THE KINEMATICS OF INTERMEDIATE-REDSHIFT Mg II ABSORBERS

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ABSTRACT

We present 23 quasar absorption-line systems selected by the Mg II λ2796, 2803 doublet with \( W_r(2796) > 0.3 \ \text{Å} \) over the redshift range \( 0.4 < z < 1.2 \). The kinematics and “profile morphologies” are studied at \( \pm 6 \ \text{km s}^{-1} \) resolution to a 5 σ equivalent width detection threshold of \( W_r(2796) = 0.015 \ \text{Å} \). We are thus sensitive to very weak “clouds” isolated in velocity. The absorption profiles were segregated into “kinematic subsystems,” and the properties (velocities, velocity widths, column densities, etc.) were measured directly from the data and by Voigt profile modeling. Most absorbers are characterized by a dominant kinematic subsystem with \( W_r(2796) > 0.2 \ \text{Å} \) and velocity spreads ranging from 10 to 50 \( \text{km s}^{-1} \) in proportion to the system equivalent width. Additional kinematic subsystems have velocity separations as large as 400 \( \text{km s}^{-1} \) relative to the dominant subsystem. The equivalent widths and velocity spreads of these weaker subsystems are anticorrelated with their velocities, and their equivalent width distribution turns down from a power law below \( W_r(2796) \approx 0.08 \ \text{Å} \). These “moderate”- and “high”-velocity subsystems are inferred to have sub-Lyman limit H I, and therefore are probably not higher redshift analogs to Galactic high-velocity clouds (HVCs). Weak subsystems are asymmetrically distributed in velocity such that they are either all blueshifted or all redshifted with respect to the dominant subsystem. This implies, that although the “kinematic morphologies” vary greatly on a case-by-case basis, a given line of sight is apparently probing a well-defined spatial and kinematic structure. We investigate a simple kinematic model that relies on a rotating disk to explain the observed asymmetries. There are systematic differences, or trends, in both the subsystem-to-subsystem velocity clustering and in the overall kinematic morphologies with increasing equivalent width; we discuss how these may provide clues to the observed differential evolution in the equivalent width distribution of Mg II absorbers.

Key words: galaxies: halos — galaxies: ISM — galaxies: kinematics and dynamics — quasars: absorption lines

1. INTRODUCTION

Ultimately, the goal of studying absorption lines in the spectra of quasars is to chart the details of cosmic evolution and to develop an understanding of the role of gas in the formation and evolution of galaxies. Strong metal-line absorption systems are excellent candidates for pursuing this line of research, because metals are produced in stars, and stars are produced in galaxies. Furthermore, an \( \alpha \)-group element is best suited since it is a tracer of the earliest stages of stellar evolution (i.e., Type II supernovae) and is not significantly produced in secondary or later stages. The resonant Mg II \( \lambda 2796 \), 2803 doublet is ideally suited for these reasons and for the reason that it is a low-ionization species that traces neutral hydrogen column densities commonly associated with galaxy environments [i.e., Lyman limit systems; \( \log N(\text{H} I) \geq 17.3 \ \text{cm}^{-2} \)].

Ground-based, low-resolution (~1–2 Å) surveys searching for Mg II absorption systems in the spectra of quasars have yielded insights into the evolution of their number density, absorption cross-section, and cosmological clustering over the redshift range \( 0.2 < z < 2.2 \) (e.g., Lanzetta, Turnshek, & Wolfe 1987; Sargent, Steidel, & Boksenberg 1988; Boissé et al. 1992; Steidel & Sargent 1992). In particular, Steidel & Sargent (1992, hereafter SS92) have presented a comprehensive look at the distributions of the equivalent widths, doublet ratios, and velocity clustering (on scales greater than 500 \( \text{km s}^{-1} \)). Mg II absorbers having rest-frame equivalent widths, \( W_r(2796) > 0.3 \ \text{Å} \) are consistent with a population of cosmologically distributed objects, i.e., galaxies. The comoving redshift path density\(^3\) is consistent with a non-evolving population of objects. However, as the sample is progressively restricted to stronger systems, evolution becomes progressively more pronounced with a high significance level; the strongest systems are evolving away with cosmic time. In other words, the mean \( W_r(2796) \) increases with redshift.

In principle, this evolution could be attributed to changes in the mean quantity of gas, or in the chemical, ionization, and/or kinematic conditions in galaxies. It is unlikely that the chemical enrichment of the gas is decreasing with cosmic time, since the mean metallicity in the universe continues to increase. Bergeron et al. (1994) established that the

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\(^2\) Work partially conducted while at UCO/Lick Observatories and the Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, CA 96054.

\(^3\) The redshift path density is defined as the number of objects per unit redshift. It constrains the product of the number density and physical cross-section projected on the sky.
mean ionization level in metal-line absorbers decreases with cosmic time over this same redshift interval. Bergeron et al. also reported finding sub-Lyman limit Mg II absorbers at the lower end of the redshift interval, indicating that the H I gas mass may be decreasing with cosmic time in these systems. In tandem with the ionization evolution, this would indicate that the total, not just the neutral, gas mass is decreasing with cosmic time, and this could be linked to the observed Mg II evolution.

On the other hand, perhaps the velocity spreads of the individual systems are decreasing with time. Petitjean & Bergeron (1990) studied ~ 30 Mg II absorbing systems with a moderate resolution of 30 km s~1. They resolved multi-component substructure in complex absorption profiles, measured the cloud-cloud velocity clustering on the scale of galaxy halo velocity dispersions, and established a correlation between the equivalent width and the number of sub-components. Since the doublet ratio does not evolve with redshift (SS92), it has been inferred that each of the individual subcomponents within an overall system is saturated, or nearly saturated. Indeed, Petitjean & Bergeron (1990) suggested that the typical subcomponent has a strength of \( W_r(2796) \approx 0.1 \ \text{Å} \), which is saturated for small Doppler parameters. The total equivalent width, then, would be proportional to the number and velocity spread of these individual, relatively narrow, saturated subcomponents. As another example of what could be governing the evolution—if the velocity spread is decreasing with cosmic time, the evolution in \( W_r(2796) \) may not be due to a decrease in the gas mass, but due to the kinematics becoming more systematic or settled with time.

Now that the general statistics and evolution of Mg II absorbers are established and that several important, but limited, observational clues are available for inferring what physically is evolving, the next logical step is to undertake a comprehensive study of the kinematics. The first goal is to simply establish the nature of the gas kinematics and the second is to investigate what physical processes are governing the redshift evolution in the \( W_r(2796) \) distribution.

High-resolution spectra are required for resolving the absorption profiles into individual components for determining both the line-of-sight velocity distributions (kinematics) and the relative component-to-component absorption strengths. In addition, high signal-to-noise ratios are required for measuring weaker transitions with similar ionization potentials (especially Mg I and Fe II). These transitions can provide clues to the ionization conditions and, in the cases where the Mg II profiles are saturated, provide the gas kinematics. With the advent of 8–10 m class telescopes and efficient, very high resolution spectrographs, it has become possible to acquire the requisite data in sufficient quantities.

In this paper, we present the high-resolution (~ 6 km s~1) absorption profiles of 23 Mg II–selected absorbing systems observed with the HIRES spectrograph (Vogt et al. 1994). In § 2, we present the observed quasars and briefly address the reduction and analysis of the data (i.e., how the varied, complex absorption profiles are parameterized into one to several quantified “properties”). The statistical properties of the sample and the individual absorbing systems are given in § 3. The observed distributions of the kinematics, absorption strengths, and column densities are presented in § 4, followed by discussions in §§ 5, 6, and 7. Conclusions are given in § 8.

2. OBSERVATIONS, DATA REDUCTION, AND ANALYSIS

A total of 25 quasars were observed with the HIRES spectrometer (Vogt et al. 1994) on the Keck I telescope over the nights of 1994 July 4–5, 1995 January 23–25, and 1996 July 19–20 UT. HIRES was configured in first-order using the 0°861 × 7°” decker, C1. Because of the first-order HIRES format, there are small gaps in the spectral coverage redward of 5100 Å where the free spectral range exceeds the width of the 2048 × 2048 Tektronix CCD. The 0°861 slit width disperses the light with \( R = \lambda / \Delta \lambda = 45,000 \) (≈ 6.6 km s~1) projected to ≈ 3 pixels per resolution element, \( \Delta \lambda \).

Three separate, consecutive integrations were obtained for each quasar spectrum, bracketed by Th-Ar calibration lamps. In a given night, almost all quasars were observed with identical HIRES echelle and cross disperser settings, so the instrument was rarely reconfigured in a given night. At the time of the observations, there was no image rotator for HIRES, so the slit was not aligned with nor held constant with respect to the parallactic angle throughout the observations.

July runs were adversely affected by high, patchy cirrus clouds, so these spectra typically have lower signal-to-noise ratios. The 1995 January spectra were obtained in clear and stable ~ 0°5 seeing conditions. In the continuum near the observed Mg II profiles, the rest-frame equivalent width detection limit (5 σ) ranges from 0.008–0.016 Å.

2.1. Sample Selection

The absorbing systems were selected from the spectroscopic surveys of SS92 and Sargent, Steidel, & Boksenberg (1988). These surveys were complete to a 5 σ rest-frame equivalent width threshold of 0.3 Å. The spectra presented here are complete to 0.02 Å within ± 500 km s~1 of the Mg II 2796 optical depth centroids.

The quasars were selected based upon the criteria that each (1) was observable during the allotted telescope time, (2) had \( V \leq 17.5 \) (in order to obtain a high signal-to-noise ratio in roughly a 3600 s integration), and (3) preferably had multiple systems along the line of sight that could be observed with a single setting of the HIRES echelle.

The journal of observations is listed in Table 1. Tabulated are the \( \mathcal{V} \) magnitudes, the emission redshifts of the quasars, the UT data of observation, the total integration time in seconds, and the wavelength coverage (not including breaks above 5100 Å). Included is the spectrum of Q1101 – 264, which was observed with the IPCS on the AAT and generously donated to this study by M. Pettini.

2.2. Data Reduction

The HIRES data were reduced with the IRAF5 APEX-TRACT package (V2.10.3) for echelle data. Further details of the data reduction can be found in Churchill (1995, 1997).

Each observed data frame was overscan subtracted, bias frame corrected, scattered light corrected, and flat-fielded in

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4 This relationship had been proposed by York et al. (1986) and Wolfe (1986).

5 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Associated Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.
the standard fashion. Cosmic rays were removed by averaging the frames with the IRAF task IMCOMBINE using the CRREJECT option. This technique was possible only because the HIRES spectograph was extremely stable between exposures; there was no quantifiable shifting of the cross disperser or echelle settings. The spectra were extracted using the optimal routines of Horne (1986) and Marsh (1989) as implemented by the IRAF APEXTRACT package. Also extracted were the uncertainty spectra and the sky spectra. Owing to the instrument stability, the Th-Ar lamps bracketing each series of quasar observations were simply added together for the wavelength calibration.

The wavelengths were calibrated to vacuum using the VACTHAR.DAT line list provided with the IRAF E-IDENTIFY task. For the dispersion correction, using DISP-CORR, the spectra were not linearized, in that the data were not interpolated to enforce equal wavelength intervals per pixel. This preserves uncorrelated counts in each pixel and leaves the profile shapes unaltered. Finally, the heliocentric velocity correction was manually applied to each echelle order, where the heliocentric velocity was calculated using the IRAF RVCORR task.

The continuum flux was normalized using the methods described by Sembach & Savage (1992; also see Churchill 1997), where the fitting was performed interactively using the IRAF SFIT task embedded in an iterative script.

### 2.3. Data Analysis

#### 2.3.1. Feature Finding

For each quasar spectrum, an objective line list of all $5 \sigma$ absorption features was constructed using a method very similar to the one described in Schneider et al. (1993). This method is optimal for finding unresolved lines (see Churchill et al. 2000a). The HIRES instrumental spread function (ISF) is well approximated as a Gaussian with $\sigma_{\text{ISF}}(\lambda) = 0.0453(\lambda/5500) \text{ Å}$. In terms of the formalism of Schneider et al., we set $J_0 = 6$. The HIRES spectra have 3 pixels per resolution element so that this value samples the ISF over 4.3 resolution elements (13 pixels).

#### 2.3.2. Feature Identification

Line and line-blending identifications were accomplished as follows. A list of roughly 100 transitions with accurate rest-frame wavelengths (Morton 1991) was compiled. The literature was exhaustively searched for known absorption systems in each quasar and a list of their redshifts was constructed (even if the strong Mg II and C IV doublets were not covered in our spectra). This list also included the redshifts of the discovered “weak” Mg II systems (Churchill et al. 1999). The point of including all known redshifts from the literature was to document line blending with transitions from other redshifts with those in our sample.

We then scanned the spectra at the expected location for each transition in our list. Output was a list identifying probable blends, i.e., instances when the expected wavelength locations covered by two or more different transitions from different redshifted systems overlapped. The final adopted identifications and limits were obtained by examining the spectra by hand. Very few blends were found, and when they were the details are given in the discussions of the individual systems.

In Table 2 we present the transitions included in our study. From left to right, the columns are the ionization species and transition identity, the vacuum laboratory wavelengths, the oscillator strengths, and the natural broadening constants. The atomic data are taken from the compilation of Morton (1991), except for the Fe II $22587$ and $\lambda 2374$ transitions, which are taken from Cardelli & Savage (1995). Tripp et al. (1996) review the reasons why these $f$ values likely represent an improvement over the Morton values.

