift path density of \( dN/dz = 1.74 \pm 0.10 \) for weak Mg II absorbers with 0.02 Å < \( W_r(2796) < 0.3 \) Å. Two-thirds of these absorbers have single clouds, unresolved at a resolution of \( \sim 6.6 \) km s\(^{-1}\), while the others have multiple clouds spread over tens to hundreds of km s\(^{-1}\).

The most surprising property of the single-cloud, weak Mg II absorbers is their high metallicities. The metallicity of the gas producing the Mg II absorption is usually constrained to be at least 10% solar when constraints are available (Rigby et al. 2002), but in several of the cases with the best constraints the values are solar or even supersolar (Charlton et al. 2003). This is surprising in view of the fact that luminous galaxies are rarely found within a ~50 h\(^{-1}\) kpc impact parameter of the quasar (Churchill et al. 1999). In some cases the ratio of Fe II to Mg II precludes the possibility of \( \alpha \)-enhancement from Type II supernovae, and therefore metals seem to be generated in situ rather than being ejected from distant giant galaxies (Rigby et al. 2002). The observed redshift path density (\( dN/dz \)) of weak Mg II absorbers is twice that of the strong Mg II absorbers, which are known to be associated with luminous galaxies [within 38(L/L\(_{\odot}\))\(^{0.15}\) h\(^{-1}\) kpc; Steidel 1995] and which fully account for almost all of the cross section such galaxies are expected to provide. We are thus drawn to the conclusion that as much of the sky is covered by significantly metal-enriched regions that are not related to giant galaxies as is covered by such galaxies.

Several other properties of the single-cloud, weak Mg II absorbers are relevant to an interpretation of their origins. From photoionization models, the thickness of the Mg II absorbing
region is on the order of $1\text{–}100$ pc (Rigby et al. 2002; Charlton et al. 2003). Centered at the same velocity as the Mg ii absorption is C iv absorption, which is constrained to arise in a separate higher ionization region. This constraint generally comes from a consideration of whether the ionization parameters consistent with the low-ionization absorption can produce the observed C iv absorption. The two-phase structure consists of a thin or small Mg ii absorbing region (with density $\sim 0.1 \text{ cm}^{-3}$) and a larger (hundreds of pc to a couple of kpc), lower density region that produces C iv absorption. The geometries of and relationship between these regions are uncertain, but flattened geometries are generally more consistent with the number statistics and kinematics of the absorbers (N. Milutinović et al. 2005, in preparation).

There are a number of such indirect clues as to the nature of weak Mg ii absorbers, but not yet any definite answers. Obviously, the situation would be simplified if a direct connection was found between the absorber and a nearby luminous structure. Such structures might be dwarf galaxies, star-forming regions in intergalactic cold dark matter filaments, or intergalactic star clusters of some sort. If such objects are to be detected, they must be at low redshift. Several absorbers have been detected at $z < 0.3$ that, although Mg ii is not covered in existing spectra, are almost certainly analogs to the weak Mg ii absorber population at $z < 1$. In the case of the $z = 0.005260$ absorber toward 3C 273, there is a post-starburst dwarf galaxy within $80 h^{-1}$ kpc of the line of sight, which leads Stocke et al. (2004) to the conclusion that winds from that dwarf are responsible for the absorption. A similar situation has been suggested to apply in the case of the $z = 0.167$ absorber toward PKS 0405–123 (Chen & Prochaska 2000). It is difficult, however, to be sure that a nearby galaxy is, in fact, itself responsible for such absorption, rather than a less luminous object in the same group or cluster. Also, it may be important to make a distinction between single- and multiple-cloud weak Mg ii absorbers, which may have different origins (Zonak et al. 2004; Ding et al. 2003b). Finding a larger sample of $0 < z < 0.3$ weak Mg ii absorber analogs was one of the motivations for this work. We report on our systematic survey of the archive of Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph (STIS) observations of quasars.

Our survey facilitates a formal calculation of the redshift path density of weak Mg ii absorber analogs at $z \simeq 0$. This number can be compared with the value at $0.4 < z < 1.4$ to consider the evolution of the population of objects that produce weak Mg ii absorption. On the basis of their properties, it is not clear that these objects should be stable. Their two phases of gas are not in pressure balance (Rigby et al. 2002; Charlton et al. 2003), and a large amount of invisible matter (baryonic or dark) would be needed to attain gravitational stability (Schaye 2001). If we are studying the evolution of a transient population, we are learning about the evolution of the processes that created the absorbing structures. On the other hand, for a population of star clusters formed at very high redshift, we would expect a stable population of weak Mg ii absorbers that followed cosmological evolution governed by a changing extragalactic background radiation.

This paper begins with a description of the HST STIS echelle data that were used for our survey. We describe how we are able to survey a significant path length by using the similar Si ii $\lambda 1260$ and C ii $\lambda 1335$ transitions as tracers of Mg ii $\lambda \lambda 2796, 2803$. In § 3.1 we first discuss the individual systems found in our survey, describing their properties and the results of previous studies of them by other investigators. We then present in § 3.2 a formal calculation of the redshift number density, $dN/dz$, correcting for our survey completeness. The expected evolution of the population of weak Mg ii absorbers, taking into account the changing extragalactic background radiation, is estimated in § 4 and compared to the observed value. In § 4.4 the consequences of this for stability of the structures that give rise to weak Mg ii absorption and for the nature of the processes that produce these structures are considered. The final section (§ 5) contains a brief summary and conclusions.

### 2. SURVEY AND DATA ANALYSIS

In order to detect weak metal-line features and to cover most of the key transitions, including the Lyman series lines from potential absorbers at $z < 0.3$, high-resolution spectra in the UV are required. The archived echelle spectra from HST STIS were used for our survey.

#### 2.1. STIS Echelle Spectra

A direct search for Mg ii $\lambda \lambda 2796, 2803$ at $z < 0.3$ would rely on spectra obtained with the E230M grating. As of 2004 July, there were about 15 spectra available that covered 2800–3110 Å, the reddest coverage with this grating. Unfortunately, each spectrum would only offer a limited redshift coverage of $0 < z < 0.11$. Therefore, the maximum cumulative path length for the interval $0 < z < 0.11$ is then approximately $15(0.11) = 1.65$, and this assumes that the whole path length exceeds the required equivalent width limit. We would expect a maximum of three weak Mg ii absorbers in this path length if $dN/dz = 1.74$ as at $(z) = 0.9$. Furthermore, the E230M spectra are quite noisy in the redward regions that would be relevant to our survey. This led us to consider and adopt an indirect approach, using Si ii $\lambda \lambda 1260$ and C ii $\lambda 1335$ as tracers of weak Mg ii absorbers in the E140M spectra.

The E140M echelle grating of STIS has a resolving power of $R \sim 45,000$ (corresponding to $6.6 \text{ km s}^{-1}$) and simultaneous wavelength coverage from 1123 to 1710 Å. For our survey we searched 20 spectra of quasars from the STIS archive that were available before 2004 July. To allow detection of weak metal lines, our search was limited to spectra that have $S/N \geq 5$ pixel$^{-1}$ over a large fraction of the wavelength coverage. Table 1 lists the 20 quasar lines of sight that we searched, with quasar redshifts and some specifics of the HST STIS observations. The Mg ii $\lambda \lambda 2796, 2803$ doublet is not covered for $z < 0.3$ in the many high-quality E140M echelle spectra available in the archive. To circumvent this limitation we instead used two other ions, Si ii and C ii, to trace low-ionization absorption. The 1260 Å transition of Si ii and the 1335 Å transition of C ii are moderately strong in absorption, and they conveniently fall within the wavelength regime of the available E140M data set for redshift $0 < z < 0.3$. The maximum possible cumulative path length for our survey would then be $g(z) = 0$, a factor of 3.6 times larger than a direct Mg ii survey using E230M spectra.

The 20 E140M spectra used for our survey were obtained for a variety of reasons, and some of these reasons could introduce a bias in our survey. For example, a line of sight observed in order to study particular strong Ly$\alpha$ forest absorbers (which were already known to be metal-line systems) could easily be biased toward having a weak Mg ii absorber analog. A line of sight observed for a high-velocity cloud (HVC) study, however, would have no bias for the presence or absence of weak Mg ii absorber analogs. We list in Table 1 the PI of the program that observed each quasar and the proposal ID to aid in consideration of this issue, which we discuss again in § 3.2.