For this work, we include only the Mg II, Mg I, and Fe II transitions that have been redshifted into our observed spectral range. In some systems Mn II, Ca II, and Ti II transitions were detected (see Churchill et al. 2000a). Since this

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### Table 1

**Journal of Observations**

| Quasar      | $V$ (mag) | $z_{\text{em}}$ | Date (UT) | Exp (s) | $\lambda$ Range (Å) |
|-------------|-----------|-----------------|-----------|--------|---------------------|
| 0002 + 051  | 16.2      | 1.90            | 1994 Jul 5| 2700   | 3655.7 – 6079.0     |
| 0117 + 213  | 16.1      | 1.49            | 1995 Jan 23| 5400   | 4317.7 – 6775.1     |
| 0420 – 014  | 17.0      | 0.92            | 1995 Jan 23| 3600   | 3810.5 – 6304.9     |
| 0454 + 039  | 16.5      | 1.34            | 1995 Jan 22| 4500   | 3765.8 – 6198.9     |
| 0454 – 220  | 15.5      | 0.53            | 1995 Jan 22| 5400   | 3765.8 – 6198.9     |
| 0823 – 223  | 15.7      | > 0.92          | 1995 Jan 24| 3600   | 3977.8 – 6411.8     |
| 1101 – 264  | 16.1      | 2.14            | ...       | 100, 200, 3791.8 – 3847.8 |
| 1148 + 384  | 17.0      | 1.30            | 1995 Jan 24| 5400   | 3765.8 – 6198.9     |
| 1206 + 459  | 16.1      | 1.16            | 1995 Jan 23| 3600   | 3810.5 – 6304.9     |
| 1222 + 228  | 15.5      | 2.04            | 1995 Jan 23| 3600   | 3810.5 – 6304.9     |
| 1241 + 176  | 15.4      | 1.28            | 1995 Jan 22| 2400   | 3765.8 – 6189.9     |
| 1248 + 401  | 16.3      | 1.03            | 1995 Jan 22| 4200   | 3765.8 – 6189.9     |
| 1254 + 044  | 16.0      | 1.02            | 1995 Jan 22| 2400   | 3765.8 – 6189.9     |
| 1317 + 274  | 16.0      | 1.01            | 1995 Jan 23| 3600   | 3810.5 – 6304.9     |
| 1354 + 193  | 16.0      | 0.72            | 1995 Jan 22| 3600   | 3765.8 – 6189.9     |
| 1421 + 331  | 16.7      | 1.91            | 1995 Jan 23| 3600   | 3818.6 – 6316.9     |
| 1634 + 706  | 14.9      | 1.34            | 1994 Jul 4, 5| 2700  | 3723.3 – 6185.7     |
| 2128 – 123  | 15.9      | 0.50            | 1996 Jul 19| 3900   | 3766.2 – 5791.3     |
| 2145 + 064  | 16.3      | 1.00            | 1996 Jul 18| 4500   | 3766.2 – 5791.3     |

*a* Observed with the IPCS on the AAT by M. Pettini and R. Hunstead.
work is focused primarily on the kinematics of Mg II–selected absorption systems, we present only the transition listed in Table 2. In the velocity ranges where Mg II profiles are saturated, i.e., where kinematic information is lost, the Fe II and Mg I kinematics can be used, assuming that they arise in the same ionization phase as the Mg II. Note that there is now evidence for both a “warm” and a “cold” H I component in damped Lyman-α absorbers (DLAs) (Lane, Briggs, & Smette 2000); some of the Mg I may arise in this separate cold phase (S. M. Rao 2000, private communication). It is possible that such multiphase structure is also present in Lyman-limit Mg II absorbers and that Mg I is partially arising in the cold phase.

2.3.3. Defining Kinematic Subsystems

Many of the overall absorption profiles are comprised of two to several absorption features that are separated by more than 3 pixels (i.e., a resolution element) of continuum flux. We quantify the properties for each of these separate absorption regions, which we call kinematic subsystems. Kinematic subsystems are defined using only the Mg II λ2796 transition. The wavelength region defining each kinematic subsystem is determined objectively by searching to either side of subsystem centroid for the wavelength at which the per pixel equivalent width (see Schneider et al. 1993; Churchill et al. 2000a) becomes insignificant, i.e., $W(\lambda_j) < \sigma_W(\lambda_j)$, where $j$ denotes the pixel index (for a graphical example, see Fig. 3 of Churchill et al. 1999).

The Mg II λ2796 profiles for each of the systems in our sample are presented in Figure 1. The upper subpanels show a rest-frame 1000 km s$^{-1}$ range about the Mg II λ2796 transition at its observed (redshifted) wavelength. Shaded regions indicate the wavelengths regions of each kinematic subsystem, which are numbered from blue to red. The lower subpanels show the 5 $\sigma$ rest-frame equivalent width threshold, given by $5\sigma_{W(\lambda_j)}$, as a function of wavelength.

2.4. Calculating Absorption Properties

We compute most absorption properties directly from the flux values of the data. For the overall systems, we compute the systemic redshift from the optical depth mean of the profile. For each kinematic subsystem, we compute the equivalent widths, velocities, velocity widths, and apparent column densities. We also parameterize the profiles using Voigt profile (VP) decomposition to measure the number of “clouds,” their column densities, velocities, and Doppler parameters. The mathematical formalism is given in Appendix A.

Analysis of the VP results will be presented in a companion paper (Churchill, Vogt, & Charlton 2001). Here we simply describe the formalism and present the VP decomposition results for two reasons: (1) the model fits need to be presented with the data, and (2) inferences based upon VP results, whether statistical or for individual systems, absolutely require extensive simulations (e.g., Hu et al. 1995; Lu et al. 1996) in order to establish the systematic effects of the fitting process. We will calibrate our VP results using simulations in the companion paper.

3. THE SYSTEMS

The HIRES data of the detected transitions are presented in Figure 2. The profiles are aligned in rest-frame velocity, where $v = 0$ corresponds to $\lambda_{sys}$, computed from equation (A1). Systems are defined to be all absorption that lies with $\pm 500$ km s$^{-1}$ of the systemic velocity zero point. In no case is there a system, weak or strong, that lies anywhere near this velocity window; in practice, this velocity window could be increased to an arbitrarily large size.

Ticks above the normalized spectra are the centroids of the VP components. The VP model spectra (the fits) are shown as solid curves superposed upon the data. Because the component velocities are tied together for all ions, ticks appear over spectral regions even where a VP column density is an upper limit.

In Table 3, we list the absorption redshifts $z_{abs}$, the kinematic spreads $\omega$, the rest-frame equivalent widths $W_r(2796)$, and the Mg II doublet ratios. We also list these quantities and the velocity $\langle v \rangle$ for all kinematic subsystem, which are numbered as illustrated in Figure 1.

3.1. Sample Properties

In Figure 3a, we present the binned redshift distribution of our sample. The redshift range is $0.36 \leq z \leq 1.17$. The mean is $\langle z \rangle = 0.77$, with 43% of the systems between 0.4 $\leq z \leq 0.7$ and 39% of the systems between 0.7 $\leq z \leq 1.0$. In panel b of Figure 3, we show the cumulative distribution of the 5 $\sigma$, rest-frame, Mg II λ2796 equivalent width detection limit for the sample. More precisely, this illustrates the distribution of the detection sensitivity to very weak Mg II absorption averaged over a 1000 km s$^{-1}$ region ($\pm 500$ km s$^{-1}$) about each absorber. The data are 100% complete to 0.017 $\AA$ and 80% to 0.014 $\AA$. There is no sensitivity below 0.007 $\AA$. That is, unresolved kinematic subsystems with $\log N($Mg II$) \approx 11.6$ cm$^{-2}$ could be detected in all absorbers in the sample; below $\log N($Mg II$) \approx 11.2$ cm$^{-2}$ there is no sensitivity.

The rest-frame equivalent width distribution for the sample is presented in Figure 4. In panel a, we show the binned distribution and in panel b we show the cumulative distribution. The dotted curve is the cumulative distribution of a “fair” sample (i.e., unbiased) over the same $W_r(2796)$ range for a power-law distribution function, $n(W_r) \propto W_r^{-\delta}$. Over the range 0.02 $\leq W_r(2796) \leq 1.3$, the power-law exponent $\delta$ was shown to be 1.0 $\pm 0.1$ (Churchill et al. 1999). The steep rise to $W_r(2796) \approx 0.6$ in the observed distribution, as compared with the fair distribution, indicates that the sample is slightly “bottom heavy,” having an over-abundance of smaller equivalent width systems. However, a Kolmogorov-Smirnov (K-S) test (Press et al. 1982) applied to the observed and fair cumulative distribution functions yields a K-S statistic of 0.21 with significance 0.25. That the observed distribution is fair cannot be ruled out by the K-S statistic; the sample apparently does not contain any significant bias with equivalent width.

### Table 2

**Transitions Covered**

| Transition | $\lambda_{sys}$ (Å) | $f$ | $\Gamma \times 10^8$ |
|------------|---------------------|-----|---------------------|
| Fe II 2344 | 2344.214             | 0.1097 | 2.6800       |
| Fe II 2374 | 2374.4612            | 0.0282 | 2.9900       |
| Fe II 2383 | 2382.765             | 0.3006 | 3.1000       |
| Fe II 2587 | 2586.650             | 0.0646 | 2.7200       |
| Fe II 2600 | 2600.1729            | 0.2239 | 2.7000       |
| Mg II 2796 | 2796.352             | 0.6123 | 2.6120       |
| Mg II 2803 | 2803.551             | 0.3054 | 2.5920       |
| Mg I 2833  | 2832.964             | 1.8100 | 4.9500       |

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Since we have a reasonably fair equivalent width distribution, we can contrast and compare inferences drawn from our moderate size sample with those drawn from the overall population, including behavior that is differential with \( W_r(2796) \). To this end, we have divided our full sample into four subsamples based upon Mg II absorption strength. In Table 4, we present the mean properties of these samples and the sample members. Sample A is the entire sample, which has \( W_r(2796) \geq 0.3 \, \text{Å} \); sample B systems have \( 0.3 \, \text{Å} \leq W_r(2796) < 0.6 \, \text{Å} \); sample C systems have \( 0.6 \, \text{Å} \leq W_r(2796) < 1.0 \, \text{Å} \); sample D systems have \( W_r(2796) \geq 1.0 \, \text{Å} \); and sample E, which is a subsample of sample D, has \( W_r(2796) \geq 1.0 \, \text{Å} \). These equivalent width ranges are chosen based upon historical precedent. SS92 have shown that each of these samples exhibits a different level of cosmological evolution (see §1).

3.2. Global Absorption Properties

In Figures 5a–5b, we present \( W_r(2796) \) and the Mg II doubling ratio (DR) versus absorber redshift. Sample B systems are plotted as open circles, sample C as open squares, and sample E as filled squares. Sample E is highly
concentrated at \( z \sim 0.9 \), whereas sample B is fairly uniform over the covered redshift range. The mean DR is 1.36 and shows no trend with redshift. The system DRs are really the flux weighted averages of the individual kinematic sub-systems, which exhibit the full range of doublet ratios (not plotted); some weak subsystems are unresolved and somewhat saturated while some are optically thin. As listed in Table 4, there is a trend for DR to decrease from sample B to sample E.

In panel a of Figure 6, we present the full system kinematic spread, \( \omega_z \), versus absorption redshift, where the data point types denote samples B, C, and E. Note that the kinematic spread of a system, as defined in equation (A5), is not the full velocity spread. For example, the full velocity spread of the \( z = 0.9276 \) system toward Q1206 +459 is \( \Delta v \approx 450 \text{ km s}^{-1} \), whereas its kinematic spread is \( \omega_z \approx 120 \text{ km s}^{-1} \). The kinematic spread provides an optical depth weighted velocity spread; it essentially is equivalent to the width of a Gaussian fitted to the complex, full system optical depth profile (i.e., it is column density weighted).

In panel b of Figure 6 we show the full system kinematic spread versus \( W_r(2796) \). Though a Spearman-Kendell test reveals a significant correlation, what is most telling is that there is a large scatter in the kinematic spread for each sample, B, C, and E; it is the mean of this scatter that is increasing with equivalent width.
In Table 5, we present the rest-frame equivalent widths for the transitions listed in Table 2. The velocity range of each kinematic subsystem is given, whereby the subsystem number is as defined in Figure 1. The velocities are the limits of integration for equation (A3). The system totals are also listed. No entry for a given transition means that it was not covered.

In Table 6, we present the integrated column densities using the apparent optical depth method (eq. [A7]). Lower limits are provided when all transitions of a given ion were saturated within the subsystem. For Mg I and Fe II, upper limits are provided when the ion was not detected in any of its transitions. No entry means that no transitions were covered for the given ion.

In Table 7, we present the VP parameters from MINFIT. Following each component’s velocity, we give the kinematic subsystem number; this allows the complexity of the subsystems to be examined. In the case of no detections, the column density is an upper limit. If there is no coverage of any transition for a given ion, an ellipsis appears.

3.3. Individual Systems

3.3.1. Q0002+051, UM 18; $z_{\text{abs}} = 0.851394$

This system has a kinematically intriguing absorption profile, with a total velocity spread of roughly 475 km s$^{-1}$; it was fitted with a total of 12 VP components. Classified as a “double” systems by Churchill et al. (2000b), the overall Mg II profile was found to have four kinematic subsystems. This is one of only two systems in our sample in which two subsystems (1 and 2) have $W_r(2796) > 0.3$ Å. Furthermore, these subsystems are separated by 180 km s$^{-1}$. Subsystem 1 is fully saturated, exhibiting the kinematic spread and morphology characteristic of a DLA Mg II profile (though it is
not a DLA; Churchill et al. 2000b). But for its proximity in velocity to subsystem 1, subsystem 2 could be considered a system in its own right. Its large equivalent width and kinematic morphology are similar to those of Q1101–264 at \( z = 0.3590 \), Q1248 + 401 at \( z = 0.7730 \), and Q1254 + 044 at \( z = 0.9342 \).

3.3.2. \( \text{PG 0117} + 213; z_{\text{abs}} = 0.576398 \)

This DLA (Churchill et al. 2000b) exhibits fully saturated Mg II profiles and a Mg I profile with definite variations in strength in velocity space. There is a slight blending in the blue wing of Mg I with the red wing of Fe II \( \lambda 2600 \) at \( z_{\text{abs}} = 0.7291 \). The profiles were fitted with four VP components, though this fit is constrained only by the Mg I profile. No Fe II transitions were captured by the CCD.

3.3.3. \( \text{PG 0117} + 213; z_{\text{abs}} = 1.047971 \)

This system has two kinematic subfeatures separated by roughly \( v \sim 100 \) km s\(^{-1}\). Both exhibit blueward asymmetry and both have very weak Mg I. The overall profile was fitted with seven VP components. This is a C IV–deficient system (Churchill et al. 2000b).

3.3.4. \( \text{Q0420} – 014; z_{\text{abs}} = 0.633004 \)

The overall profile is comprised of two kinematic subfeatures separated by \( v \sim 200 \) km s\(^{-1}\). One of them is broad and complex. The redmost saturated components in subsystem 2 have Mg I and Fe II, whereas the bluer, more complex components do not. This suggests either strong variations in abundance patterns or in ionization/density conditions. A total of nine VP components were fitted.

3.3.5. \( \text{PKS 0454} + 039; z_{\text{abs}} = 0.859565 \)

This DLA was studied by Steidel et al. (1995) and by Lu et al. (1996) and Churchill et al. (2000a, 2000b). The profile is a single fully saturated feature with a \( v \sim 200 \) km s\(^{-1}\) spread. Though eleven VP components were fitted, the column densities and Doppler \( b \) values for components
three through eight are not well constrained. In Table 7, formal errors are not provided for these components, only the approximate \( N \) and \( b \) values; any inferences regarding this system based upon the VP decomposition should be viewed with caution. Based upon the profile fit to the \( \text{Fe} \ II \) \( \lambda 2344 \) transition, there may be an offset in the continuum placement across that profile. There is a spurious, unidentified, weak feature at \( v = +100 \) km s\(^{-1}\) relative to \( \text{Mg} \ II \) \( \lambda 2803 \).

3.3.6. PKS 0454+039; \( z_{\text{abs}} = 1.153248 \)

This “classic” system (Churchill et al. 2000b) has the only profile in the sample that has weak, high-velocity absorption distributed symmetrically about the central main absorption region. However, there is confusion near both the \( \text{Mg} \ II \) doublet transitions, in that weak, unidentified absorption features are seen. Additionally, there appears to be a weak, unidentified feature precisely where \( \text{Fe} \ II \) \( \lambda 2374 \) transition is predicted. This is apparent because of the unphysical strength ratios with respect to the other \( \text{Fe} \ II \) transitions and is further suggested by another possible nearby unidentified feature. Very weak \( \text{Mg} \ I \) is detected in the core of the strongest \( \text{Mg} \ II \) component, but, again, there is a weak, unidentified feature within \(-50\) km s\(^{-1}\).

3.3.7. PKS 0454−220; \( z_{\text{abs}} = 0.474410 \)

Though not a DLA, based upon the definition \( \log N(\text{H} \ I) \geq 20.3 \) cm\(^{-2}\), this system has been classified as “DLA/\( \text{H} \ I \)-rich” by Churchill et al. (2000b). A total of eight VP components were fitted to this broad saturated profile. Though formal uncertainties are quoted in Table 7, it should be noted that the column density uncertainties in most central components are greater than a dex. Thus, inferences regarding this system based upon the VP parameters should be
viewed with caution. There is possibly a weak component missed at $v = +80 \text{ km s}^{-1}$ in the wings of Mg II; however, it was formally rejected by MINFIT. The Fe II $\lambda\lambda2344, 2374,$ and 2383 transitions were not captured by the CCD.

3.3.8. PKS 0454 – 220; $z_{\text{abs}} = 0.483340$

This system is classified as C IV–deficient (Churchill et al. 2000b). There are no higher velocity kinematic subsystems; the absence of these subsystems is a common characteristic of C IV–deficient systems. The profile was fitted with a total of seven VP components, which were all well constrained in that they have small fractional errors. The strongest Fe II and Mg I components are aligned in velocity with the maximum Mg II absorption.

3.3.9. PKS 0823 – 223; $z_{\text{abs}} = 0.911017$

This system is classified as a “double” (Churchill et al. 2000b). Unlike other double systems, this one exhibits strong, complex absorption over most of the kinematic spread of $\sim 350 \text{ km s}^{-1}$. Most double systems are characterized by a single, large subsystem with a velocity spread less than $20 \text{ km s}^{-1}$ and several weak, narrow, higher velocity subsystems. The Mg II $\lambda2803$ transition was captured only for subsystem 1. A total of 18 VP components were fitted to the system. The system is rich in Fe II absorption in all subsystems. Mg I, on the other hand, is unambiguously strong only in VP components four, five, and nine. From this, it can be inferred that there is a strong variation in the ionization conditions between the complex at $-50 \text{ km s}^{-1} \leq v \leq -90 \text{ km s}^{-1}$ and at $-10 \text{ km s}^{-1} \leq v \leq +30 \text{ km s}^{-1}$, even though the Fe II might suggest otherwise (unless there are abundance differences in the [x/Fe]).

3.3.10. Q1101 – 264; $z_{\text{abs}} = 0.359153$

The fully reduced and continuum normalized spectra studied in this work were kindly provided by Max Pettini.
The observations were obtained with the UCL echelle spectrograph on the AAT, with the IPCS as the detector. The resolution is 6 km s$^{-1}$ FWHM (or approximately 0.07–0.08 Å at the wavelengths covered here).

The Mg II transitions lie in the Lyα forest of this line of sight, but there is no apparent contamination from H I. A fit to the profiles yields six VP components. Strong Fe II λλ 2300 and Mg I have been reported by Carswell et al. (1991), but they are not presented here.

3.3.11. Q1148 + 384; $z_{\text{abs}} = 0.553362$

This system has a very interesting profile that is comprised of eight VP components in a single kinematic system spread over 200 km s$^{-1}$. The absorption strengths symmetrically decrease with increasing velocity, giving the overall profile a Gaussian “envelope” appearance. However, it is apparent that the Fe II to Mg II ratio is not symmetric; Fe II is relatively stronger in the blue components of the system. The Fe II λλ 2344, 2374, and 2383 transitions were not captured.

3.3.12. PG 1206 + 459; $z_{\text{abs}} = 0.927602$

The kinematics and ionization conditions of this rich, complex system have been studied in detail by Churchill & Charlton (1999). It has been classified as a double system (Churchill et al. 2000b). The overall system was fitted with twelve VP components over a total of five subsystems. Fe II and Mg II are present only in VP components eight, 10, and 12 in subsystem 5.

3.3.13. Q1222 + 228; $z_{\text{abs}} = 0.668052$

The profile is characterized by a central strong absorption and a “high”-velocity subsystem at $v \sim 230$ km s$^{-1}$. This weak subsystem (2) has relatively strong Fe II, and perhaps very weak Mg I. Velocities less than $-100$ km s$^{-1}$ were not observed for the Mg II λ 2796 transitions, but were
for the $\lambda2803$ transition. There is no detectable absorption at those velocities. A total of five VP components were fitted to the main, stronger subsystem, and a single component was fitted to the high-velocity subsystem. Fe II exhibits fine velocity structure in subsystem 1.

3.3.14. PG 1241+176; $z_{\text{abs}} = 0.550482$

The main Mg II profile of this “classic” system (Churchill et al. 2000b) exhibits a redward subcomponent and a smooth blueward asymmetry that is suggestive of bulk motions with varying line-of-sight density rather than a blend of two VP components. The asymmetry is not significant in Fe II and Mg I, but it may be present just below detection levels. There is a subsystem at $v \approx +140$ Å with no detected Fe II or Mg I. A total of four VP components was fitted to the system. The Fe II $\lambda\lambda2344, 2374,$ and $2383$ transitions were not captured by the CCD for the given HIRES configuration.

3.3.15. PG 1248+401; $z_{\text{abs}} = 0.772953$

This system is classified as a “classic” (Churchill et al. 2000b). The Mg II profiles exhibit the “double horn” shape
| QSO          | $z_{abs}$ | System | $\langle v \rangle$ (km s$^{-1}$) | $\sigma$ (km s$^{-1}$) | $W_{i}(2796)$ (Å) | DR |
|-------------|---------|--------|-----------------|-----------------|-----------------|----|
| Q002 + 051  | 0.85139 | 1      | $-120.0 \pm 0.4$ | $17.8 \pm 0.2$  | 0.658 $\pm$ 0.005 | 1.06 $\pm$ 0.01 | |
|             |         | 2      | $170.5 \pm 0.3$  | $14.5 \pm 0.3$  | 0.379 $\pm$ 0.006 | 1.13 $\pm$ 0.03 | |
|             |         | 3      | $296.6 \pm 1.0$  | $52 \pm 1.0$    | 0.039 $\pm$ 0.004 | 1.63 $\pm$ 0.33 | |
|             |         | 4      | $408.6 \pm 0.9$  | $48.9 \pm 0.9$  | 0.043 $\pm$ 0.004 | 1.32 $\pm$ 0.22 | |
|             |         | Total  | $97.7 \pm 0.9$   | $0.030 \pm 0.003$ | 0.022 $\pm$ 0.003 | 0.005 $\pm$ 0.005 |
| Q0117 + 213 | 0.57640 | 1      | $-86.6 \pm 0.3$  | $6.1 \pm 0.4$   | 0.097 $\pm$ 0.003 | 1.80 $\pm$ 0.09 | |
| Q0117 + 213 | 1.04797 | 2      | $3.5 \pm 0.3$    | $15.7 \pm 0.3$  | 0.321 $\pm$ 0.004 | 1.58 $\pm$ 0.03 | |
|             |         | Total  | $-39.4 \pm 0.3$  | $0.417 \pm 0.005$ | 1.63 $\pm$ 0.03 | |
| Q0420 - 014 | 0.63300 | 1      | $-222.4 \pm 0.6$ | $6.0 \pm 0.7$   | 0.089 $\pm$ 0.005 | 1.50 $\pm$ 0.14 | |
| Q0420 - 014 | 0.63300 | 2      | $-6.4 \pm 1.2$   | $31.0 \pm 0.4$  | 0.783 $\pm$ 0.009 | 1.30 $\pm$ 0.02 | |
| Q0454 + 039 | 0.85957 | Total  | $61.1 \pm 1.4$   | $0.873 \pm 0.010$ | 1.32 $\pm$ 0.02 | |
| Q0454 + 039 | 1.15325 | 1      | $-96.1 \pm 0.6$  | $2.8 \pm 1.0$   | 0.032 $\pm$ 0.003 | 1.72 $\pm$ 0.25 | |
| Q0454 + 039 | 1.15325 | 2      | $2.5 \pm 0.3$    | $15.9 \pm 0.5$  | 0.389 $\pm$ 0.005 | 1.39 $\pm$ 0.03 | |
|             |         | Total  | $59.2 \pm 0.6$   | $4.2 \pm 0.8$   | 0.037 $\pm$ 0.003 | 2.20 $\pm$ 0.33 | |
| Q1101 - 264 | 0.35900 | Total  | $24.6 \pm 0.5$   | $0.550 \pm 0.006$ | 1.31 $\pm$ 0.02 | |
| Q1148 + 384 | 0.55336 | Total  | $45.5 \pm 0.8$   | $0.642 \pm 0.011$ | 1.74 $\pm$ 0.06 | |
| Q1206 + 459 | 0.92760 | 1      | $-404.9 \pm 0.7$ | $50.0 \pm 0.7$  | 0.032 $\pm$ 0.002 | 1.82 $\pm$ 0.27 | |
| Q1206 + 459 | 0.92760 | 2      | $-339.6 \pm 0.6$ | $12.5 \pm 0.4$  | 0.083 $\pm$ 0.003 | 1.66 $\pm$ 0.11 | |
|             |         | 3      | $-257.3 \pm 0.3$ | $3.9 \pm 0.4$   | 0.064 $\pm$ 0.002 | 1.71 $\pm$ 0.12 | |
|             |         | 4      | $-183.8 \pm 0.5$ | $6.8 \pm 0.4$   | 0.049 $\pm$ 0.003 | 2.15 $\pm$ 0.24 | |
| Q1241 + 176 | 0.55048 | 1      | $7.1 \pm 0.7$    | $25.9 \pm 0.3$  | 0.661 $\pm$ 0.004 | 1.26 $\pm$ 0.01 | |
| Q1241 + 176 | 0.55048 | 2      | $226.3 \pm 0.6$  | $5.6 \pm 0.8$   | 0.064 $\pm$ 0.003 | 1.42 $\pm$ 0.12 | |
| Q1248 + 401 | 0.77296 | Total  | $54.5 \pm 1.1$   | $0.694 \pm 0.005$ | 1.27 $\pm$ 0.02 | |
| Q1254 + 044 | 0.51939 | 1      | $-261.1 \pm 1.0$ | $6.5 \pm 0.9$   | 0.062 $\pm$ 0.006 | 2.63 $\pm$ 0.64 | |
|             |         | 2      | $-159.0 \pm 1.1$ | $6.2 \pm 0.8$   | 0.048 $\pm$ 0.006 | 1.58 $\pm$ 0.04 | |
| Q1254 + 044 | 0.51939 | 3      | $1.9 \pm 0.8$    | $13.9 \pm 0.4$  | 0.446 $\pm$ 0.009 | 1.17 $\pm$ 0.04 | |
| Q1317 + 274 | 0.66005 | Total  | $87.5 \pm 4.7$   | $0.556 \pm 0.013$ | 1.38 $\pm$ 0.05 | |
| Q1317 + 274 | 0.66005 | 1      | $-3.2 \pm 0.2$   | $9.1 \pm 0.2$   | 0.226 $\pm$ 0.003 | 1.49 $\pm$ 0.04 | |
| Q1421 + 331 | 0.90287 | 2      | $45.2 \pm 1.2$   | $4.7 \pm 1.1$   | 0.014 $\pm$ 0.002 | 1.26 $\pm$ 0.01 | |
| Q1421 + 331 | 1.17261 | 3      | $89.3 \pm 0.7$   | $10.8 \pm 0.7$  | 0.078 $\pm$ 0.003 | 1.67 $\pm$ 0.16 | |
| Q1634 + 706 | 0.99024 | Total  | $54.1 \pm 1.0$   | $1.041 \pm 0.010$ | 1.32 $\pm$ 0.02 | |
| Q2128 - 123 | 0.42973 | 1      | $24.1 \pm 0.5$   | $0.516 \pm 0.006$ | 1.40 $\pm$ 0.03 | |
| Q2145 + 064 | 0.79078 | 2      | $105.1 \pm 0.3$  | $6.6 \pm 0.3$   | 0.158 $\pm$ 0.004 | 1.33 $\pm$ 0.05 | |
| Q2145 + 064 | 0.79078 | 3      | $66.8 \pm 0.5$   | $13.1 \pm 0.4$  | 0.208 $\pm$ 0.005 | 1.51 $\pm$ 0.07 | |
| Q2145 + 064 | 0.79078 | Total  | $74.7 \pm 0.4$   | $0.517 \pm 0.008$ | 1.47 $\pm$ 0.04 | |

* The J2803 transition was only partially covered by the CCD.

b The J2803 transition was not formally detected in some subsystems. However, the subsystems are deemed real, based upon VP decomposition.
Fig. 3.—(a) Binned redshift distribution of our sample. (b) Cumulative distribution of the 5 $\sigma$, rest-frame equivalent width detection threshold within a 1000 km s$^{-1}$ range about Mg II $\lambda 2796$.

Fig. 4.—(a) Binned, rest-frame equivalent width distribution for Mg II $\lambda 2796$ of our sample. (b) The cumulative distribution of our sample (histogram) compared with the distribution for an unbiased survey with the same equivalent width range as observed (dotted curve).