The reduction and calibration of the E140M spectra were performed using the standard STIS pipeline (Brown et al. 2002).
Combination of separate exposures employed weighting by exposure time. Similarly, overlapping orders were combined with equal weight. Weighting by inverse variance (as employed, e.g., by Tripp et al. 2001) was considered but was found to bias the flux downward due to the lower variance of pixels with smaller counts. Even smoothing over several pixels would not eliminate this effect in cases in which individual exposures have S/N $< 1$.

For some quasars that were observed at times separated by months or years, there was often a small shift in the echelle angle and thus a change in the wavelength corresponding to a given pixel. In this case we selected one scale and combined the others by choosing the nearest pixel, rather than interpolation, which would lead to smoothing. The drawback to the procedure we employed is a small effective decrease in resolution. The continuum fit was performed interactively by using the IRAF SFIT task and employing standard methods as described in Sembach & Savage (1992).

### 2.2. Survey Method

To facilitate comparison to the intermediate-redshift survey of Churchill et al. (1999), we estimate the rest-frame equivalent width that a weak Si $\lambda 1260$ and C $\lambda 1335$ absorption feature would have, corresponding to the equivalent width threshold value of 0.3 Å for Mg $\lambda 2796$. Given the fact that the ionization...
potentials of Mg, Si, and C are similar, the relative equivalent widths of Si $\parallel$, C $\parallel$, and Mg $\parallel$ in any system would be largely governed by abundance pattern and by the oscillator strength of individual electronic transitions for each atom or ion. The lack of broad spectral coverage at high resolving power limits the number of weak systems for which the equivalent widths of Si $\parallel \lambda$1260, C $\parallel \lambda$1335, and Mg $\parallel \lambda$2796 are measured. However, the three single-cloud weak Mg $\parallel$ absorbers found in the spectra of PG 1634+706 have all three absorption transitions covered and detected (Charlton et al. 2003). The Si $\parallel \lambda$1260 line is a blended feature in one of the three absorption systems ($z = 0.9055$), and hence only an upper limit could be established for that particular line. The ratio $W_r(1260)/W_r(2796)$ is $0.67 \pm 0.17$ for the $z = 0.8181$ system and $0.68 \pm 0.26$ for the $z = 0.6534$ system. Similarly, the ratios of $W_r(1335)/W_r(2796)$ are $1.45 \pm 0.32 (z = 0.6534), 0.57 \pm 0.12 (z = 0.8181)$, and $0.85 \pm 0.04 (z = 0.9055)$. On the basis of these known values, we used the average values of 0.68 for the Si $\parallel$/Mg $\parallel$ ratio and 0.96 for C $\parallel$/Mg $\parallel$. These values are also representative of those for isolated components of strong Mg $\parallel$ absorbers (Ding et al. 2003a, 2003b, 2005). In summary, a metal-line absorber in our survey is classified as weak if the rest-frame equivalent width $W_r(1260) < 0.20 \, \text{Å}$ and $W_r(1335) < 0.29 \, \text{Å}$. Similarly, a detection limit of 0.02 $\, \text{Å}$ in Mg $\parallel \lambda$2796 (as used by Churchill et al. 1999) corresponds to 0.013 $\, \text{Å}$ in Si $\parallel \lambda$1260 and 0.02 $\, \text{Å}$ in C $\parallel \lambda$1335.

To detect weak, low-ionization systems we first identified all absorption features detected at greater than 5 $\sigma$ significance, as illustrated in Figure 1. Assuming that each identified feature was a redshifted Si $\parallel \lambda$1260 transition, we searched for a 5 $\sigma$ detection at the expected location of C $\parallel \lambda$1335. The equivalent width limits for an unresolved line centered at each pixel were measured, taking into account the instrumental spread function, following the formalism of Steidel & Sargent (1992). In the event that both Si $\parallel \lambda$1260 and C $\parallel \lambda$1335 were detected at a significance level of 5 $\sigma$, we then searched for absorption in neutral hydrogen, through Ly$\alpha$ and Ly$\beta$ transitions at the derived redshift, in order to confirm the detection. In the absence of spectral coverage of both these Lyman series features, we visually inspected the alignment and profile shapes of the low-ionization features of Si $\parallel$ and C $\parallel$.

3. RESULTS FROM SURVEY

For the 20 quasar lines of sight, we found six weak Mg $\parallel$ analog absorbers in a redshift path length of $\Delta z \sim 5.3$ within the redshift interval of $0 \leq z \leq 0.3$. Of these, two have multiple clouds (resolved low-ionization spectral features offset in velocity space), and the other four can be fitted as single-cloud, low-ionization absorbers. The key transitions covered in the STIS spectra are illustrated for the six systems in Figures 2–7, and the equivalent widths and equivalent width limits for these transitions are listed in Table 2. For selected transitions, the column densities and Doppler parameters derived by performing Voigt profile fitting are listed in Table 3.

3.1. Discussion of Individual Systems

3.1.1. 3C 273, $z_{\text{abs}} = 0.005260$

This system is the weakest low-ionization system that we detected in the STIS E140M archive. It is also the nearest extragalactic metal-line system known so far. With $W_r(1260) = 0.010 \pm 0.002 \, \text{Å}$, it falls below the completeness limit of our survey (see § 3.2). This system is unusual for a weak Mg $\parallel$ absorber analog in that C iv $\lambda$1548 is not detected to a $3 \sigma$ limit of $W_r(1548) < 0.012 \, \text{Å}$. In a Far Ultraviolet Spectroscopic Explorer (FUSE) spectrum, Sembach et al. (2001) detect Ly$\beta$ and six other Lyman series lines and use these to derive log $N$(H i) = 15.85, and possibly detect O vi at a $2-3 \sigma$ level. Tripp et al. (2002) combine that information from the FUSE spectrum with the STIS E140M spectrum and derive physical conditions of the absorber. The low-ionization gas is found to arise in a surprisingly thin cloud ($\sim 70 \, \text{pc}$), consistent with sizes derived for...
some intermediate-redshift single-cloud weak Mg ii absorbers (Charlton et al. 2003). The derived metallicity of $\frac{[C/H]}{C}$ is, however, somewhat lower than that derived for many intermediate-redshift counterparts (Charlton et al. 2003; Rigby et al. 2002). The absorber is thought to be in the outskirts of the nearby Virgo Cluster. Specifically, Stocke et al. (2004) find a dwarf post-starburst galaxy, which is part of the Virgo Cluster, at coincident velocity at an impact parameter of $71 h^{-1}$ kpc from the line of sight and use this to support the idea that winds from that galaxy are responsible for the absorption.

3.1.2. RX J1230.8+0115, $z_{abs} = 0.005671$

This system is clearly a multiple-cloud, weak Mg ii absorber analog, with two components resolved in Si ii $\lambda 1260$ and C ii $\lambda 1335$. The derived metallicity of $\frac{[C/H]}{C}$ is, however, somewhat lower than that derived for many intermediate-redshift counterparts (Charlton et al. 2003; Rigby et al. 2002). The absorber is thought to be in the outskirts of the nearby Virgo Cluster. Specifically, Stocke et al. (2004) find a dwarf post-starburst galaxy, which is part of the Virgo Cluster, at coincident velocity at an impact parameter of $71 h^{-1}$ kpc from the line of sight and use this to support the idea that winds from that galaxy are responsible for the absorption.

3.1.2. RX J1230.8+0115, $z_{abs} = 0.005671$

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different line of sight through the outskirts of the Virgo Cluster, as it is only 350 $h^{-1}$ kpc (less than 1° in the sky) from the 3C 273 line of sight. This absorber is also part of the cluster environment at a coincident velocity with the absorber discussed previously, at $z_{abs} = 0.005260$ along that line of sight. The large line-of-sight thickness of $\sim 20$ kpc that resulted from this relatively highly ionized cloud ($\log U \sim -2.7$) is in contrast to the small size of $\sim 70$ pc derived for the 3C 273 absorber (Tripp et al. 2002). This led Rosenberg et al. (2003) to suggest that a large filamentary structure, perhaps related to a wind, connects the two lines of sight. This line of sight was selected for observation because of its proximity to 3C 273 toward the Virgo Cluster. Because of its special location, there could be a bias introduced to our survey (most likely a positive one), but no specific absorption system was known to exist in advance of the observation.

3.1.3. PG 1211+143, $z_{abs} = 0.051216$

The absorber is a single-cloud, weak Mg $\II$ system analog. The C $\II$ $\lambda 1335$ absorption profile is blended with Galactic Si $\IV$ $\lambda 1403$. The blend is confirmed by the detection of Si $\IV$ $\lambda 1394$ at $z = 0$. The C $\IV$ $\lambda\lambda 1458, 1550$ and Si $\IV$ $\lambda\lambda 1394, 1403$ resonant doublets for the absorber are covered and detected in the spectrum and are likely to be produced by a separate high-ionization phase of the absorber. Multiple components are clearly detected in C $\IV$, extending blueward of the strongest component. Stocke et al. (2004) have previously reported the presence of this metal-line absorber. Although current imaging surveys are below the sensitivity limit to detect a dwarf galaxy ($m_B > 22$) at the redshift of the absorber, a more luminous galaxy was found at a projected distance of $\sim 100$ $h^{-1}$ kpc from the line of sight at a comparable recession velocity (Stocke et al. 2004; Tumlinson et al. 2005). Since the PG 1211+143 line of sight was observed in order to study two strong Ly$\alpha$ forest absorbers that were known to have Si $\III$ absorption, it was quite likely to have a weak Mg $\II$ absorber analog.

3.1.4. PHL 1811, $z_{abs} = 0.080917$

We classify this system as a single-cloud, weak Mg $\II$ system analog, and the strength is directly confirmed by detection of Mg $\II$ $\lambda 2296, 2803$ with $W_r(2796) = 0.145 \pm 0.053$ Å in a low-resolution G230 spectrum from STIS (Jenkins et al. 2003). In the E140M spectrum, the Si $\II$ $\lambda 1260$ and C $\II$ $\lambda 1335$ transitions are saturated but can be consistently fitted with a single component. Both Si $\II$ $\lambda 1260$ and Si $\III$ $\lambda 1206$ are blended, possibly with Ly$\alpha$ absorption from metal-poor regions at redshifts $z = 0.1205$ and 0.0735, respectively. There is C $\IV$ centered at the same velocity of the low-ionization component, and an offset component at approximately $\sim 50$ km s$^{-1}$ is also possibly detected in a noisy region of spectrum. The Ly$\alpha$ is also asymmetric relative to the low-ionization gas, with additional absorption to the blue. This system has been studied by Jenkins et al. (2003), using a FUSE spectrum and G140L and G230L spectra from STIS. In the FUSE spectrum, O $\VI$ is detected, and the Lyman series lines and Lyman limit break indicates that this is a Lyman limit system, with log N(H $\I$) $> 17.5$ (Jenkins et al. 2003). This is noteworthy, since most weak Mg $\II$ systems at $z \sim 1$ do not produce Lyman limit breaks. There is an $L_*$ galaxy consistent with the redshift of the absorber at an impact parameter of $34 h_70^{-1}$ kpc (Jenkins et al. 2003). Thus, it appears this may be an absorber similar to a strong Mg $\II$ absorber, which might tend to produce weak low-ionization absorption because of a relatively high impact parameter. Since this line of sight was observed in order to study the same particular system that we have found in our survey, it clearly was biased.
By our fitting procedure, this system is a single-cloud, weak Mg II analog absorber. A possible second component did not significantly improve (by an $F$-test) a simultaneous fit to the Si II $\lambda 1260$ and Si II $\lambda 1193$ lines or a fit to the C II $\lambda 1335$ line. However, Sembach et al. (2004) do claim that a second component is needed to fit the low-ionization lines, and this is certainly a possibility, especially in view of the similarity of their line profiles. In this case, the system is a multiple-cloud, weak Mg II absorber with a very weak offset component close in velocity to the primary.

The C IV $\lambda\lambda 1548, 1550$ doublet is not covered in the STIS E140M spectrum. The absorber could be part of a galaxy group at the system redshift (see § 3.1.5). [See the electronic edition of the Journal for a color version of this figure.]

### TABLE 2

| $z_{abs}$ | QSO        | $W_r(1260)$ (Å) | $W_r(1335)$ (Å) | $Z(W_r, R)$ |
|----------|------------|-----------------|-----------------|-------------|
| 0.005260 | 3C 273     | 0.010 ± 0.002   | 0.010 ± 0.002   | ...         |
| 0.005671 | RX J1230.8+0115 | 0.10 ± 0.01 | 0.11 ± 0.01 | 5.28 |
| 0.051216 | PG 1211+143 | 0.020 ± 0.005  | 0.03 ± 0.01    | 4.90        |
| 0.080917 | PHL 1811   | $\sim 0.16^a$  | 0.16 ± 0.01    | 5.29        |
| 0.138470 | PG 1116+215 | 0.057 ± 0.003  | 0.082 ± 0.005  | 5.24        |
| 0.167121 | PKS 0405−123 | 0.13 ± 0.01  | 0.19 ± 0.01    | 5.29        |

* Obtained by fitting a Gaussian to data.

were detected in the FUSE spectrum. Sembach et al. (2004) noted that this absorber had a particularly high ratio of H I to O VI, which they took as evidence for its multiphase or multi-temperature nature. No specific galaxy has been identified with this absorber, but there is an excess of galaxies at this redshift, indicating a possible galaxy group (Sembach et al. 2004; Tripp 2004).
distinct clouds separated by

et al. 1998). This line of sight was proposed for observation in order to study a Milky Way HVC, so it is not biased for the purpose of our survey.

3.1.6. PKS 0405–123, \( z_{\text{abs}} = 0.167121 \)

This system is a multiple-cloud, weak Mg \( \text{II} \) analog with two distinct clouds separated by \( \sim 40 \) km s\(^{-1} \). The E140M spectrum does not provide coverage of C IV \( \lambda \lambda 1548, 1550 \). It is, however, detected in a HST FOS spectrum, with \( W_{\lambda} (1548) = 0.54 \pm 0.05 \) Å (Jannuzi et al. 1998). Higher ionization transitions, O vi and N v, are also detected in the STIS spectrum, clearly indicating multiphase conditions (Chen & Prochaska 2000). The H i for this system is detected in the STIS spectrum through Ly\( \alpha \) and Ly\( \beta \) features. On the basis of the derived column density of neutral hydrogen \( [N(\text{H} i) \sim 10^{16} \text{ cm}^{-2}] \), the system is classified as a partial Lyman limit system (Chen & Prochaska 2000). Spinrad et al. (1993) report the presence of a spiral galaxy (\( L_K = 0.02L_X^{\star} \)) and a luminous elliptical galaxy (\( L_K = 1.12L_X^{\star} \)) at the absorber’s redshift, at impact parameters of 63 and 75 kpc, respectively. The elliptical galaxy has a spectroscopic signature of a recent starburst event (Spinrad et al. 1993). Chen & Prochaska (2000) infer a metallicity greater than 10\% solar, with a value at least solar being most likely. On the basis of these facts, they suggest that a weak Mg \( \text{II} \) analog absorber is created by heavier elements transported from the elliptical galaxy by the starburst activity. This line of sight is only weakly biased for the purpose of our survey due to its proximity to the Virgo Cluster. The original observation was for the purpose of Ly\( \alpha \) forest studies, but no specific metal-line systems were targeted.

3.2. Survey Completeness and Redshift Number Density

The completeness of the survey as a function of redshift was calculated using the formalism given by Steidel & Sargent (1992) and Lanzetta et al. (1987). The cumulative redshift path length covered by the survey of 20 quasars over the redshift range \( 0 < z < 0.3 \) is given by

\[
Z(W_r, R) = \int_0^{0.3} g(W_r, z, R) dz,
\]

where \( g(W_r, z, R) \) is the function that gives the number of sight lines along which Si \( \text{II} \) \( \lambda 1260 \) and C \( \text{II} \) \( \lambda 1335 \), at redshift \( z \) and with rest-frame equivalent width greater than or equal to \( W_r \) in Si \( \text{II} \) \( \lambda 1260 \), could have been detected at a 5 \( \sigma \) level. We define \( R \) as the expected ratio of the equivalent widths of C \( \text{II} \) \( \lambda 1335 \) and Si \( \text{II} \) \( \lambda 1260 \). As discussed in \( \S \) 2.2, we adopt \( R = 1.41 \) on the basis of empirical results. Table 2 lists the values of cumulative redshift path length over which the individual systems that we found in our survey could have been detected, and Figure 8 presents the completeness as a function of \( W_r(1260) \). Our survey is 30\% complete for an equivalent width threshold of \( W_r(1260) = 0.013 \) Å \( (R = 1.41) \), corresponding to \( W_r(2796) = 0.02 \) Å. For comparison, the Churchill et al. (1999) survey at \( z \sim 1 \) was 80\% complete at \( W_r(2796) = 0.02 \) Å. Although our survey is less complete than that of Churchill et al. (1999) at small equivalent widths, we note that it is quite complete for an equivalent width threshold of \( W_r(1260) = 0.02 \) Å and that we are nevertheless correcting for incompleteness. Below we consider the effects of eliminating quasars with low S/N spectra from the sample.