Fig. 5.—(a) Rest-frame, Mg II $\lambda 2796$ equivalent width vs. absorber redshift. Open circles represent sample B ($0.3 \text{ \AA} \leq W_r(2796) < 0.6 \text{ \AA}$) and open squares represent sample C ($0.6 \text{ \AA} \leq W_r(2796) < 1.0 \text{ \AA}$). Sample E [$W_r(2796) \geq 1.0 \text{ \AA}$] is represented with filled squares. (b) Mg II doublet ratio vs. absorber redshift. Data points are as defined in (a). Measurement errors are given, on average, by the size of the data points for the data in both panels.
TABLE 4
SAMPLES AND SUBSAMPLES

| Parameter          | Sample A | Sample B | Sample C | Sample D | Sample E |
|--------------------|----------|----------|----------|----------|----------|
| N                  |          |          |          |          |          |
| $\langle W_r(2796) \rangle$ (Å) | 0.56     | 0.48     | 0.80     | 0.98     | 1.04     |
| $\langle z \rangle$ | 0.77     | 0.66     | 0.69     | 0.81     | 0.86     |
| $\langle DR \rangle$ | 1.4      | 1.4      | 1.4      | 1.3      | 1.1      |

Membership Chart

|                |          |          |          |          |
|----------------|----------|----------|----------|----------|
| 0002 + 051 0.85139...... | X        |          |          |
| 0117 + 213 0.57640...... | X        |          |          |
| 0117 + 213 1.04797...... | X        | X        |          |
| 0420−014 0.63300...... | X        |          |          |
| 0454+039 0.85957...... | X        | X        |          |
| 0454+039 1.15325...... | X        | X        |          |
| 0454−220 0.47441...... | X        |          |          |
| 0454−220 0.48334...... | X        |          |          |
| 0823−223 0.91102...... | X        |          |          |
| 1101−264 0.35900...... | X        |          |          |
| 1148+384 0.55336...... | X        |          |          |
| 1206+459 0.92760...... | X        |          |          |
| 1222+228 0.66805...... | X        |          |          |
| 1241+176 0.55048...... | X        | X        |          |
| 1248+401 0.77296...... | X        |          |          |
| 1254+044 0.51939...... | X        | X        |          |
| 1254+044 0.93423...... | X        | X        |          |
| 1317+274 0.66005...... | X        | X        | X        |
| 1421+331 0.90287...... | X        | X        | X        |
| 1421+331 1.17261...... | X        | X        |          |
| 1634+708 0.99024...... | X        | X        |          |
| 2128−123 0.42973...... | X        | X        |          |
| 2148+064 0.79078...... | X        | X        |          |

Fig. 6.—(a) Kinematic velocity spread of Mg II λ2796 vs. absorber redshift. Data points are as defined for Fig. 5. (b) Kinematic velocity spread of Mg II λ2796 vs. the rest-frame equivalent width of Mg II λ2796.
| System       | \((v^-, v^+)^\) | \(W'(2853)\) | \(W'(2344)\) | \(W'(2374)\) | \(W'(2383)\) | \(W'(2587)\) | \(W'(2600)\) |
|--------------|-----------------|--------------|-------------|-------------|-------------|-------------|-------------|
| 1            | \((-55, 60)\)   | 0.166 ± 0.027| 0.225 ± 0.022| 0.077 ± 0.025| 0.347 ± 0.016| 0.170 ± 0.025| 0.349 ± 0.014|
| 2            | \((125, 219)\)  | <0.027       | 0.047 ± 0.025| <0.023      | 0.082 ± 0.019| <0.025      | 0.070 ± 0.017|
| 3            | \((282, 314)\)  | <0.012       | 0.025 ± 0.010| <0.010      | <0.009      | <0.011      | <0.007      |
| 4            | \((393, 423)\)  | <0.011       | <0.010      | <0.009      | <0.008      | <0.011      | <0.008      |
| Total        | \((-55, 423)\)  | 0.161 ± 0.027| 0.297 ± 0.035| 0.077 ± 0.025| 0.429 ± 0.025| 0.170 ± 0.025| 0.419 ± 0.022|
| Total        | \((-62, 91)\)   | 0.155 ± 0.023| ...         | ...         | ...         | ...         | ...         |
| 1            | \((-109, -63)\) | 0.012 ± 0.005| <0.006      | <0.006      | 0.018 ± 0.005| <0.006      | 0.014 ± 0.005|
| 2            | \((-46, 51)\)   | 0.015 ± 0.010| 0.016 ± 0.012| 0.012       | 0.061 ± 0.009| <0.012      | 0.051 ± 0.009|
| Total        | \((-109, 51)\)  | 0.027 ± 0.011| 0.016 ± 0.012| <0.018      | 0.080 ± 0.011| <0.019      | 0.065 ± 0.010|
| 1            | \((-241, -201)\)| <0.009       | <0.073      | <0.049      | <0.051      | <0.027      | <0.018      |
| 2            | \((-96, 51)\)   | 0.062 ± 0.031| 0.0229      | <0.153      | 0.174       | <0.097      | 0.076 ± 0.054|
| Total        | \((-241, 51)\)  | 0.062 ± 0.031| <0.302      | <0.202      | <0.225      | <0.124      | 0.076 ± 0.054|
| Total        | \((-91, 80)\)   | 0.078 ± 0.068| ...         | ...         | ...         | ...         | ...         |
| 1            | \((-119, 135)\) | ...          | 0.765 ± 0.020| 0.485 ± 0.033| 1.072 ± 0.019| ...         | 1.131 ± 0.019|
| 2            | \((143, 176)\)  | ...          | <0.005      | <0.007      | <0.006      | 0.014 ± 0.006| ...         |
| Total        | \((-119, 176)\) | ...          | 0.765 ± 0.020| 0.485 ± 0.033| 1.072 ± 0.019| ...         | 1.146 ± 0.020|
| Total        | \((-95, 121)\)  | 0.306 ± 0.022| 0.978 ± 0.015| 0.719 ± 0.021| 1.144 ± 0.018| 1.007 ± 0.016| 1.232 ± 0.014|
| 1            | \((-109, -79)\) | <0.004       | <0.005      | <0.004      | ...         | <0.004      | 0.009 ± 0.005|
| 2            | \((-55, 81)\)   | 0.026 ± 0.012| 0.048 ± 0.017| 0.019 ± 0.014| 0.056 ± 0.020| 0.014 ± 0.013| 0.073 ± 0.014|
| 3            | \((83, 115)\)   | <0.004       | <0.006      | <0.005      | <0.007      | <0.004      | <0.005      |
| Total        | \((-109, 115)\) | 0.026 ± 0.012| 0.048 ± 0.017| 0.019 ± 0.014| 0.056 ± 0.020| 0.014 ± 0.013| 0.084 ± 0.015|
| Total        | \((-98, 106)\)  | 0.333 ± 0.014| ...         | ...         | 0.677 ± 0.067| 0.975 ± 0.029| ...         |
| Total        | \((-60, 41)\)   | 0.070 ± 0.010| ...         | ...         | 0.069 ± 0.028| 0.162 ± 0.043| ...         |
| 1            | \((-157, 75)\)  | 0.189 ± 0.029| 0.123 ± 0.050| 0.006 ± 0.054| 0.371 ± 0.039| 0.118 ± 0.026| 0.298 ± 0.024|
| 2            | \((105, 185)\)  | 0.034 ± 0.011| 0.048 ± 0.020| <0.022      | 0.123 ± 0.014| 0.037 ± 0.009| 0.111 ± 0.009|
| 3            | \((199, 230)\)  | <0.005       | <0.010      | <0.011      | <0.007      | <0.005      | 0.007 ± 0.005|
| Total        | \((-157, 230)\) | 0.224 ± 0.031| 0.171 ± 0.054| 0.006 ± 0.054| 0.494 ± 0.041| 0.155 ± 0.028| 0.416 ± 0.026|
| Total        | \((-57, 94)\)   | ...         | ...         | ...         | ...         | ...         | ...         |

**TABLE 5**

**Subfeature Equivalent Widths for Target Transitions**
| System       | ($\nu^-$, $\nu^+$) | $W_j$(2853) | $W_j$(2344) | $W_j$(2374) | $W_j$(2383) | $W_j$(2587) | $W_j$(2600) |
|--------------|---------------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Q1148 + 384 | ($-96, 101$)        | $<0.063$    | $\ldots$    | $\ldots$    | $0.065 \pm 0.081$ | $0.151 \pm 0.071$ | $\ldots$    |
| Q1206 + 459 | ($-66, 310$)        | $<0.007$    | $<0.009$    | $<0.009$    | $<0.010$    | $<0.008$    | $\ldots$    |
| Q1213 - 003 | ($-73, 235$)        | $<0.010$    | $<0.008$    | $<0.007$    | $<0.010$    | $<0.008$    | $\ldots$    |
| Q1225 + 317 | ($-147, 136$)       | $0.275 \pm 0.046$ | $0.300 \pm 0.043$ | $0.086 \pm 0.035$ | $0.661 \pm 0.025$ | $\ldots$ | $0.620 \pm 0.050$ |
| Q1241 + 176 | ($-49, 161$)        | $0.098 \pm 0.030$ | $\ldots$ | $\ldots$ | $0.096 \pm 0.047$ | $0.236 \pm 0.048$ | $\ldots$ |
| Q1248 + 401 | ($-52, 69$)         | $0.049 \pm 0.021$ | $0.105 \pm 0.026$ | $0.045 \pm 0.026$ | $0.241 \pm 0.021$ | $0.116 \pm 0.019$ | $0.233 \pm 0.018$ |
| Q1254 + 044 | ($-33, 40$)         | $0.169 \pm 0.019$ | $\ldots$ | $\ldots$ | $0.185 \pm 0.029$ | $0.298 \pm 0.024$ | $\ldots$ |
| Q1317 + 274 | ($-61, 32$)         | $0.005 \pm 0.019$ | $0.021 \pm 0.022$ | $\ldots$ | $0.056 \pm 0.022$ | $0.040 \pm 0.020$ | $0.051 \pm 0.015$ |
| Q1329 + 412 | ($-45, 25$)         | $<0.033$    | $<0.037$    | $<0.030$    | $0.069 \pm 0.021$ | $<0.034$ | $0.051 \pm 0.031$ |
| Q1329 + 412 | ($-45, 25$)         | $<0.033$    | $<0.037$    | $<0.030$    | $0.069 \pm 0.021$ | $<0.034$ | $0.051 \pm 0.031$ |

**TABLE 5—Continued**

...
that Lanzetta & Bowen (1992) derived for a smooth density, constant infall velocity kinematic halo model. The velocity separation of the two main absorbing regions is ~50 km s\(^{-1}\). The blue horn is comprised of three VP components due to the asymmetry in the overall profile. This central profile is quite similar to the Q1101 – 264 system at \(z_{\text{abs}} = 0.3590\). At \(v = +225\) km s\(^{-1}\), there is an outlying high-velocity, optically thin subsystem. This outlier exhibits a small redward asymmetry. Several Fe II transitions (\(\lambda\lambda 2344, 2374, 2383, 2587, \) and 2600) have been detected. The high-velocity subsystem is detected in the \(\lambda 2600\) transition, but is not detected to 5 \(\sigma\) in the other Fe II transitions. A clear detection of Mg I is also present in the high-velocity system. Normally, these optically thin high-velocity subsystems are not seen to exhibit neutral absorption (this is a rare occurrence).

3.3.16. **Q1254 + 044; \(z_{\text{abs}} = 0.519389\)**

The main subsystem in this absorber exhibits an asymmetry, like that in Q1241 + 176 at \(z = 0.5505\), suggestive of bulk motion and varying line-of-sight density. The absorption is stronger, however, such that the asymmetry is seen most strongly in the neutral gas as traced by Mg I. This main feature has been fitted with three VP components and shows a typical rotating disk shape as can especially be seen in the Mg I transitions. There are two high-velocity, optically thin single VP component subsystems at negative velocities, \(v = -160\) and -360 km s\(^{-1}\). Neither Mg I nor Fe II were detected in these two subsystems. The Fe II \(\lambda\lambda 2344, 2374, \) and 2383 transitions were not captured by the CCD.

3.3.17. **Q1254 + 044; \(z_{\text{abs}} = 0.934232\)**

The kinematics of this system are very similar to those of Q1248 + 401 at \(z = 0.7730\) and also subsystem 2 of Q0002 + 051 at \(z = 0.8514\). Again, this is the classic double horn shape that Lanzetta & Bowen (1992) derived for a smooth density, constant infall velocity kinematic halo model. The velocity separation of the two main absorbing regions is ~40 km s\(^{-1}\). A total of two VP components, one modeling each of the horns, were fitted to the profiles. The Fe II is prominent only in one of the components. Mg I is also present in this particular component, but is not detected in the other.

3.3.18. **Q1317 + 277, TON 153; \(z_{\text{em}} = 0.660051\)**

This C IV–deficient system (Churchill et al. 2000b) has a full velocity spread of ~150 km s\(^{-1}\) with a main subsystem that has a full width of ~50 km s\(^{-1}\) and an asymmetric profile shape. Three subsystems were found and a total of eight VP components were fitted. Subsystem 3 is the most complex of any subsystem at high velocities. Though fitted with three VP components, the profile is more suggestive of bulk motions. Fe II has been detected in the main and next strongest subsystems only. Weak Mg I absorption is detected in the component with the highest Fe II column density.