![FIG. 8.—Cumulative redshift path of the survey as a function of Si \( \text{II} \) \( \lambda 1260 \) equivalent width for a 5 \( \sigma \) detection of both Si \( \text{II} \) \( \lambda 1260 \) and C \( \text{II} \) \( \lambda 1335 \). The redshift interval is \( 0 < z < 0.3 \). Here \( R \) is defined as the ratio of the equivalent widths of C \( \text{II} \) \( \lambda 1335 \) and Si \( \text{II} \) \( \lambda 1260 \) (see \( \S \) 2.2).](image-url)
The number of absorbers per unit redshift \(\frac{dN}{dz}\) was calculated as the sum of the reciprocal of the cumulative redshift path lengths, using the formalism given in Lanzetta et al. (1987):

\[
\frac{dN}{dz} = \sum_i \left[ Z(W_i, R_i) \right]^{-1},
\]

and the variance in \(dN/dz\) is given by

\[
\sigma^2_{dN/dz} = \sum_i \left[ Z(W_i, R_i) \right]^{-2}.
\]

To facilitate comparison with the Churchill et al. (1999) estimation of \(dN/dz\) at 0.4 \(\leq z \leq 1.4\), the rest-frame equivalent width upper and lower limits for Si \(\lambda 1260\) were chosen to be 0.2 and 0.013 Å, respectively. Over the redshift range of 0 \(\leq z \leq 0.3\), five systems were detected for the equivalent width ranges of 0.013 Å \(\leq W_r(1260) < 0.2\) Å and 0.019 Å \(\leq W_r(1335) < 0.29\) Å, and the redshift number density was found to be \(dN/dz = 1.0 \pm 0.20\).

The system at \(z = 0.005260\) along the line of sight toward 3C 273 was excluded while computing the redshift path length \(Z(W_r, R_i)\), since the Si \(\lambda 1260\) was only detected at a 4.5 \(\sigma\) level, and the rest-frame equivalent width of its Si \(\lambda 1260\) was only 0.010 Å, less than the equivalent width lower limit of 0.013 Å.

Figure 9 is a plot of \(dN/dz\) versus redshift for the equivalent width threshold range corresponding to 0.02 Å \(\leq W_r(2796) < 0.3\) Å, with our \(z = 0.15\) point included, along with higher redshift values from Churchill et al. (1999). The curves represent the no-evolution expectations for a \(\Lambda\)CDM universe (\(\Omega_m = 0.3\) and \(\Omega_\Lambda = 0.7\); solid curve), a critical universe with deceleration parameter \(q_0 = 0.5\) (dashed curve), and an open universe with \(q_0 = 0\) (dotted curve), all normalized to \(dN/dz = 1.74\) at \(z = 0.9\). The redshift dependence of the number density of absorbers is consistent with no evolution.

### 3.3. Possible Systematics and Biases of \(dN/dz\)

Two potentially important parameters that could affect our observed \(dN/dz\) value are the ratios \(W_r(1260)/W_r(2796)\) and \(W_r(1335)/W_r(2796)\). As we described in § 2.2, we estimate the typical values of these ratios on the basis of the several weak Mg \(\parallel\) absorbers for which all three transitions were covered in a spectrum. There is a spread of values, and even the mean is not well determined. However, our method for determining \(dN/dz\) and the particulars of our data set imply that the value we would obtain for \(dN/dz\) is not sensitive to the choice of the equivalent ratios, within their possible range.

More specifically, only if the ratio \(W_r(1335)/W_r(2796)\) was taken to be greater than 1.5 would the system toward PG 1211+143 (see Table 2) be excluded from our survey. In this unlikely case, there would only be four terms included in our \(dN/dz\) calculation using the reciprocals of cumulative path lengths and the result would be \(dN/dz = 0.74 \pm 0.14\), not very different from our actual value.

Similarly, only if both \(W_r(1335)/W_r(2796)\) and \(W_r(1260)/W_r(2796)\) were less than 0.5 would the system toward 3C 273 be included in the \(dN/dz\) summation. On the basis of experience with both strong and weak Mg \(\parallel\) systems, it seems unlikely that Si \(\parallel\) would be so weak compared to Mg \(\parallel\). Nonetheless, if we compute \(dN/dz\) including the 3C 273 system, we obtain \(dN/dz = 2.0 \pm 1.2\). The large error value is due to the large incompleteness (~18%) of the survey for systems as weak as that one.

We adopted the lower limit of \(W_r(1260) \geq 0.013\) Å for our survey to facilitate comparison to the survey of Churchill et al. (1999). However, we noted above that the survey is only 30% complete at that limit. We do not expect any biases due to this incompleteness, and the formal error in our calculated \(dN/dz\) appropriately includes the uncertainty. Also, for the weakest system actually included in our survey (as opposed to the weakest that could have been found), the completeness was 73%, so the correction calculated by equation (2) was relatively small. Nonetheless, we have done the experiment of eliminating the noisiest 10 spectra and recomputing \(dN/dz\) for the remaining 10 quasars. With these 10 spectra our completeness at \(W_r(1260) = 0.013\) Å is ~60%. For this reduced sample, we estimate \(dN/dz = 1.0 \pm 0.6\). This is not that different than our value from the full sample of 20 quasars; thus, we adopt that value, with its smaller error, for further discussion.

As discussed for each of the individual weak Mg \(\parallel\) absorber analogs in our sample in § 3.1, this survey is biased because some lines of sight were observed because of known absorbers that were likely to fall in this category. To first order, the bias is likely to yield a larger \(dN/dz\) value than an unbiased survey. Indeed, all of the weak Mg \(\parallel\) absorber analogs that we detected in this survey had already been studied by other authors. Because of this, we can consider the number \(dN/dz = 1.0 \pm 0.20\) an upper limit. The correct value could be somewhat lower. However, we should note that there are quasars in the sample that would appear to have a similar level of positive bias that do not have detected weak Mg \(\parallel\) absorber analogs. We do not think this systematic bias is large, and, as it turns out, even a factor-of-2 reduction in the value would not affect our basic conclusions.

After considering these possible systematics and biases, we expect that our observed value of \(dN/dz = 1.0 \pm 0.20\) for 0.02 Å \(\leq W_r(2796) < 0.3\) Å at 0 \(< z < 0.3\) is an accurate representation of the true value. Systematics due to assumptions about the relationship between Si \(\parallel\), C \(\parallel\), and Mg \(\parallel\) are unlikely to be large. The largest inaccuracy is judged to be a possible bias
in quasars selected for STIS observations toward the detection of weak Mg ii absorbers.

4. EXPECTED EVOLUTION OF ABSORBERS DUE TO CHANGING EXTRAGALACTIC BACKGROUND RADIATION

The population of structures that produce weak Mg ii absorption could be different at different redshifts due to a variety of factors. The process of hierarchical structure growth and merging leads to a change in the distribution of the total hydrogen column density in the universe. The metallicity of the universe gradually increases, and supernovae and their cumulative effects, superbubbles and superwinds, redistribute gas. Finally, the ionization state of the absorbers changes due to the evolution of the metagalactic flux in the present epoch. Qualitatively, the decreasing intensity of the EBR should lead to an increase in the ratio of low- to high-ionization states of an atom (e.g., Si iv and C iv) for a gaseous metal-line absorber. A larger contribution to the EBR by star-forming galaxies, in general, leads to a lower ionization state due to the relative absence of high-energy photons. However, none of our conclusions below are significantly altered by varying assumptions about escape fraction from star-forming galaxies or about absorption by the Lyπ forest, as we mention when relevant.

4.2. Analysis of Evolution using Sample Weak Mg ii Systems

Photoionization calculations using CLOUDY (Ferland 2001) have yielded estimates of densities, metallicities, and temperatures in the low- and high-ionization phases of weak Mg ii gas clouds at \( z \sim 1 \) (Rigby et al. 2002; Charlton et al. 2003; Ding et al. 2005). Almost all of the weak Mg ii absorbers for which information is available have been demonstrated to have a multiphase structure. The low-ionization phase has a higher density and a smaller thickness or size than the high-ionization phase. To guide our thinking on the evolution of weak Mg ii absorbers, we consider the expected evolution of three specific single-cloud, weak Mg ii absorbers at redshifts of \( z = 0.81, 0.90, \) and 0.65 along the line of sight to the quasar PG 1634+704 (Charlton et al. 2003). These three absorbers appear to have phase structures that are typical of other weak Mg ii systems that were found at intermediate redshifts (Rigby et al. 2002) and can hence be treated as representatives of the absorber population. For detailed photoionization models for the three systems, see Charlton et al. (2003).

For the purpose of this thought experiment, we assume that an absorber exists at \( z \sim 0 \) for which the total hydrogen column densities, \( N_{\text{tot}} \), electron number densities, \( n_e \), and metallicities,
log $Z$ (in solar units), of each of the two phases have the same values as they have for the absorber observed at intermediate redshift. These values, listed in Table 4, are taken from Charlton et al. (2003). In other words, we are considering the effect of the EBR change on an otherwise static structure. The changing photon number density $n_i$ from the EBR leads to a change in the ionization parameter, $\log U = n_i/h_\nu$, which directly affects the ionization state of the absorber. The CLOUDY code (Ferland 2001) was used to solve for the ionization state of each phase of the absorber. The changes in the column densities of the various key transitions from the observed redshift to $z = 0$ are listed in Tables 5, 6, and 7. We then synthesized model spectra, noise-free, for the evolved model systems at $z = 0$ as they would appear if observed at a resolution of $R = 45,000$. In order to synthesize these spectra, we used the column densities and temperature output by CLOUDY. The latter was used along with the turbulent $b$-parameter from the intermediate-redshift model cloud in order to determine the observed $b(H)$ and the corresponding $b$-values for all elements. Figures 10, 11, and 12 present the results of this evolution experiment. The individual model components are shown separately at the observed redshift and at $z = 0$, as well as the result of combining these components.

The $z = 0.81$ system, summarized in Table 5 and Figure 10, is the simplest system, with only a single component required to fit the high-ionization phase absorption. In this case, at $z = 0$ the $N(Mg\ II)$ contribution from the high-ionization phase has increased by an order of magnitude, while its $N(C\ IV)$ contribution has decreased by about the same factor. This leads to a substantially stronger weak, low-ionization absorber at $z = 0$, which has $C\ IV$ absorption that may not even be detected in some spectra.

Table 6 and Figure 11 present results for evolution of the $z = 0.90$ system, which has two high-ionization phase clouds,

| Species | Mg\ II Phase | C\ IV Phase, $v = 0$ km s$^{-1}$ | C\ IV Phase, $v = 15$ km s$^{-1}$ |
|---------|-------------|---------------------------------|----------------------------------|
| $N(Mg\ II)$ | 12.5 → 13.2 | 9.8 → 11.9 | 10.9 → 12.3 |
| $N(C\ IV)$ | 13.1 → 11.4 | 14.0 → 13.5 | 13.9 → 13.1 |
| $N(H\ i)$ | 15.5 → 16.6 | 14.2 → 15.3 | 14.5 → 15.6 |
| $N(H\ ii)$ | 18.0 → 17.9 | 17.9 → 19.1 | 17.9 → 17.9 |

**Table 5: Change in Column Density Due to Declining Ionizing Background from $z = 0.8$ to 0**

Note.—Number density of Lyman limit photons from the Haardt-Madau spectrum, with normalization $\log n_i = -5.51$ at $z = 0.8$ and $\log n_i = -6.48$ at $z = 0$.

| C\ IV Phase, $v = 0$ km s$^{-1}$ | $N(Mg\ II)$ | $N(C\ IV)$ | $N(H\ i)$ | $N(H\ ii)$ |
|---------------------------------|-------------|-------------|------------|------------|
| $12.0 → 12.2$ | 11.2 → 12.4 | 9.2 → 7.6 | 13.5 → 12.5 | 15.3 → 16.0 |
| $16.3 → 16.0$ | 17.4 → 17.4 | 13.4 → 15.3 |

**Table 6: Change in Column Density Due to Declining Ionizing Background from $z = 0.9$ to 0**

Note.—Number density of Lyman limit photons from the Haardt-Madau spectrum, with normalization $\log n_i = -5.43$ at $z = 0.9$ and $\log n_i = -6.48$ at $z = 0$.

one aligned with the low-ionization absorption and one offset by $\sim 15$ km s$^{-1}$. As we expect, the $Mg\ II$ absorption strength increases and the $C\ IV$ absorption strength decreases at $z = 0$. However, the most noteworthy change is that the $Mg\ II$ absorption from the offset high-ionization component becomes detectable at low redshift. This system may be classified as a multiple-cloud, weak $Mg\ II$ absorber at $z = 0$.

The $z = 0.65$ system, presented in Table 7 and Figure 12, would also evolve into a multiple-cloud, weak $Mg\ II$ absorber at $z = 0$. For this system, although the $C\ IV$ absorption is substantially weaker at $z = 0$ than at $z = 0.65$, it is still comparable to that of $Mg\ II$ at $z = 0.2796$.

In general, the decreasing EBR leads to an increase in the $Mg\ II$ equivalent width for a given system. For these representative systems, this does not occur as a result of an increased equivalent width for the small, $\sim 1–100$ pc, structure that produces the $Mg\ II$ absorption at $z \sim 1$. Instead, it is the result of a large increase in the $Mg\ II$ absorption contributed by the larger (hundreds of pc to a few kpc) structure that produced the $C\ IV$ absorption at $z \sim 1$. Often the $C\ IV$ profiles for weak $Mg\ II$ absorbers at $z \sim 1$ have multiple components (Charlton et al. 2003). There could be detectable $Mg\ II$ absorption at $z \sim 0$ from each of the structures that produces such a $C\ IV$ component at $z \sim 1$. Therefore, we expect a larger number of multiple-cloud, weak low-ionization absorbers at low redshift. Also, there is an increase in $W(C(2796)$ centered on the original weak $Mg\ II$ absorber, both from the small, higher density component and from the large, lower density structure. These effects lead to detection of a larger number of weak, low-ionization systems at $z \sim 0$ than at $z \sim 1$. An excellent example of this is the $z = 0.65$ system toward PG 1634+459 (see Fig. 12).

In fact, this system was just below the detection threshold of the Churchill et al. (1999) survey and was not detected in that survey. It would very easily be detectable if the same structure existed at $z = 0$, primarily due to the $Mg\ II$ contributed by the larger, lower density—phase clouds.

4.3. Expected Value of dN/dz at $\langle z \rangle = 0.15$

Due to Evolving EBR

Assuming the observed equivalent width distribution for $\langle z \rangle = 0.9$, we can estimate the expected $d\lambda/d\lambda$ for that same population, evolved to $\langle z \rangle = 0.15$ (the median for our survey) and subject to the changing EBR. Our survey was limited to weak systems corresponding to the equivalent width interval $0.02 \Lambda < W(2796) < 0.3 \Lambda$. We demonstrated in § 4.2 that at $\langle z \rangle = 0.15$ these can result from the evolved $Mg\ II$ phase or the evolved $C\ IV$ phase of an absorber at $\langle z \rangle = 0.9$. They can also result from $\langle z \rangle = 0.9$ $C\ IV$ clouds that are not related to detected $Mg\ II$ absorbers at that time. For both of these possible predecessors of
Fig. 10.—Evolution of the $z \sim 0.8$ weak Mg II absorber from its observed redshift to the present epoch. **Top left:** Data with photoionization model from Charlton et al. (2003) superimposed. **Top right:** Low-density, high-ionization and high-density, low-ionization phases, shown separately. The red synthetic spectrum shows the high-density Mg II phase centered at 0 km s$^{-1}$ in velocity space. The green synthetic spectrum shows the contribution from the low-density C IV phase. The C IV phase is centered on the Mg II phase (an offset of 0 km s$^{-1}$). **Bottom left:** Example of what the absorption feature of a similar system present at $z = 0$ would look like. The data are superimposed on the synthetic spectrum to highlight changes in absorption-feature strengths for individual transitions. **Bottom right:** Dense, parsec-sized Mg II phase and less dense, kiloparsec-sized C IV phase, shown separately, for the $z = 0$ scenario. The extent of the change in column density for Mg II, C IV, and H i is summarized in Table 5. [See the electronic edition of the Journal for a color version of this figure.]
the $\langle z \rangle = 0.15$ weak Mg ii absorber population, we estimate the expected $dN/dz$ result. We calculate what interval of equivalent width of the Mg ii or C iv cloud predecessors would give rise to $0.02 \, \text{Å} \leq \mathcal{W}_\lambda(2796) < 0.3 \, \text{Å}$ at $\langle z \rangle = 0.15$. Then we integrate the appropriate observed equivalent width distribution for Mg ii or C iv absorbers at $z \sim 1$ (Churchill et al. 1999; Sargent et al. 1988; Tripp et al. 1996) using those new corresponding values as limits. This is an estimate of how many absorbers should be in the observed interval at present.