3.3.19. **Q1421 + 331; \(z = 0.902871\)**

This complex system shows rich variations in ionization and/or chemical conditions, as can be seen by the variations in Fe II to Mg II strengths across subsystems. The Fe II profiles show a strong blueward asymmetry, with a complexity that suggest unresolved fine structure in the data. Mg I absorption is seen only in subsystem 2 in the velocity region where Mg II is most strongly saturated and exhibits a
| System | $(v^-, v^+)$ | Mg $n$ | Mg $t$ | Fe $n$ |
|--------|-------------|--------|--------|--------|
| Q0002 + 051; $z_{abs} = 0.851394$ | | | | |
| 1 ........ | (−55, 60) | 13.773 ± 0.001 | 12.188 ± 0.024 | 13.753 ± 0.003 |
| 2 ........ | (125, 219) | 13.379 ± 0.003 | < 10.874 | 12.801 ± 0.024 |
| 3 ........ | (282, 314) | 12.001 ± 0.035 | < 10.655 | < 11.300 |
| 4 ........ | (393, 423) | 12.028 ± 0.031 | < 10.642 | < 11.279 |
| Total .... | (−55, 423) | 13.931 ± 0.001 | 12.232 ± 0.022 | 13.802 ± 0.004 |
| Q0117 + 212; $z_{abs} = 0.5764$ | | | | |
| Total .... | (−62, 91) | > 14.080 | 12.144 ± 0.019 | |
| Q0117 + 212; $z_{abs} = 1.047971$ | | | | |
| 1 ........ | (−109, −63) | 12.486 ± 0.010 | 11.006 ± 0.077 | 12.038 ± 0.045 |
| 2 ........ | (−46, 51) | 13.075 ± 0.005 | 11.065 ± 0.097 | 12.616 ± 0.018 |
| Total .... | (−109, 51) | 13.174 ± 0.004 | 11.337 ± 0.063 | 12.718 ± 0.017 |
| Q0420 − 014; $z_{abs} = 0.633004$ | | | | |
| 1 ........ | (−241, −201) | 12.456 ± 0.019 | < 10.517 | < 11.806 |
| 2 ........ | (−96, 51) | > 13.753 | 11.745 ± 0.057 | 12.840 ± 0.081 |
| Total .... | (−241, 51) | 13.774 ± 0.001 | 11.770 ± 0.054 | 12.879 ± 0.075 |
| Q0454 + 039; $z_{abs} = 0.859565$ | | | | |
| Total .... | (−95, 121) | > 14.323 | 12.453 ± 0.009 | 15.068 ± 0.028 |
| Q0454 + 039; $z_{abs} = 1.153254$ | | | | |
| 1 ........ | (−109, −79) | 11.933 ± 0.028 | < 10.186 | 11.804 ± 0.108 |
| 2 ........ | (−35, 81) | 13.391 ± 0.008 | 11.271 ± 0.072 | 12.773 ± 0.020 |
| 3 ........ | (83, 115) | 11.943 ± 0.028 | < 10.195 | < 11.126 |
| Total .... | (−109, 115) | 13.421 ± 0.008 | 11.338 ± 0.061 | 12.826 ± 0.020 |
| Q0454 − 220; $z_{abs} = 0.474410$ | | | | |
| Total .... | (−98, 106) | > 14.272 | 12.532 ± 0.005 | > 14.515 |
| Q0454 − 220; $z_{abs} = 0.483340$ | | | | |
| Total .... | (−60, 41) | > 13.527 | 11.849 ± 0.018 | 13.384 ± 0.051 |
| Q0823 − 223; $z_{abs} = 0.911017$ | | | | |
| 1 ........ | (−157, 75) | > 13.752 | 12.234 ± 0.016 | 13.470 ± 0.007 |
| 2 ........ | (105, 185) | 13.072 ± 0.007 | 11.411 ± 0.057 | 12.987 ± 0.012 |
| 3 ........ | (199, 230) | 11.827 ± 0.038 | < 10.305 | 11.513 ± 0.198 |
| Total .... | (−157, 230) | 13.839 ± 0.001 | 12.299 ± 0.016 | 13.597 ± 0.006 |
| Q1101 − 264; $z_{abs} = 0.359002$ | | | | |
| Total .... | (−57, 94) | > 13.621 | |
| Q1148 + 384; $z_{abs} = 0.553362$ | | | | |
| Total .... | (−96, 101) | 13.433 ± 0.019 | < 11.077 | 13.186 ± 0.046 |
| Q1206 + 459; $z_{abs} = 0.927602$ | | | | |
| 1 ........ | (−421, −386) | 11.910 ± 0.031 | < 10.262 | < 11.140 |
| 2 ........ | (−366, −310) | 12.384 ± 0.014 | < 10.366 | < 11.242 |
| 3 ........ | (−275, −236) | 12.304 ± 0.015 | < 10.286 | < 11.156 |
| 4 ........ | (−204, −160) | 12.099 ± 0.022 | < 10.306 | < 11.187 |
| 5 ........ | (−80, 89) | > 13.683 | 11.535 ± 0.053 | 12.870 ± 0.019 |
| Total .... | (−421, 89) | 13.738 ± 0.001 | 11.627 ± 0.042 | 12.905 ± 0.018 |
| Q1222 + 228; $z_{abs} = 0.668052$ | | | | |
| 1 ........ | (−43, 42) | 13.290 ± 0.010 | 11.477 ± 0.068 | 12.988 ± 0.030 |
| 2 ........ | (213, 253) | 12.412 ± 0.019 | < 10.509 | 12.518 ± 0.055 |
| Total .... | (−43, 253) | 13.344 ± 0.009 | 11.521 ± 0.061 | 13.115 ± 0.026 |
The complex strong centers of higher column density gas. This systems is classiﬁed as C IV deficient (Churchill et al. 2000b). The lack of higher velocity subsystems is characteristic of C IV−deﬁcient systems. The total proﬁle velocity spread is ~80 km s⁻¹ and was ﬁtted with five VP components. The Fe II proﬁles exhibit the classic double horn shape, with an overall redward asymmetry.

3.3.21. PG 1634 + 706; $z_{\text{abs}} = 0.990239$

The signal-to-noise ratio for this system is the highest in our sample for the Mg II and Mg I transitions. It is a single kinematic system with no moderate- to high-velocity subsystems to an equivalent width limit of 0.007 Å. This system is classiﬁed as C IV−deﬁcient (Churchill et al. 2000b). The lack of higher velocity subsystems is characteristic of C IV−deficient systems. The total proﬁle velocity spread is ~80 km s⁻¹ and was ﬁtted with ﬁve VP components. The Fe II proﬁles exhibit the classic double horn shape, with an overall redward asymmetry.

3.3.22. PKS 2128−123; PHL 1598; $z_{\text{em}} = 0.429735$

This system, also C IV−deﬁcient (Churchill et al. 2000b) and typical of this class of Mg II system, has no higher velocity subsystems. There is a “double-like” characteristic
| System     | Cloud (c) | Mg ii | Fe ii | Mg i |
|------------|-----------|-------|-------|------|
| QSO        | z_{abs}   | \log N (cm^{-2}) | b (km s^{-1}) | \log N (cm^{-2}) | b (km s^{-1}) | \log N (cm^{-2}) | b (km s^{-1}) |
| 002 + 051  | 0.85139   | 13.36 ± 0.70  | 7.36 ± 1.66 | 13.13 ± 0.01 | 3.70 ± 0.01 | <10.23 | ... |
| 0117 + 213 | 0.57640   | 13.48 ± 0.31  | 10.53 ± 2.20 | ... | ... | 11.37 ± 0.14 | 19.02 ± 6.54 |
| 0117 + 213 | 1.04797   | 13.48 ± 0.31  | 19.49 ± 2.81 | ... | ... | 11.78 ± 0.05 | 8.66 ± 0.82 |
| 0420 – 014 | 0.63300   | 13.48 ± 0.31  | 13.59 ± 0.11 | ... | ... | 11.77 ± 0.04 | 23.15 ± 2.65 |
| 0454 + 039 | 0.85957   | 13.48 ± 0.31  | 15.07 ± 0.44 | ... | ... | 11.84 ± 0.04 | 12.48 ± 6.33 |
| 0454 + 039 | 1.15325   | 13.48 ± 0.31  | 15.07 ± 0.44 | ... | ... | 11.84 ± 0.04 | 12.48 ± 6.33 |
| 0454 – 220 | 0.47441   | 13.48 ± 0.31  | 15.07 ± 0.44 | ... | ... | 11.84 ± 0.04 | 12.48 ± 6.33 |
| 0454 – 220 | 0.48334   | 13.48 ± 0.31  | 15.07 ± 0.44 | ... | ... | 11.84 ± 0.04 | 12.48 ± 6.33 |
| System | Mg u | Fe u | Mg i |
|--------|------|------|------|
| Cloud | log $N$ | $b$ | log $N$ | $b$ | log $N$ | $b$ |
| QSO | ($\langle v \rangle$) | (cm$^{-2}$) | (km s$^{-1}$) | (cm$^{-2}$) | (km s$^{-1}$) | (cm$^{-2}$) | (km s$^{-1}$) |
| --- | --- | --- | --- | --- | --- | --- | --- |
| 0823 – 223 | 13.17 ± 0.11 | 5.69 ± 3.48 | 13.41 ± 0.10 | 7.75 ± 0.52 | 11.45 ± 0.07 | 2.83 ± 0.79 |
| 0.91102 | 13.92 | 1.53 ± 0.12 | 12.21 ± 0.01 | 1.97 ± 0.68 | 10.76 ± 0.56 | 5.64 ± 4.65 |
| 1222 | 13.25 ± 0.01 | 4.23 ± 0.29 | 12.22 ± 0.01 | 4.23 ± 0.77 | 10.74 ± 0.57 | 11.87 ± 22.52 |
| 119.3 | 17.54 ± 0.01 | 7.17 ± 0.15 | 13.04 ± 0.01 | 6.56 ± 0.20 | 11.93 ± 0.01 | 6.90 ± 0.44 |
| 122.8 | 31.90 ± 0.01 | 3.41 ± 0.33 | 12.33 ± 0.01 | 1.02 ± 0.17 | 11.48 ± 0.04 | 3.32 ± 0.72 |
| 1148 | 12.44 ± 0.01 | 27.52 ± 2.05 | < 10.95 | ... | ... | ... |
| 0.01 | 1.09 ± 0.87 | 11.69 ± 0.46 | 11.27 ± 10.67 | ... | ... | ... |
| 1.06 | 12.27 ± 0.01 | 0.95 ± 0.20 | 11.92 ± 0.02 | 0.85 ± 0.21 | < 10.90 | ... |
| 1101 – 264 | 12.62 ± 0.04 | 2.58 ± 0.44 | 12.55 ± 0.01 | 0.96 ± 0.22 | 11.34 ± 0.34 | 11.53 ± 8.76 |
| 0.35900 | 12.98 ± 0.01 | 17.78 ± 0.65 | 12.81 ± 5.04 | 16.70 ± 12.77 | < 10.55 | ... |
| 13.8 | 12.53 ± 0.01 | 9.92 ± 0.40 | 12.43 ± 0.01 | 10.33 ± 0.97 | < 10.18 | ... |
| 46.2 | 11.45 ± 0.03 | 0.77 ± 0.14 | < 11.53 | ... | ... | ... |
| 6.29 | 12.48 ± 0.08 | 9.78 ± 1.08 | 12.37 ± 0.09 | 8.26 ± 1.70 | 11.09 ± 0.33 | 18.87 ± 12.10 |
| 131.2 | 12.40 ± 0.11 | 3.53 ± 0.89 | 12.31 ± 0.11 | 1.96 ± 1.15 | < 10.55 | ... |
| 140.3 | 12.35 ± 0.09 | 10.27 ± 2.05 | 12.52 ± 0.09 | 8.84 ± 2.03 | 11.31 ± 0.47 | 22.59 ± 15.07 |
| 166.1 | 12.30 ± 0.05 | 3.93 ± 0.43 | 12.19 ± 0.05 | 1.88 ± 0.87 | < 10.54 | ... |
| 216.5 | 11.79 ± 0.03 | 3.64 ± 0.59 | 12.02 ± 0.09 | 2.43 ± 1.99 | < 10.54 | ... |
| 1148 + 384 | 12.56 ± 0.04 | 2.90 ± 0.27 | 13.23 ± 1.90 | 1.88 ± 0.97 | < 10.92 | ... |
| 0.55336 | 12.78 ± 0.02 | 6.02 ± 0.24 | 12.61 ± 0.07 | 5.29 ± 1.34 | < 10.91 | ... |
| 0.01 | 3.40 ± 0.34 | 1.18 ± 0.48 | ... | ... | ... | ... |
| 30.2 | 12.98 ± 0.02 | 6.26 ± 0.40 | ... | ... | ... | ... |
| 46.6 | 12.42 ± 0.03 | 5.40 ± 0.48 | ... | ... | ... | ... |
| 71.4 | 11.57 ± 0.07 | 3.99 ± 1.28 | ... | ... | ... | ... |
| 1148 + 384 | 12.56 ± 0.04 | 2.90 ± 0.27 | 13.23 ± 1.90 | 1.88 ± 0.97 | < 10.92 | ... |
| 0.55336 | 12.78 ± 0.02 | 6.02 ± 0.24 | 12.61 ± 0.07 | 5.29 ± 1.34 | < 10.91 | ... |
| 0.01 | 3.40 ± 0.34 | 1.18 ± 0.48 | ... | ... | ... | ... |
| 30.2 | 12.98 ± 0.02 | 6.26 ± 0.40 | ... | ... | ... | ... |
| 46.6 | 12.42 ± 0.03 | 5.40 ± 0.48 | ... | ... | ... | ... |
| 71.4 | 11.57 ± 0.07 | 3.99 ± 1.28 | ... | ... | ... | ... |
| 1148 + 384 | 12.56 ± 0.04 | 2.90 ± 0.27 | 13.23 ± 1.90 | 1.88 ± 0.97 | < 10.92 | ... |
| 0.55336 | 12.78 ± 0.02 | 6.02 ± 0.24 | 12.61 ± 0.07 | 5.29 ± 1.34 | < 10.91 | ... |
| 0.01 | 3.40 ± 0.34 | 1.18 ± 0.48 | ... | ... | ... | ... |
| 30.2 | 12.98 ± 0.02 | 6.26 ± 0.40 | ... | ... | ... | ... |
| 46.6 | 12.42 ± 0.03 | 5.40 ± 0.48 | ... | ... | ... | ... |
| 71.4 | 11.57 ± 0.07 | 3.99 ± 1.28 | ... | ... | ... | ... |
| 1148 + 384 | 12.56 ± 0.04 | 2.90 ± 0.27 | 13.23 ± 1.90 | 1.88 ± 0.97 | < 10.92 | ... |
| 0.55336 | 12.78 ± 0.02 | 6.02 ± 0.24 | 12.61 ± 0.07 | 5.29 ± 1.34 | < 10.91 | ... |
| 0.01 | 3.40 ± 0.34 | 1.18 ± 0.48 | ... | ... | ... | ... |
| 30.2 | 12.98 ± 0.02 | 6.26 ± 0.40 | ... | ... | ... | ... |
| 46.6 | 12.42 ± 0.03 | 5.40 ± 0.48 | ... | ... | ... | ... |
| 71.4 | 11.57 ± 0.07 | 3.99 ± 1.28 | ... | ... | ... | ... |
| 1148 + 384 | 12.56 ± 0.04 | 2.90 ± 0.27 | 13.23 ± 1.90 | 1.88 ± 0.97 | < 10.92 | ... |
| 0.55336 | 12.78 ± 0.02 | 6.02 ± 0.24 | 12.61 ± 0.07 | 5.29 ± 1.34 | < 10.91 | ... |
| 0.01 | 3.40 ± 0.34 | 1.18 ± 0.48 | ... | ... | ... | ... |
| 30.2 | 12.98 ± 0.02 | 6.26 ± 0.40 | ... | ... | ... | ... |
| 46.6 | 12.42 ± 0.03 | 5.40 ± 0.48 | ... | ... | ... | ... |
| 71.4 | 11.57 ± 0.07 | 3.99 ± 1.28 | ... | ... | ... | ... |

TABLE 7—Continued
to the profiles. The system has been fitted with a total of four VP components. Mg I is associated with all four Mg II components and shows a redward asymmetry in the strongest two. Unfortunately, none of the Fe II transitions reported by Tytler et al. (1987) and Petitjean & Bergeron (1990) were captured by the CCD.

3.2.3. PKS 2145+067; $z_{abs} = 0.790777$

This “classic” system (Churchill et al. 2000b) has three subsystems, each having been fitted with two VP components. These subsystems are separated by $\sim 90 \text{ km s}^{-1}$. Only subsystems 1 and 3 have detected Fe II and none have detected Mg I. The Fe II $\lambda 2587$ transition was not included in the analysis because it was positioned near the pen mark on the HIRES CCD.