First, we consider the $\langle z \rangle = 0.15$ weak Mg ii absorbers that evolve from Mg ii clouds with $\mathcal{W}_\lambda(2796) < 0.02 \, \text{Å}$ at $\langle z \rangle = 0.9$. On the linear part of the Mg ii curve of growth, $\mathcal{W}_\lambda(2796) = 0.02 \, \text{Å}$ corresponds to $N(\text{Mg ii}) \sim 10^{11.7} \, \text{cm}^{-2}$ for the full range of plausible Doppler $b$-parameters. For a metallicity and density
Fig. 12.—Same as Fig. 10, but for the $z \sim 0.6$ weak Mg ii absorber. Top left: Data with photoionization model from Charlton et al. (2003) superimposed. Top right: Four different component clouds, with their contributions toward absorption shown separately. The tick marks placed above the features represent the center of the absorption feature for each component cloud. The red curve represents the Mg ii phase, centered at 0 km s$^{-1}$ in velocity space. The other curves represent the three low-density, high-ionization C iv phases, offset in velocity by 0, +24, and +54 km s$^{-1}$. Bottom left: Example of what the absorption feature of a similar system present at $z = 0$ would look like. The data are superimposed on the synthetic spectrum to highlight changes in absorption-feature strengths for individual transitions. Bottom right: Four separate phases are shown for the evolved absorber at $z = 0$. The changes in column density for Mg ii, C iv, and H i are summarized in Table 7. [See the electronic edition of the Journal for a color version of this figure.]
that is typical for weak Mg ii absorbers (log \(Z = -1\) in solar units and \(n_t \sim 10^{-2} \text{ cm}^{-3}\); Churchill et al. 1999; Charlton et al. 2003), a Mg ii absorber with \(W_r(2796) = 0.02 \, \text{Å}\) at \(z = 0.15\) can arise from a single-cloud absorption system with total neutral hydrogen column density \(N_{\text{H}_\text{tot}} \sim 10^{17.35} \text{ cm}^{-2}\). Under the influence of the stronger EBR at \(z = 0.9\), a cloud structure with the same \(N_{\text{H}_\text{tot}}\) and with the same metallicity, density, and size would produce an absorption feature with \(N(\text{Mg ii}) \sim 10^{11.34} \text{ cm}^{-2}\). This corresponds to \(W_r(2796) = 0.008 \, \text{Å}\). We obtain the same number for a QSO-only EBR.

Next we consider how the strongest cloud in our survey \([W_r(2796) = 0.3 \, \text{Å} \, \text{at} \, (z) = 0.15]\) would relate to the equivalent width distribution at \((z) = 0.9\). A single, low-ionization cloud with \(N(\text{Mg ii}) = 10^{15.3} \text{ cm}^{-2}\) has \(W_r(2796) = 0.3 \, \text{Å}\) for a typical Doppler \(b\)-parameter of 4 km s\(^{-1}\). Assuming again the typical parameters, \(\log Z = -1\) and \(n_t \sim 10^{-2} \text{ cm}^{-3}\), we find that the structure has \(N_{\text{H}_\text{tot}} \sim 10^{21.25} \text{ cm}^{-2}\). From that same structure, at \((z) = 0.9\), the Mg ii absorption lines would be only slightly weaker, with \(W_r(2796) = 0.29 \, \text{Å}\). In reality, it is more likely that a \(W_r(2796) = 0.3 \, \text{Å}\) absorber is produced by multiple clouds. If these are blended and saturated, the change in \(W_r(2796)\) would be even smaller.

We therefore expect that the physical structures that would produce weak Mg ii absorption at \(z = 0.15\) with \(0.02 \, \text{Å} \leq W_r(2796) < 0.3 \, \text{Å}\) would correspond to the equivalent width interval 0.008 Å \(\leq W_r(2796) < 0.29 \, \text{Å}\) at \((z) = 0.9\). From this result and the assumption that weak Mg ii absorbers have similar total hydrogen column densities, densities, and metallicities at \((z) = 0.9\) and 0.15, a value for \(dN/dz\) that we would expect to observe at \((z) = 0.15\) can be calculated as follows.

The equivalent width distribution function, \(n(W_r)\), gives the number of Mg ii absorption systems with rest-frame equivalent width \(W_r\) per unit equivalent width per unit redshift path. The function is represented by the power-law expression

\[
n(W_r)d(W_r) = C W_r^{-\delta} dW_r, \tag{4}
\]

with \(C \sim 0.4\) and \(\delta = 1.04\) (Churchill et al. 1999). The ratio

\[
\frac{\int_{0.029}^{0.29} n(W_r)dW_r}{\int_{0.02}^{0.3} n(W_r)dW_r} = 1.35 \tag{5}
\]

shows the factor by which the number of absorbers in the equivalent width interval of 0.008 Å \(\leq W_r(2796) < 0.29 \, \text{Å}\) exceeds the number of absorbers in the interval 0.02 Å \(\leq W_r(2796) < 0.3 \, \text{Å}\). Therefore, the expected value for \(dN/dz\) of weak Mg ii systems at the present epoch, leading from the evolution of the Mg ii phase of the absorber population at \(z \sim 1\), is estimated to be a factor of \(\sim 1.35\) higher than the statistical redshift number density computed from the survey by Churchill et al. (1999). Taking into account the expected cosmological evolution, for a \(\Omega_{\Lambda} = 0.7\) cosmology (a factor of 0.56 decrease from \(z = 0.9\) to 0.15), we predict a contribution of \(dN/dz = 1.3\) to the expected numbers of weak Mg ii absorbers.

We consider how this estimate varies for different parameters describing the \(z = 1\) population. On the basis of previous studies (Rigby et al. 2002; Charlton et al. 2003), we consider \(-1.5 < \log Z < 0\) and \(10^{-3} \text{ cm}^{-3} < n_t < 10^{-1} \text{ cm}^{-3}\), and \(b\)-values from 2 to 8 km s\(^{-1}\). In the optically thin regime, metallicity has little effect. However, density has a strong effect on the change of \(N(\text{Mg ii})\) with redshift. This is due to the relatively strong dependence of \(N(\text{Mg ii})\) on the ionization parameter, particularly in the range \(-2.5 < \log U < -1.5\). The photon number density \(n_p\) changes from \(-5.6\) to \(-6.3\) over the range 0.9 \(\geq z \geq 0.15\). The value of \(\log U = \log n_p - \log n_e = 1.05\) at \((z) = 0.15\) for a density of \(n_e = 3.8 \text{ cm}^{-3}\). Low densities produce the largest changes in \(N(\text{Mg ii})\). Since the Mg ii phases of the weak Mg ii absorbers at \((z) = 0.9\) have higher densities, they are not very strongly affected by the EBR. However, we have found in § 4.2 that the C iv phases of these absorbers do have a drastic change in their Mg ii column densities. That is because their densities are in the range \(10^{-3} \text{ cm}^{-3} < n_e < 10^{-3} \text{ cm}^{-3}\) (Charlton et al. 2003).

Next, we give a rough estimate of the \(dN/dz\) of the population of weak Mg ii absorbers at \((z) = 0.15\) that should result from the evolved population of C iv absorbers from \(z \sim 1\). This is quite uncertain because of the sensitivity to uncertain physical parameters of C iv absorbers and because of uncertainties in the observed equivalent width distribution of that population at \(z \sim 1\). The equivalent width distribution for C iv absorbers is best measured for \(z > 1.3\), for which C iv is in the optical. We therefore estimate the equivalent width of the C iv absorber, \(W_r(1548)\), at \(z = 1.3\) that would evolve to have \(W_r(2796) = 0.02 \, \text{Å} \, \text{at} \, (z) = 0.15\). For cloud densities \(n_e = 4 - 5 \text{ cm}^{-3}\), an absorber with \(N_{\text{H}_\text{tot}} \sim 10^{20.5} \text{ cm}^{-2}\) would be the equivalent width \(N(\text{Mg ii}) \sim 10^{11.7} \text{ cm}^{-2}\). Assuming a QSO-only EBR would decrease these values somewhat, as \(W_r(1548) = 0.02 \, \text{Å} \, \text{at} \, (z) = 1.3\). Using a QSO-only EBR would extrapolate to lower \(W_r(1548)\):

\[
n(W_r)dW_r = (N_e/W_r) \exp(-W_r/W_r) dW_r, \tag{6}
\]

with \(N_e = 4.60 \, \text{Å}\) and \(W_r = 0.46 \, \text{Å}\) down to \(W_r(1548) = 0.15 \, \text{Å}\) (sample A4 of Sargent et al. 1988). We obtain \(dN/dz = 3.5\), integrating from \(W_r(1548) = 0.12 \, \text{Å}\) to \(\infty\), corresponding to \(n_e = 10^{-5} \text{ cm}^{-3}\), and \(dN/dz = 4.3\), integrating from \(W_r(1548) = 0.03 \, \text{Å}\) to \(\infty\), corresponding to \(n_e = 10^{-3} \text{ cm}^{-3}\). Even though the largest change in \(N(\text{Mg ii})\) is for \(n_e \sim 10^{-3} \text{ cm}^{-3}\), we find the larger \(dN/dz\) for \(n_e \sim 10^{-3} \text{ cm}^{-3}\) since the fraction of magnesium in the form of Mg ii is larger at any redshift for such a cloud. However, Tripp et al. (1996) produced a more sensitive and direct survey for C iv absorbers, particularly in the latter equivalent width range, that has \(W_r(1548) > 0.03 \, \text{Å}\) at \(1.5 < z < 2.9\). They found a somewhat larger number, \(dN/dz = 7.1 \pm 1.7\), although it is consistent within 2 \(\sigma\). We estimate that \(4 < dN/dz < 7\) for \(z = 1.3\) C iv absorbers that would evolve to have \(W_r(2796) > 0.02 \, \text{Å} \, \text{at} \, (z) = 0.15\).