4. DISCUSSION OF PROPERTIES

In order to investigate trends in the absorption properties with kinematics (i.e., velocities and kinematic spreads), we have divided the subsystems into three classes, the “low”, “intermediate”, and “high-velocity” subsystems. Recall that the velocity zero points are set by the absorption redshifts, which are computed using equation (A1). There is a natural break in the subsystem velocity distribution at

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**Table 7—Continued**

| System | Cloud $<\langle v \rangle$ (km s$^{-1}$) | Mg II $\log N$ (cm$^{-2}$) $b$ (km s$^{-1}$) | Fe II $\log N$ (cm$^{-2}$) $b$ (km s$^{-1}$) | Mg I $\log N$ (cm$^{-2}$) $b$ (km s$^{-1}$) |
|--------|---------------------------------------|-----------------------------------------|-------------------------------------------|-------------------------------------------|
| 1245+044 ....... 0.51939 | $-262.4$ | $12.25 \pm 0.04$ | $3.31 \pm 0.52$ | $<12.17$ |
| 1245+044 ....... 0.93423 | $-37.6$ | $12.72 \pm 0.01$ | $9.68 \pm 0.27$ | $<10.67$ |
| 1317+274 ....... 0.66005 | $-10.4$ | $12.63 \pm 0.04$ | $7.29 \pm 0.49$ | $<10.54$ |
| 1421+331 ....... 0.90287 | $-103.6$ | $11.96 \pm 0.14$ | $7.57 \pm 1.65$ | $<10.69$ |
| 1421+331 ....... 1.17261 | $-43.4$ | $12.46 \pm 0.03$ | $4.08 \pm 0.42$ | $<10.69$ |
| 1634+706 ....... 0.99024 | $-21.9$ | $13.11 \pm 0.01$ | $7.39 \pm 0.15$ | $<10.54$ |
| 2128−123 ....... 0.42973 | $-39.8$ | $12.38 \pm 0.04$ | $7.66 \pm 0.91$ | $<10.67$ |
| 2145+064 ....... 0.79078 | $-109.5$ | $12.55 \pm 0.01$ | $2.04 \pm 0.01$ | $<10.69$ |
$v = 40 \text{ km s}^{-1}$, so we divided the low- and intermediate-velocity classes at 40 km s$^{-1}$ (note that there is only one subsystem with $20 \text{ km s}^{-1} \leq v \leq 40 \text{ km s}^{-1}$; we conservatively chose 40 km s$^{-1}$). The median velocity of all subsystems with $v > 40 \text{ km s}^{-1}$ is 165 km s$^{-1}$, which is where we divided the intermediate- and high-velocity classes. For the following, we represent the low-velocity class with open diamond data points, the intermediate class with open triangles, and the high-velocity class with filled triangles.

### 4.1. Kinematics

In Figure 7a and 7b, we show subsystem Mg II $\lambda$2796 equivalent widths versus subsystem velocity and the subsystem kinematic spreads versus subsystem velocities, respectively. A horizontal dotted line at $W_r(2796)$ Å indicates the sample minimum equivalent width cutoff for the full absorption systems. In general, Mg II systems characteristically have a “dominant,” optically thick absorbing subsystem. The majority of Mg II absorbers have one to a few “intermediate”- and “high”-velocity subsystems.

The equivalent widths of the low-velocity, dominant subsystems are $W_r(2796) < 1.0$ Å, with the majority ranging from 0.3 Å $\leq W_r(2796) \leq 0.6$ Å. Their kinematic spreads typically range between $10 \leq \omega_r \leq 30$ km s$^{-1}$. The two systems in Figure 7a with $W_r(2796) \approx 1.5$ Å and $\omega_r \approx 50$ km s$^{-1}$ are DLA/H I-rich systems; neither of which have intermediate- or high-velocity subsystems (which may be a characteristic of lower redshift DLAs; Churchill et al. 2000b).

The moderate- and high-velocity subsystems have $W_r(2796) \approx 0.1$ Å and kinematic spreads less than 10 km s$^{-1}$. They contribute only 10%–20% to the system total equivalent width. Out of 24, two have $W_r(2796) > 0.3$ Å (subsystem 2 in the $z = 0.9110$ system toward Q0823–223 and subsystem 2 in the $z = 0.8514$ system toward Q0002+051, respectively). They are contributing members in double systems (Churchill et al. 2000b).

There is a break in the velocity distribution at $v \approx 40$ km s$^{-1}$, which arises because the dominant subsystems, many of which exhibit complex kinematic structure, remove flux over a total velocity span of 30–40 km s$^{-1}$. The intermediate-velocity subsystems have a mean kinematic spread of $\approx 6.8$ km s$^{-1}$ and those at high velocity have a mean of $\approx 5.5$ km s$^{-1}$. The large majority of the high-velocity subsystems are unresolved, whereas roughly half of the intermediate-velocity subsystems are resolved. The anticorrelation between subsystem kinematic spread and velocity is significant at 3 $\sigma$. This implies that the high-velocity subsystems have little to no bulk motions, whereas the moderate-velocity subsystems exhibit a slightly broader range of bulk motions.

What is gleaned from Figures 7a–7b is that moderate-redshift Mg II systems have characteristic kinematics. They are not characterized by multiple “large” subsystems of comparable kinematic spreads and/or equivalent widths separated in velocity. They are characterized by a dominant subsystem with a kinematic spread of a few tens of kilometers per second that is often accompanied by significantly smaller subsystems at relative velocities ranging from a few tens to a few hundreds of kilometers per second and kinematics spreads of a few to several kilometers per second. These facts suggest that the lines of sight through intermediate-redshift Mg II systems with $W_r(2796) > 0.3$ Å are picking out a dominant, relatively more massive structure with somewhat systematic kinematics of a few tens of kilometers per second, often surrounded by smaller fragments of gas over a fairly large range of relative velocities.

### 4.2. Equivalent Width Distribution

The Mg II equivalent widths of the intermediate- and high-velocity subsystems are similar in strength to those of the weak Mg II systems (Churchill et al. 1999). It is of interest, therefore, to explore whether the physical nature of isolated weak systems is similar to those of the moderate- and high-velocity subsystems clustered within systems with $W_r(2796) \geq 0.3$ Å. The equivalent width distribution provides one means for comparison.

In Figure 8a, we plot the rest-frame equivalent width distribution for the intermediate- and high-velocity subsystems, those with $v > 40$ km s$^{-1}$. The data have been binned for purpose of presentation. The shaded region gives the equivalent width range over which the detection completeness drops from 100% to zero for unresolved absorption. Compared with a power-law distribution, there appears to be a turnover below $W_r(2796) \approx 0.08$ Å, well above the region of partial completeness. The dotted line is a maximum likelihood power-law fit to $n(W_r) \propto CW_r^{-\delta}$ for $W_r > 0.08$ Å, which yielded $\delta = 1.6 \pm 0.7$.
Churchill et al. (1999) showed that the equivalent width distribution of an unbiased sample of Mg II systems follows a power law with $\delta = 1.0 \pm 0.1$ down to $W_r(2796) = 0.02$ Å. The number density of very small equivalent width systems in the “field” continues to increase as $W_r(2796)$ decreases well below 0.08 Å. In contrast, the Mg II equivalent width distribution of intermediate- and high-velocity subsystems turns over below $W_r(2796) = 0.08$ Å. It may be that both the shape and the slope of the equivalent width distribution differs between the population of weak systems and the intermediate- and high-velocity subsystems of “strong” systems.

Because of the large error in the slope fitted to the kinematic subsystems, however, we cannot discern whether the two slopes differ significantly. The turnover below $W_r(2796) < 0.08$ Å, on the other hand, is unambiguous and represents a fundamental difference in the two distributions.

### 4.3. AOD Column Densities

In Figure 8b, we present the apparent optical depth (AOD) Mg II column densities for the intermediate- and high-velocity subsystems versus the subsystem velocity. The shaded region shows the range of column densities where the detection completeness drops from 100% to zero for unresolved absorption. The sample is 100% complete to log $N$(Mg II) = 11.6 Å. The largest columns, log $N$(Mg II) $\approx$ 13 cm$^{-2}$ are primarily distributed among the intermediate-velocity subsystems of the double systems (see Churchill et al. 2000b). The more typical column density is less than log $N = 12.5$ cm$^{-2}$. As evident from the turnover in the equivalent width distribution (Fig. 8a), there is a paucity of subsystems with log $N \leq 12$ cm$^{-2}$, which is 0.4 dex above where the column density detection sensitivity begins to decline.

It could be argued that smaller column density subsystems are present but that they have very broad kinematic spreads and are therefore not detectable because of the noise in the data (i.e., they have been “removed” during the continuum-fitting process). However, this argument is not supported by the data. The kinematic spreads of very small column density subsystems are tightly clustered about a small value (see Fig. 7); if there were broader subsystems it would be expected that a range of kinematic spreads would be seen in the data. Otherwise, it would have to be argued that a bimodal distribution exists and that one mode has been systematically missed.

In Figures 8c and 8d, we show the logarithmic ratio of $N$(Fe II)/$N$(Mg II) versus $N$(Mg II) and versus subsystem velocity, respectively. In the moderate- and high-velocity subsystems, the ratio $N$(Fe II)/$N$(Mg II) varies in the log...
It is fair to say that, over the range $12.2 \leq N(\text{Mg} \, \text{II}) \leq 13.4 \, \text{cm}^{-2}$ observed in moderate- and high-velocity subsystems, the likelihood of finding $\log \frac{N(\text{Fe} \, \text{II})}{N(\text{Mg} \, \text{II})} = 0$ is as likely as finding $\log \frac{N(\text{Fe} \, \text{II})}{N(\text{Mg} \, \text{II})} = -0.5$. It is not clear whether subsystems in this Mg II column density range commonly have $\log \frac{N(\text{Fe} \, \text{II})}{N(\text{Mg} \, \text{II})} \leq -1$, though one has been found. It does appear that subsystems with $N(\text{Mg} \, \text{II}) \leq 12.2 \, \text{cm}^{-2}$ may often have $\log \frac{N(\text{Fe} \, \text{II})}{N(\text{Mg} \, \text{II})} \sim -1$, though again, there is an exception to this possibility. If all this holds true, it may be that the highest-velocity clouds, which have some of the smallest $N(\text{Mg} \, \text{II})$, will have some of the smallest $N(\text{Fe} \, \text{II})$ to $N(\text{Mg} \, \text{II})$ ratios. The data in Figure 8d are somewhat suggestive of this trend. However, more systems would need to be analyzed in order to make definitive statements. It is interesting to speculate, however, that a trend in $N(\text{Fe} \, \text{II})/N(\text{Mg} \, \text{II})$ with subsystem velocity might indicate a very real physical origin and evolution of the highest-velocity subsystems.

In Figure 9, we present the apparent optical depth column densities of Mg II (top), Mg I (middle), and Fe II (bottom) for all subsystems in a given system. The systems, which are labeled across the top, are ordered by increasing $W_r(2796)$ from left to right. Sample membership is marked below the bottom panel. This ordering is to allow comparisons within and across samples. The shaded region in the top panel gives the range of detection thresholds of unresolved Mg II features. Data point types denote velocity class (low, intermediate, and high). Upper and lower limits are shown with downward and upward pointing arrows, respectively.

From Figure 9, it can be seen how often and with what strengths Mg I and Fe II are detected in intermediate- and high-velocity subsystems. An interesting contrast, for example, is seen between the high-velocity subsystem in the $z = 0.7730$ system toward Q1248+401 and that in the $z = 0.6330$ system toward Q0420–014. Both have comparable Mg II column densities, yet the $z = 0.7730$ system has a fairly large Mg I column density, while the $z = 0.6330$ system has a restrictive upper limit. The Fe II columns may also track this behavior.

### 4.4. Kinematics and System Absorption Strength

In Figure 10a–10b, we show Mg II $\lambda$2796 equivalent width of the full system versus subsystem velocities and versus the velocity spreads of the subsystems, respectively.
As with Figures 5 and 6, open circles represent sample B, open boxes represent sample C, and filled boxes represent sample E. Horizontal dotted lines separate the samples.

The striking trend seen in Figure 10a is the relative paucity of high-velocity ($v > 165$ km s$^{-1}$) subsystems in sample B. Though the demarcation between samples B and C at $W_r(2796) = 0.6$ Å is arbitrary (being based upon previous studies), there appears to be a trend with decreasing system equivalent width. Smaller equivalent width systems have fewer high-velocity subsystems; most of their subsystems are at intermediate velocities.

In Figure 10b, the intermediate- and high-velocity subsystems occupy the left-hand region ($\omega_v \lesssim 10$ km s$^{-1}$) of the diagram, whereas the low-velocity, dominant subsystems are distributed across a broad range of kinematic spreads. Sample B systems have no dominant subsystems with $\omega_v > 25$ km s$^{-1}$, whereas all sample C and E systems have dominant subsystems with $\omega_v > 25$ km s$^{-1}$.

To investigate whether these apparent kinematic trends are statistically significant, we computed the two-point velocity correlation function (TPCF) of the kinematic subsystems for samples B, C, D, and E. The TPCF is simply the frequency distribution of subsystem velocity splittings, $\Delta v_{ij} = |v_i - v_j|$ for $i \neq j$, where $i$ and $j$ represent any two subsystems in the sample.

In Figure 11, we present the cumulative distribution of the TPCFs for sample B (solid curve), sample C (dotted curve), and sample E (dashed curve). Sample D, which is the union of samples C and E, is not plotted. There is a fast rise at very small velocity separations for samples B and C that is not present for sample E. This reflects the fact that dominant, low-velocity subsystems in the largest equivalent width systems tend to have larger kinematic spreads, which suppresses small velocity separations. The smaller equivalent width systems in sample B do not have velocity pair separations greater than $\sim 300$ km s$^{-1}$, whereas both samples C and E have velocity pair separations as large as $\sim 400$ km s$^{-1}$.

Kolmogorov-Smirnov (K-S) tests of sample B versus samples C, D, and E yielded probabilities no greater than $10^{-3}$ that either sample C, D, or E exhibits the same TPCF as sample B. On the other hand, a K-S test of sample C versus sample E yielded a probability of 0.1; it cannot be ruled out that samples C and E have the same distribution of subsystem velocity splittings.

5. ON THE NATURE OF THE KINEMATIC SUBSYSTEMS

5.1. Dominant Kinematic Subsystems

Virtually all Mg II absorbers in our sample are characterized by a dominant, often saturated, kinematic subsystem. For sample B, the kinematic spreads, $\omega_v$, of these dominant subsystems are no greater than 25 km s$^{-1}$. It is rare for there to be a second kinematic subsystem with comparable kinematic spread and equivalent width (the $z = 0.79$ system toward PKS 2145+064 is an exception).

As reported by Steidel, Dickinson, & Persson (1994) and by Steidel (1995), there appears to always be a normal, bright galaxy within $\sim 40$ h$^{-1}$ kpc (sky projected) of the absorbing gas. Furthermore, the physical extent of the absorbing gas was shown to have near-unity covering factor and to be related to the galaxy $K$ luminosity, such that $R(L_K) \sim 40$ h$^{-1}$L$_K^{0.15}$ kpc. These results further support the scenario in which absorbing gas is associated, in some way, with the total mass (number of stars) in a “host” galaxy, or that there is a strong link between the host galaxy mass and the extended gaseous environment in
which the galaxy is evolving (also see Churchill et al. 1996). Since virtually the entire Mg II equivalent width in a given absorber arises from the dominant kinematic subsystem, it has been these subsystems alone that are governing the statistics of absorber-galaxy associations.

There is an observed one-to-one correspondence between optically thick H I and Mg II systems with \(W_r(2796) > 0.3 \, \text{Å} \) and a one-to-one correspondence between optically thin H I and weak systems with \(W_r(2796) \leq 0.2 \, \text{Å} \) (Churchill et al. 2000a). This would suggest that the moderate- and high-velocity kinematic subsystems are optically thin in H I, that the optically thick H I arises in one or a few of the subcomponents in the dominant kinematic subsystem. Photoionization models (Cloudy, Ferland 1996) are consistent with this statement (Churchill et al. 1999; Churchill & Charlton 1999).

The narrow kinematic spreads and larger H I column densities of the dominant subsystems would suggest that dominant subsystems arise in higher density structures with some level of systematic kinematics. An unresolved issue is whether the optically thick absorbing gas is distributed quasi uniformly (giving rise to the unity covering factor) in an extended, “spherical” halo (Lanzetta & Bowen 1990; Bergeron & Boissé 1991; Steidel 1993; 1995; Steidel et al. 1997), or in a more flattened, “disk” geometry (Bowen et al. 1995; Charlton & Churchill 1996, 1998). Absorption-line models using random lines of sight through extended disk structures, with flat rotation curves and reasonable vertical velocity dispersions, naturally explain the characteristic properties of the dominant subsystems (Charlton & Churchill 1998).

This by no means renders the disk model a unique interpretation of the strongest subsystems in complex absorption-line data. However, any simple interpretation must explain the ubiquity and narrow kinematic range of the dominant subsystems. If galaxy disks are not a significant contribution to the absorption, then we are required to suggest a more complex scenario; spatial and kinematic distributions of the absorbing gas from galaxy to galaxy suggest a more complex scenario; spatial and kinematic distributions of the absorbing gas from galaxy to galaxy must explain the ubiquity and narrow kinematic range of the strong subsystems in complex absorption-line data. However, any simple interpretation of the strongest subsystems in complex absorption-line data must explain the ubiquity and narrow kinematic range of the strong subsystems in complex absorption-line data.

5.2. Moderate- and High-Velocity Kinematic Subsystems

There is no direct evidence whether or not the small \(W_r(2796)\), moderate- to high-velocity subsystems are components in the same spatial distribution around galaxies as the dominant subsystems (i.e., reside within \(R(L_\odot)\) or reside at larger galactocentric distances). As such, inferring their nature and their relationship to the dominant kinematic subsystem is difficult. However, there are some clues to be drawn from the data, which we discuss below.

5.2.1. Comparison with Galactic HVCs

The physical locations, sizes, metallicities, and kinematics of Galactic high-velocity clouds (HVCs; e.g., Wakker & van Woerden 1997) are currently a matter of debate (e.g., Blitz et al. 1999; Braun & Burton 1999; Charlton, Churchill, & Rigby 2000; also see the series of articles in Hibbard, Rupen, & van Gorkom 2000). It is clear that some HVCs are associated with the Galaxy in that they are within a few kiloparsecs and/or are members of large complexes that appear to lie along great circles on the sky. What is not definitive, however, is whether some HVCs are remnants of galaxy group formation and whether or not they are spatially and kinematically distributed throughout the Local Group, consistent with material inflowing from the intersection of intergalactic filaments where multiple galaxies form (e.g., Zhang et al. 1997). Note, however, that the results of Zwaan & Briggs (1999) and Charlton et al. (2000) have placed strong constraints limiting the parameter space of group formation models.

HVCs, including the compact HVCs (Braun & Burton 1999), are detected in H I 21 cm emission, for which the present sensitivity is typically a few times \(10^{18} \, \text{atoms cm}^{-2}\); they are optically thick in H I and would give rise to Lyman limit breaks if detected in absorption. Photoionization modeling (using Cloudy; Ferland 1996) has revealed that Mg II absorption with \(W_r(2796) \approx 0.1 \, \text{Å} \) arises in optically thin H I gas, i.e., \(N(\text{H}) \leq 10^{17.3} \, \text{cm}^{-2}\), over four decades of ionization parameter \(Z_{\odot} \) for metallicities greater than 0.01 \(Z_{\odot}\) (see Figs. 11 and 12 of Churchill et al. 1999). Detailed modeling of the \(z = 0.93\) system toward PKS 1206+459 has revealed that the moderate- and high-velocity subsystems in that absorber are tightly constrained to be low-ionization, sub-Lyman limit pockets of gas with relatively high metallicities, i.e., \(Z \geq 0.1Z_{\odot}\) (Churchill & Charlton 1999). These “clouds,” which have inferred masses and sizes of about few times \(10^5 \, M_\odot\) and about a few times 10–100 pc, respectively, are aligned in velocity with highly ionized material (i.e., C IV, N V, and O VI) that arises in a separate gas phase. This multiphase ionization structure is present in most all Mg II absorbers having moderate- and high-velocity subsystems (Churchill et al. 2000).

Though the ionization structure and metallicities of HVCs are not well known, a comparison of the H I column densities and the inferred masses and sizes of moderate- and high-velocity subsystems reveals that they very probably are not higher redshift analogs to Galactic HVCs. Because of the large disparity in the H I column densities, this holds independent of whether HVCs are closely associated with galaxies, remnants of group formation, or both.

5.2.2. Comparison with Weak Systems

The population of weak Mg II systems (Churchill et al. 1999) has a range of equivalent widths, line widths, and doublet ratios similar to those of the intermediate- and high-velocity subsystems. As mentioned above, the kinematic subsystems are optically thin in H I, have small masses and sizes, and are aligned in velocity with higher ionization gas in a separate phase. Rigby et al. (2000) have shown that most single-cloud weak systems are also aligned in velocity with a separate high-ionization gas phase and that the H I is optically thin. Furthermore, the masses, sizes, and metallicities of many weak systems are similar to the kinematic subsystems, being about a few \(10^4 \, M_\odot\) and about a few times 10–100 pc, respectively (Churchill & Charlton 1999; Rigby et al. 2000).

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6 We caution that the sample size is small, \(\sim 15\).
At face value, these considerations would suggest that the origins, sizes, lifetimes, and chemical and ionization conditions of small $W(2796)$ subsystems and of single-cloud weak systems are governed by similar physical processes, even if the environments in which they arise are quite varied. However, as shown in Figure 8 and discussed in §4, there is a clear drop in the number of moderate- and high-velocity subsystems with $W(2796) < 0.08 \AA$, whereas no such decrease is seen for the weak systems down to $W(2796) = 0.02 \AA$ (Churchill et al. 1999). Therefore, for the weakest subsystems, the governing physical processes must diverge from those of the weakest weak systems.

It is reasonable to explore the possibility that the putative different processes are induced by environment, such as the mass of the potential well (galactic environment) or the distance of the absorbing gas from the potential center. The kinematical subsystems are known to be associated with bright, galaxies with a range of mass, including those with $L_K$ about a few times $L^*$. Though the impact parameters are $\sim 40$ kpc or less, the actual galactocentric distances of these weak subsystems are not known. On the other hand, the majority of Mg II absorbers selected by $W(2796) < 0.3 \AA$ do not have $L_K \geq 0.05L^*$ galaxies within $\sim 40$ kpc (Churchill et al. 1999); they are either further out in similar halos or are associated with the small halos of dwarf galaxies with $L_K \leq 0.05L^*$.

Consider photoionized absorbing, cool-phase gas clouds that are pressure confined in hot, virialized gaseous galactic halos with $T_h \sim V_{200}^2 \times 10^6$ K, where $V_{200}$ is the halo circular speed in units of 200 km s$^{-1}$ (proportional to the total mass within the virial radius). The dominant destruction methods would include Rayleigh-Taylor instability, cloud-cloud collisions, Kelvin-Helmholtz instability, and evaporation or condensation (e.g., Mo & Miralda-Escudé 1996). The timescales for these are dependent upon various combinations of the “cloud” masses, $M_{\text{cl}}$, sizes, $r_{\text{cl}}$, densities, $n_{\text{cl}}$, and temperatures, $T_{\text{cl}}$, and upon the virialized halo temperature, $T_h$, density, $n_h$, and pressure, $P_h$, the latter two being functions of distance out in the halo, $R$. For the following, we will assume that $W(2796)$ is a rough indicator of cloud size, $r_{\text{cl}}$.

Rayleigh-Taylor instability sets in when the drag force (ram pressure) on a cloud exceeds the surface self-gravitational force (surface tension). For a cloud of fixed mass, the velocity at which instability sets in varies as $(n_{\text{cl}}/n_h)^{1/2}V_{200}^{-3/2}(M_{\text{cl}}/r_{\text{cl}})$, where $n_{\text{cl}}$ scales as $R^{-1}$ and $n_{\text{cl}}$ scales with slightly less sensitivity, resulting in a very weak antiproportionality with $R$. Smaller clouds are much favored in lower mass halos with little dependence upon galactocentric distance.

The timescale for cloud-cloud collisions depends upon the cloud covering factor, $f_{\text{ct}}$, and scales as $f_{\text{ct}}^{-1}RV_{200}$. For fixed $f_{\text{ct}}$, the destruction rate of clouds by collisions decreases at large galactocentric distances and is smaller in lower mass halos. If $f_{\text{ct}}$ decreases with increasing $R$, the timescale increases with galactocentric distance more rapidly than to the first power.

Pressure confined clouds moving at the sound speed in an external medium are destroyed by Kelvin-Helmholtz (hydrodynamic) instability on the order of the cloud dynamical time, which scales as $t_d \sim T_{1/2}^{1/2}$ (Murray et al. 1993). Clouds with lower densities and smaller sizes are most likely to be destroyed by heat conduction (evaporation) on a timescale very sensitive to the mass of the virialized halo. The evaporation timescales as $M_{\text{cl}}r_{\text{cl}}^{-1}V_{200}^5$ (Cowie & McKee 1977). Mo & Miralda-Escudé (1996) have suggested that, in cases where the cloud covering factor approaches unity, cloud creation should balance cloud disruption and evaporation. In such a scenario, the minimum cloud mass in this equilibrium process will be smaller in environments where the destruction timescales are longer for small clouds, which occurs in smaller mass halos.

The upshot is that each cloud destruction mechanism favors longer lifetimes for small clouds in smaller mass halos and at large galactocentric distances. This by no means explains the differences in the equivalent width distribution of moderate- and high-velocity subsystems and weak systems for small $W(2796)$. However, it is suggestive that small $W(2796)$ clouds are less favored in larger mass halos. Of course, this assumes the ionization conditions and/or metallicities do not systematically vary between weak systems and weak subsystems. As stated above, current evidence is that they do not.

6. PROFILE ASYMMETRIES AND KINEMATICS

One clue to the nature of the moderate- and high-velocity subsystems may be the kinematic asymmetries of the overall Mg II profiles; in virtually every system with multiple subsystems, those with moderate and high velocity are either all blueshifted or all redshifted with respect to the dominant subsystem. This phenomenon would naturally arise if moderate- and high-velocity subsystems are small components of a systematic distribution of gas (both spatially and kinematically) that is offset relative to the dominant subsystem, even if this structure extends well beyond $R(L_K)$. Examples are small clouds within a Magellanic Stream-like structure (which does not have a unity covering factor around the Galactic halo), or between the large column density, H I bridges flowing between M81 and its satellite galaxies (Yun, Ho, & Lo 1994). The systematic asymmetries would not typically arise, however, from absorbing gas with both unity covering factor and a random spatial and kinematic distribution with respect to the dominant kinematical subsystem.

To illustrate a possible spatial-kinematic relationship between the dominant subsystem and weak, moderate- to high-velocity subsystems, we examine a simplistic model of an edge-on rotating disk and a spherical infalling halo. We use the probability distribution functions, $\Phi(v)$, for intercepting an absorbing component (“cloud”) at a given line-of-sight velocity through the disk and halo derived by Lanzetta & Bowen (1992; see their eqs. (1)-(5) and Figs. 9–11). This model assumes an $r^{-2}$ spatial density profile for the absorbing components.

We have normalized these probability distributions such that $\int_{-\infty}^{\infty} \Phi(v)dv = N_{\text{tot}}$ where $N_{\text{tot}}$ is the integrated Mg II column density of the line of sight passing through the model structure. Using this normalization, one can interpret $\Phi(v)dv$ as $N(v)dv$, the probable column density per unit velocity in the velocity interval $v$ to $v + dv$. We normalize the disk component to the average Mg II column densities (eq. [A7]) of the dominant subsystems and the halo component to that of the moderate- and high-velocity subsystems (sample B). These are $\log N_{\text{tot}} = 13.6 \text{ cm}^{-2}$ for the disk and $12.3 \text{ cm}^{-2}$ for the halo, respectively.

In Figures 12a–12d, we show the logarithm probable column density velocity distribution for a combined halo/disk structure with $v = 0$ km s$^{-1}$ set to the disk/halo sys-
temic velocity. The disk rotation and halo infall velocities are set to $w_0 = 150$ km s$^{-1}$, typical of a sub-$L^*$ galaxy. The sense of the disk rotation is chosen toward the line of sight. Each panel illustrates log $N(v)$ for the ratio of the impact parameter, $D$, to the size of the absorbing structure, $R$ (the model geometry is illustrated in Fig. 9 of Lanzetta & Bowen). The dotted curve is the halo absorption and the dashed curve is the disk absorption. The solid curve is the combined absorption.

The most salient feature of this model is that the disk absorption is systematically offset from the halo absorption for all impact parameters; the model consistently predicts asymmetric profiles. The peak predicted column density per unit velocity from the disk is always larger than that predicted from the halo. This is governed by the normalization, which is tuned to the data. As impact parameter is increased, the kinematic spreads of both the disk and halo components decrease. For $D/R > 0.7$, the disk absorption and halo absorption no longer overlap in velocity space.

In Figure 12e–12l, we show Mg II apparent optical depth column density profiles, log $N_a(v)$, for eight of the systems in our sample that show strong asymmetries (computed from eq. [A6]). These profiles are generated by inverting the smooth Voigt profile models for display purposes. The Mg II $\lambda 2803$ transition is used because it is often not as saturated in the strong line cores.$^8$ The velocity zero points and the sign of the velocities have been adjusted arbitrarily to better match the probability distributions for display purposes.

Qualitatively, the observed profiles are remarkably similar to those predicted by the simple models of discreet absorbing components in a disk/halo absorbing structure. The disk absorption could be interpreted to represent the probability distribution of the dominant kinematic sub-system and the halo absorption to represent the probability distribution of the weak, intermediate- to high-velocity sub-systems.

Such an interpretation is consistent with the observed kinematic asymmetries and provides a prediction of what parts of galaxies give rise to the observed kinematic sub-systems. That is, many of the observed profile velocity asymmetries may be governed by the passage of the line of sight through a rotating disk. This structure would give rise to a dominant kinematic sub-systems offset in velocity from the systemic velocity. Its covering factor must be near unity in order to account for the ubiquity of absorption features...
with velocity spreads on the order of the disk component of the models. The weak subsystems at intermediate to high velocities would then arise in the “halo” structure comprised of smaller absorbing clouds. This structure would have a somewhat broader, symmetric distribution of velocities. Statistically, this “halo” structure would have a covering factor near unity, based upon 24 moderate- to high-velocity subsystems observed in 23 systems. However, only 13 systems actually have these subsystems.