Some of these absorbers would, however, already have given rise to weak or strong Mg ii absorption at \((z) = 1.3\). All but a small fraction of Mg ii absorbers, denoted as “C iv–deficient” (Churchill et al. 2000), do have C iv detected at the same or similar velocity, although it is likely to be in a different phase. We estimate \(dN/dz \sim 0.6\) at \((z) = 1.3\) for \(W_r(2796) > 0.3 \, \text{Å}\), using the redshift parameterization given in Nestor et al. (2005). Similarly, Churchill et al. (1999) measured \(dN/dz = 2.2 \pm 0.4\) at 1.07 \(< z < 1.4\). Adding these two numbers and subtracting from the \(dN/dz\) of the relevant C iv population listed above yields
the range 1 < dN/dz < 4 for (z) = 1.3 C IV absorbers that would evolve into “new” weak Mg II absorbers at (z) = 0.15. We must also again consider the cosmological evolution of that population to determine the expected dN/dz of its low-redshift counterparts. For an ΩΛ = 0.7 cosmology, dN/dz changes by a factor of 0.48 from (z) = 1.3 to 0.15. Therefore, 0.5 < dN/dz < 2 is our final estimate for the expected number of Mg II absorbers with \( W_r (2796) > 0.02 \) Å at z = 0.15 due to the evolution of the C IV absorber population subject to the changing EBR. We consider the upper part of this range more probable since it was derived from the more direct Tripp et al. (1996) measurement of the \( z \sim 1.3 \) C IV absorber population.

4.4. Discussion of Comparison of Observed and Expected Values of dN/dz and the Nature of Weak Mg II Absorbers

We have found that the observed dN/dz at (z) = 0.15 is 1.0 ± 0.20. Considering sample bias, this is likely to be an upper limit to the true number. However, if we take two types of absorption systems that exist at z ~ 1 and evolving these populations to z = 0.15, we would expect a larger number, 2 < dN/dz < 3. This expectation includes the evolution of the Mg II phases of the small, parsec-scale absorbers that produce weak Mg II absorption at z ~ 1 (dN/dz ~ 1; hereafter parsec-scale structures)\(^4\) and the evolution of the C IV absorbers at z ~ 1 that would contribute to the weak Mg II absorber population at lower redshift (dN/dz ~ 2; hereafter kiloparsec-scale structures). Our expectations for dN/dz at z = 0.15 resulting from absorber populations at z ~ 1 are valid only if the absorbers are physically stable over large timescales or if their rate of formation per comoving volume is constant. Our results suggest that one, or more likely both, of the types of z ~ 1 structures that evolve into low-redshift weak Mg II absorbers are evolving away.

It is important to note that, in fact, the expected increase in the dN/dz of weak Mg II absorbers from (z) = 0.9 or 1.3 to lower redshifts should already be apparent in the lowest redshift bin of the Churchill et al. (1999) survey, (z) = 0.57. If we repeat the estimate in § 4.3 for (z) = 0.57, we find that the expected increase in the number of parsec-scale structures producing weak Mg II absorption from (z) = 0.9 is balanced almost exactly by cosmological evolution, yielding an expected dN/dz ~ 1.7. The expected contribution to weak Mg II absorption from kiloparsec-scale structures at (z) = 0.57 is similarly estimated to be dN/dz ~ 1. The combination is already twice the observed value in this redshift bin of the Churchill et al. (1999) survey. Thus, the indicated evolution is occurring substantially from z = 1 to 0.5, not just at the lower redshift range we have surveyed here.

In principle, the question of the predecessors of the (z) = 0.15 population of weak Mg II absorbers is a simple one. We should simply examine the physical nature (e.g., density and size) of the systems that produce the absorption at (z) = 0.15 and see which category they fall in (e.g., whether they are produced by only a kiloparsec-scale structure or by a line of sight passing through both a parsec-scale and a kiloparsec-scale structure). However, in practice this is difficult to determine because of the possibility of “hidden phases.” Specifically, there can be narrow (a couple of km s\(^{-1}\)) low-ionization profiles superimposed on a broader profile from higher ionization phases. As discussed in § 4.3, this is expected to be more common at (z) = 0.15 than at (z) = 0.9 because of the contribution to the low-ionization absorption from the clouds that produce C IV absorption. Figures 10–12 show that at (z) = 0.15, the three example systems toward PG 1634+459 have evolved so that, although it is present at the same level as before, the parsec-scale, high-density phase is not likely to be distinguishable through profile fitting and photoionization modeling.

We can begin to consider what type of weak Mg II absorbers exist in the present by analyzing the six systems present in our survey. Several of the systems discussed in § 3.1 have evidence for multiphase structure (the z = 0.051 system toward PG 1211+143, the z = 0.138 system toward PG 1116+215, the z = 0.167 system toward PKS 0405–123, and the z = 0.081 system toward PHL 1811), but in several cases the multiphase conditions are required by the presence of O VI and not specifically by C IV. The z = 0.0057 absorber toward RX J1230.8+0115 and the z = 0.0053 absorber toward 3C 273 could both be single-phase systems (Rosenberg et al. 2003; Tripp et al. 2002), but the former could be produced by a kiloparsec-scale structure, while the latter has a size of only 70 pc (Tripp et al. 2002). It is also important to note that at least two of the systems (the z = 0.051 system toward RX J1230.8+115, the z = 0.167 system toward PKS 0405–123, and possibly the z = 0.138 system toward PG 1116+215) are multiple-cloud, weak Mg II absorbers. These could either arise from evolved multiple kiloparsec-scale cloud systems or from several parsec-scale clouds in a larger structure. It seems that the z ~ 0 population of weak Mg II absorbers is an inhomogeneous group with multiple origins. However, fundamentally, we cannot demonstrate that any one of the systems definitely does not have a parsec-scale structure along the line of sight.

Since individual cases cannot be classified, we turn to a statistical comparison of the numbers of weak Mg II absorbers at (z) = 0.9 and 0.15. Roughly dN/dz ~ 1 is observed at both epochs, but we would expect dN/dz ~ 2–3 at (z) = 0.15 on the basis of the evolving EBR. This expectation was divided into dN/dz ~ 1 from parsec-scale structures and dN/dz ~ 1–2 from kiloparsec-scale structures. On the basis of these numbers, three possibilities exist: (1) virtually all kiloparsec-scale structures evolve away from (z) = 0.9 to 0.15, (2) most kiloparsec-scale structures evolve away and most parsec-scale structures evolve away over this interval, and (3) most kiloparsec-scale and some fraction of the parsec-scale structures evolve away. Note that the fate of the parsec-scale structures is uncertain, but that in all three possibilities either most or all of the kiloparsec-scale structures evolve away. With this in mind, we consider the expected dN/dz for different possible origins of each of these types of structures.