If disks play a role in governing the kinematics of Mg II absorbers, the disk orientation is going to give rise to variations in location of the disk component of the model velocity distribution (recall, those presented are for edge-on disks only). In the case of face-on orientations, the velocity width of the disk component will be proportional to the velocity dispersion of the gas perpendicular to the disk (see Charlton & Churchill 1998). The disk systemic velocity will be centered at approximately $v = 0 \text{ km s}^{-1}$ with the velocities of any “halo” structure distributed symmetrically. In Figure 12I, we present a possible example of the kinematics expected from a face-on disk orientation.

This absorber is the only one with weak subsystems to both sides of the dominant subsystem. At $z = 1.15325$ toward PKS 0454 + 039 (Fig. 2f), the candidate absorber is difficult to resolve in an WFPC2/HST image from the HST archive (also see Le Brun et al. 1997). However, there is an example of a $D = 13.2$ kpc, face-on, disk galaxy (see Fig. 1 in Churchill 2000) associated with the $z = 0.55336$ absorber toward Q1148 + 384 (Fig. 2d) that has a central dominant absorption component. Though this system technically is a single kinematic subsystem, several clouds are present whose column densities decrease as subsystem velocity separations from the central component increase. Overall, however, profiles in which the weaker, and/or moderate- to high-velocity subsystems are distributed symmetrically about the dominant subsystem are rare in our sample.

7. WHAT IS EVOLVING?

The differential evolution in the Mg II equivalent width distribution has been determined by measuring the redshift path density, $dN/dz$, for samples with different minimum equivalent widths (see SS92). Absorbers with $W_r(2796) > 0.3 \AA$ exhibit no cosmological evolution. However, as the minimum $W_r(2796)$ is increased, both the mean redshift of the sample and the rate of evolution (slope of the redshift path density) increase, indicating that the strongest systems evolve away with cosmic time and that the largest systems evolve the most rapidly.

Though we have quantified the Mg II absorption properties from the profiles, we point out that qualitative visual inspection can be more revealing than parameterized representations, especially for the profile “shapes,” or kinematic morphologies. We have divided our data into samples B, C, and E, using the same minimum equivalent width cutoffs.
employed by SS92, i.e., greater than 0.3, 0.6, and 1.0 Å, respectively. In the top three panels of Figure 13, we illustrate the Mg II λ2796 profiles in increasing equivalent width order, with the data separated into these three samples. The profiles are presented in rest-frame velocity with the flux normalized and VP models superposed, including ticks that indicate the number of VP components and their velocities. In the lower corner of each subpanel, the equivalent width is given in angstroms.

The mean kinematic spread of the dominant subsystems increases along the sequence from sample B to C to E. This is not surprising, given that the dominant subsystems of larger equivalent width systems are often saturated over a fair fraction of their velocity range. This is reflected in the trend for the largest $W_r(2796)$ systems to have only lower limits on the integrated apparent column densities of their dominant subsystems (see Fig. 9). Thus, the equivalent width is directly proportional to the velocity width of the dominant subsystems, which would not hold true if the moderate- and high-velocity subsystems were often saturated. This could imply, then, that the differential evolution in the equivalent width distribution is primarily due to kinematic evolution (decrease in velocity spread) of the dominant subsystems. However, this is not a unique interpretation.

In the bottom panel of Figure 13, we present examples of higher redshift systems as representatives of the very largest $W_r(2796)$ absorbers. Each has an equivalent width consistent with or greater than 2.0 Å and a redshift greater than $z = 1.3$. If these profiles are representative at higher redshift, then they indicate that large, “double” optically thick subsystems are characteristic of systems that evolve away most rapidly. It has been shown, as one interpretation, that the Mg II evolution rate is consistent with the evolution of galaxy pairs (Churchill et al. 2000b), assuming that each saturated region of the Mg II profiles arise from a separate galaxy.

However, and this cannot be addressed by the current data, there is the question of whether the weak, moderate- and high-velocity subsystems are vestiges of what is evolving. If they are, then the disappearance of multiple, optically thick subsystems, such as those shown in Figure 13, could be explained as either ionization or structure evolution into the weak, moderate- and high-velocity subsystems. Incorporating knowledge of the profile asymmetries discussed in § 6, this would imply that the Mg II evolution is kinematically asymmetric. In the disk/halo scenario outlined above for connecting galaxy structure to the profile asymmetries, such evolution would imply a reduction in the number of “halo” absorbing components, or clouds.

8. CONCLUSION

We have presented the Mg II λ2796, 2803 absorption profiles, resolved at $\pm 6$ km s$^{-1}$ with HIRES/Keck I, for 23 quasar absorption-line systems having $W_r(2796) > 0.3$ Å. We have also presented Fe II, and Mg I profiles when the transitions were detected. The overall absorption properties of many of these systems have been previously investigated (Churchill et al. 2000a).

The complex kinematics were parameterized by defining kinematic subsystems and by Voigt profile fitting. We have discussed the absorber properties, including the distributions of equivalent widths, subsystem-to-subsystem column densities, and velocity separations (see § 4). A companion paper (Churchill et al. 2001) will present analysis of the Voigt profile results. The data were divided into three samples by equivalent width range. We found that there are systematic differences, or trends, in the kinematics with increasing equivalent width and that this may provide clues to the observed differential evolution in the equivalent width distribution of Mg II absorbers (e.g., SS92).

The properties of the “moderate”- and “high”-velocity kinematic subsystems have been compared with those of the Galactic high-velocity clouds (HVCs) and to those of the population of single-“cloud” weak systems. We have inferred that the moderate- and high-velocity subsystems are not higher redshift analogs to HVCs primarily because of the low H I column densities in the former. Though the subsystems and weak systems are comparable in their inferred sizes, metallicities, and ionization conditions, the turnover in the subsystem equivalent width distribution at $W_r(2796) \sim 0.08$ Å would indicate that they reside in different environments. We discussed the timescales for cloud destruction and point out that the smallest clouds are most favored to survive in the smallest mass halos and at the largest galactocentric distances.

Direct knowledge of the kinematic evolution of Mg II absorbers will require an unbiased, higher redshift data set with HIRES/Keck resolution. It is likely that a clear understanding will require charting the kinematics of the higher ionization phases (as seen in C IV absorption, for example) in order to understand the multiphase structure of the gas. It is in the relative kinematics of these ionization phases that the energetics and gas phase structure can be employed to infer the actual mechanisms (i.e., star formation, pair evolution, intergalactic medium infall, chemical enrichment, etc.) that drive the differential evolution in the Mg II equivalent width distribution.

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FORMALISM OF MEASURED QUANTITIES

Here we outline the mathematical formalism for measuring absorption properties directly from the data themselves. We computed these quantities and their measurement errors (uncertainties) for both the overall systems and each of their kinematic subsystems. The computational formalism, including careful treatment of the uncertainties, has been presented in detail in the appendices of Sembach & Savage (1992) and in Churchill (1997), where a few corrections to the Sembach & Savage derivations have been noted.

A1. SYSTEMIC REDSHIFTS

The systemic redshift of each absorbing system is used to define the velocity zero point. We determined each absorber’s systemic redshift, \( z_{\text{abs}} \), from the optical depth mean of the Mg II \( \lambda 2796 \) profiles. We solved the implicit equation

\[
\int_{\lambda_b}^{\lambda_a} \tau_d(\lambda) d\lambda = \int_{\lambda_b}^{\lambda_a} \frac{I(\lambda)}{I(\lambda_0)} d\lambda
\]

for \( \lambda_{\text{sys}} \), the observed wavelength at the optical depth median, where \( \lambda_b \) and \( \lambda_a \) are the extreme blueward and redward wavelengths of the overall system, respectively, and \( \tau_d(\lambda) \) is the apparent optical depth (Savage & Sembach 1991),

\[
\tau_d(\lambda) = \ln \left[ \frac{I(\lambda)}{I(\lambda_0)} \right].
\]

The optical depth median, as opposed to the flux median (i.e., \( 1 - [I(\lambda)/I(\lambda_0)] \)) is used because it weights the absorption by \( \frac{1}{1 - z} \), less than \( (1 - z) \), providing a column density weighted median. Where the profiles are saturation, i.e., \( I(\lambda) \leq |\sigma(\lambda)| \), the apparent optical depth is a lower limit, given by \( \tau_d(\lambda) = \ln [I(\lambda)/|\sigma(\lambda)|] \). Between kinematic subsystems, \( \tau_d \equiv 0 \) in order to eliminate continuum noise.

The absorber redshift is then obtained from \( z_{\text{abs}} = \lambda_{\text{sys}}/\lambda_{2796} - 1 \). The formal redshift uncertainties are typically \( 1 - 5 \times 10^{-6} \), less than \( \sim 1 \) km s\(^{-1}\) (comoving).

A2. EQUIVALENT WIDTHS

The standard expression for the observed equivalent width is

\[
W = \int_{\lambda_b}^{\lambda_a} \left[ 1 - \frac{I(\lambda)}{I(\lambda_0)} \right] d\lambda.
\]

The integration is performed for each kinematic subsystem and then the total system equivalent width is obtained by the sum. The limits of integration \( \lambda_b \) and \( \lambda_a \) are determined as described in § 2.3.3.

A3. SUBSYSTEM VELOCITIES

Each kinematic subsystem has a nonzero velocity. As with the absorber systemic redshifts, we compute the velocities from the apparent optical depth across the Mg II \( \lambda 2796 \) profile. The velocity \( \langle v \rangle \) is the first velocity moment of the optical depth,

\[
\langle v \rangle = \frac{\tau_d^{(1)}}{\tau_d} = \frac{\int \tau_d(v) v dv}{\int \tau_d(v) dv},
\]

where \( v = (c/\lambda_{\text{sys}})(\lambda - \lambda_{\text{sys}}) \) and where the integration is performed over the wavelength region defining each kinematic subsystem.

A4. VELOCITY WIDTHS

The velocity width of a kinematic subsystem \( \omega_v \) is defined by the second moment of the apparent optical depth,

\[
\omega_v^2 = \frac{\tau_d^{(2)}}{\tau_d} = \frac{\int \tau_d(v)[v - \langle v \rangle]^2 dv}{\int \tau_d(v) dv}.
\]

This quantity is the equivalent Gaussian width of the optical depth profile.

A5. APPARENT COLUMN DENSITIES

The “apparent optical depth” technique of Savage & Sembach (1991) was employed to compute column density profiles \( N(v) \) (atoms cm\(^{-2}\)) from

\[
N_d(v) = \frac{m_p c \tau_d(v)}{\pi e^2 f_{\lambda_0}},
\]

where fundamental constants have the usual meanings, and the apparent optical depth is given by equation (A2). The \( N_d(v) \) profiles of doublets, or other same-ion transitions having \( f_{\lambda_0} \) differing by a factor of 2, can be used to discern the velocity location of unresolved saturation in absorption profiles.
Savage & Sembach have shown that this technique yields accurate column densities when the width of the instrumental spread function does not exceed the intrinsic line widths by more than a factor of a few. No corrections (see also Jenkins 1996) have been applied to the measured \( N_a(v) \).

The integrated apparent column density of a system or subsystem is given by

\[
N_a = \int_{v_b}^{v_t} N_a(v) dv ,
\]

where \( v_b \) and \( v_t \) are the velocity extrema of the system or kinematic subsystem being measured.

For adopting the “best value” of \( N_a \) for an ion, there are three possibilities: (1) All transitions of an ion exhibit some saturation between \( v_b \) and \( v_t \), so that \( N_a(v) \) is a lower limit. Often, the transition with the smallest \( f \) provides the best constraints on the lower limit. (2) All but one transition of an ion exhibits saturation, in which case, the adopted column density is taken from the unsaturated transition. And (3) all or more than one transition of an ion are unsaturated, providing multiple independent measurements. The adopted value is computed from the optimally weighted mean [i.e., weighted by \( 1/\sigma^2(N_a) \)].

### A6. VOIGT PROFILE DECOMPOSITION

Voigt profile (VP) decomposition is an established technique for modeling absorption profiles, because it is well suited for parameterizing the absorbing gas properties into physically meaningful quantities, i.e., the number of components (clouds), their line-of-sight velocities, column densities, and Doppler \( b \) parameters.

When an absorption line having optical depth \( \tau(\lambda) \) is recorded by an instrument having a finite resolution defined by its instrumental spread function (ISF) \( \Phi(\delta \lambda) \), the measured spectrum is the convolution of the intrinsic spectrum and the ISF,

\[
I_{\text{obs}}(\lambda) = \Phi(\delta \lambda) \otimes \{ I_o(\lambda) \exp \left[-\tau(\lambda)\right] \} ,
\]

where \( I_o(\lambda) \) is the emitted intensity, and \( I_{\text{obs}}(\lambda) \) is the observed intensity.

The optical depth is the product of the line-of-sight integrated column density \( N = \int m(l) dl \, \text{cm}^{-2} \) and the atomic absorption coefficient \( a(\lambda) \), and it is given by

\[
\tau(\lambda) = N a(\lambda) = \frac{\sqrt{\pi} e^2}{m_e c^2} \frac{N_j f_j^2}{\Delta \lambda} \times u(x, y) ,
\]

where \( u(x, y) \) is the Voigt function evaluated at \( x = (\lambda - \lambda_o)/\Delta \lambda \) and \( y = \lambda_o^2 \Gamma/4\pi c \Delta \lambda \), and where \( \Gamma \) is the transition damping constant (see Table 2) and \( \Delta \lambda \) is the Doppler width. This formalism assumes that the dominant line broadening mechanism is a Lorentzian convolved with a Gaussian (the former being the intrinsic line width and the latter being due to line-of-sight thermal and/or bulk motions). For the computation of the Voigt function, we used the real part of the complex probability function

\[
w(z) = e^{-z^2} \left( 1 + \frac{2i}{\sqrt{\pi}} \int_0^z e^{-t^2} dt \right)
\]

\[
= e^{-z^2} \text{erfc} \left(-iz\right)
\]

\[
= u(x, y) + it(x, y) ,
\]

which is accurately computed using the very efficient routine Cpf12 (Humlicek 1979).

Thus, for each VP, there are three free parameters, \( N, \lambda_o, \) and \( \Delta \lambda \). When a systems is a complex blend of multiple VP components, the optical depth used in equation (A8) is the sum of the individual components,

\[
\tau(\lambda) = \sum_{i=1}^{N_{vp}} \tau_i(\lambda) ,
\]

where \( \tau_i(\lambda) \) is given by equation (A9), and the number of free parameters becomes \( 3N_{vp} \).

The component velocities of all transitions are “tied” together, as are the column densities of all transitions of a given ion. The column density of each ion is allowed to vary freely as are the \( b \) parameters. For the statistical modeling, we use a \( \chi^2 \) minimization with a code of our own design, MINFIT (Churchill 1997), which uses the least-squares minimizing algorithm DNLSE1 (More 1978) and the supporting SLATEC library made publicly available by http://www.netlib.org.

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