The parsec-scale size and small velocity dispersions (a few km s\(^{-1}\)) for the structures responsible for the low-ionization phase of weak Mg II absorbers at z ~ 1 suggests that they might be unstable over astronomical timescales. The clouds are not in simple pressure equilibrium, since the temperatures for the high- and low-ionization phases are approximately the same, with high density contrast. The criterion for these gaseous regions to be confined by gravity can be estimated from the method given in Schaye (2001). For an optically thin absorber to be gravitationally bound, the radial size of the cloud is given by the expression

\[
L \sim 10^2 \text{ kpc} \left( \frac{N_{\text{H} I}}{10^{14} \text{ cm}^{-2}} \right)^{-1/3} T_{4}^{0.51} \Gamma_{12}^{-1/3} \left( \frac{f_9}{0.16} \right)^{2/3}, \tag{7}
\]

where \( N(\text{H} I) \) is the column density of neutral hydrogen for the absorbing region, \( T \) is the temperature in kelvins, \( \Gamma_{12} \) is the

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\(^4\) Sizes of this phase range from ~1 to ~100 pc (Rigby et al. 2002; Charlton et al. 2003).
hydrogen photoionization rate normalized to $10^{-12}$ s$^{-1}$, and $f_g$ is the fraction of mass in the form of gas given by the ratio $\Omega_g/\Omega_m$. At low redshifts the estimated rate of photoionization is $10^{-13}$ s$^{-1}$ (Davé & Tripp 2001). The typical value of the baryon mass gas fraction is $\sim 0.16$ (Schaye 2001 and references therein). Hence, the size of low-ionization clouds that produce weak Mg II absorption must exceed $\sim 10$–$20$ kpc in order to be gravitationally stable, much larger than the parsec-scale sizes inferred from photoionization models.

These structures would not be gravitationally stable unless $f_g$ was much larger. However, a larger $f_g$ is feasible, either due to dark matter or due to additional baryons. Rigby et al. (2002) suggested that the weak Mg II absorbers could be remnant gas between the stars in a population of intergalactic star cluster, where the star-to-gas ratio could be $\sim 10^4$. This is comparable to present limits on the amount of gas that could be present in globular clusters. In an intergalactic star cluster model, the C IV absorption seen in $z \sim 1$ weak Mg II absorbers would be produced by gas ejected by supernovae from the cluster, which is housed in the dark matter halo that surrounds it (Rigby et al. 2002). Both the parsec-scale and the kiloparsec-scale components in such a star cluster or dark matter halo model should be relatively stable.

Alternatively, the structures could be transient but could be regenerated at a rate consistent with the observed $dN/dz$. One possibility of this type, also discussed by Rigby et al. (2002), is that weak Mg II absorption arises in structures related to supernova remnants, or to superbubbles or superwind, as favored by Stocke et al. (2004). In this scenario, C IV absorption would arise in an interface layer between the low-ionization shell or sheet and a hotter interior. These structures would not be stable on cosmological timescales, but similar structures would be continuously forming at a rate approximately proportional to the star formation rate. Since the intensity of the EBR is found to decrease since $z \sim 1$ (Haardt & Madau 1996, 2001), a scenario of this type would predict a decline in the overall number of weak Mg II absorbers from $z \sim 1$ to $\sim 0$.

A third possibility for the origin of weak Mg II absorbers is that they are in HVCs, such as those observed around the Milky Way. The observations of O vi HVCs are consistent with coherent motions of extended sheets of gas that cover more than 60% of the sky (Sembach et al. 2003). The O vi has been hypothesized to arise in turbulent boundaries between warm or cold clouds and the hot intragroup medium through which they are travelling (Sembach et al. 2003; Fox et al. 2004). These large structures are likely to have multiphase layers, giving rise to C IV, as well as coincident lower ionization absorption from the warm or cold clouds, which has been observed in most sight lines (Wakker 2001). Most schemes for the origin of HVCs (e.g., material falling into the Local Group, material ejected from the Galaxy, or tidal debris related to satellites) would lead to the prediction of a decreasing $dN/dz$ from $z \sim 1$ to $\sim 0$.

We must also consider the possible origins of the kiloparsec-scale structures that could evolve to produce weak Mg II absorption at $z \sim 0$. These structures are similar to the high-ionization phases of weak Mg II absorbers at $z = 1$ and should be closely related to the C IV absorber population. The C IV systems observed at low redshift have been found to be closely related to galaxies. Absorption in C IV is detected over most of a $100 h^{-1}$ kpc radius region surrounding all $L_B$, galaxies, with the radius scaling at $L_B^{0.5}$ (Chen et al. 2001). Those authors favor accreting satellites as the main mechanism for metal production at these large distances, although they also consider Galactic fountains. Either of these models would predict a transient population that would evolve away due to decreasing numbers of satellites or star formation activity.

5. CONCLUSIONS

We have presented the results of a survey of 20 HST STIS E140M spectra in order to determine the redshift path density of weak Mg II absorbers [0.02 Å < $W$(2796) < 0.3 Å] at $z = 0.15$. The redshift path covered by our survey was 5.3 at a completeness limit of 26%. We found $dN/dz = 1.0 \pm 0.2$, which is consistent with no evolution from $z = 0.9$, where Churchill et al. (1999) found $dN/dz = 1.74 \pm 0.10$. Our survey may be slightly biased toward lines of sight with weak Mg II absorbers; thus, the actual number may be somewhat smaller.

The apparent lack of evolution is deceptive because it suggests no change in the population of objects producing the absorption. However, the extragalactic background radiation intensity is known to decrease by a factor of $\sim 8$ from $z = 0.9$ to 0.15 (Haardt & Madau 1996, 2001). Therefore, the ionization state of absorbers will change. We considered how the three single-cloud, weak Mg II absorbers observed toward PG 1634+706 at $z = 0.65$, 0.81, and 0.90 would change if the same structures existed in the present. In general, the low-ionization absorption grows stronger as the high-ionization absorption becomes weaker. We found that the large, low-density clouds that produced C IV absorption at $z \sim 1$ would produce observable, but weak, Mg II at $z \sim 0$. Thus, what was a single-cloud weak Mg II absorber at $z \sim 1$ can become a multiple-cloud weak Mg II absorber at $z \sim 0$.

Because of the decreasing ionization state of absorbers from $z \sim 1$ to $\sim 0$, there would be Mg II absorbers that fell below a 0.02 Å threshold at $z \sim 1$ but became detectable at $z \sim 0$. Considering the expected evolution, and integrating the observed $z \sim 1$ equivalent width distribution, we found that in fact this does not lead to a significant increase in the weak Mg II absorber population at $z \sim 0$. The Mg II column density is not very sensitive to ionization parameter in the relevant range. We predict a value of $dN/dz \sim 1$ for the $\langle z \rangle = 0.15$ population of parsec-scale, weak Mg II absorbers. On the other hand, there are also many kiloparsec-scale C IV absorption systems that did not have detectable Mg II absorption at $z \sim 1$ but would become detectable in Mg II at $z \sim 0$. Again, considering the $z \sim 1$ population of C IV absorbers and their properties, and assuming that they are stable and change only due to the changing EBR, we expect $dN/dz \sim 1$ at $z = 0.15$.

We conclude that the evolved population of structures observed to exist at $z \sim 1$ should give rise to roughly 2–3 times more weak Mg II absorbers than are observed at $z \sim 0$. This expected $z \sim 0$ population would likely be dominated by kiloparsec-scale, low-density structures that only gave rise to C IV absorption at $z \sim 1$. However, it would also have a 30%–50% contribution from the evolved population of parsec-scale, higher density absorbers that produced weak Mg II absorption at $z \sim 1$. The numbers indicate that most kiloparsec-scale structures are evolving away from $z \sim 1$ until the present. If all of them are evolving away, then it is possible that none of the parsec-scale structures are evolving away. This could mean that they are stable or that they are regenerated at a roughly constant rate. On the other hand, it seems somewhat more likely that some of the kiloparsec-scale structures will remain at $z \sim 0$. They could be related to satellites and their interactions or to superwind activity, effects that would decrease with time but would not disappear. If so, then the parsec-scale structures would have to be transient, and their rate of generation would have to decrease with time. This would be consistent with models that explain weak Mg II absorption as supernova remnants, superbubbles, superwinds, or
high-velocity clouds, but not necessarily with intergalactic star clusters.

Although we have shown that weak Mg\(\text{ II}\) absorbers exist at \(z \approx 0\), we only now have hints about the relationship between the structures that produce this population and those that produce similar Mg\(\text{ II}\) absorption at \(z > 0\). If the low-ionization absorption profiles could be observed at much higher resolution (\(R > 100,000\)), it should be possible to dissect the \(z \approx 0\) population into parsec-scale and kiloparsec-scale components. Clearly, studies that identify luminous objects that are related to the \(z \approx 0\) population are of great value. For both of those types of studies of \(z \approx 0\) weak Mg\(\text{ II}\) absorbers, a larger sample would be quite useful (larger than the six mentioned in this paper). For this, future UV spectroscopy missions are essential. Finally, charting the evolution of the weak Mg\(\text{ II}\) absorber population to redshifts of \(z \approx 2\) and \(\approx 3\) will also provide constraints on its origins.

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