THE MULTIPLE PHASES OF INTERSTELLAR AND HALO GAS IN A POSSIBLE GROUP OF GALAXIES AT $z \sim 1$

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ABSTRACT

We used HIRES/Keck profiles ($R \sim 6$ km s$^{-1}$) of Mg II and Fe II in combination with Hubble Space Telescope (HST) Faint Object Spectrograph (FOS) spectra ($R \sim 230$ km s$^{-1}$) to place constraints on the physical conditions (metallicities, ionization conditions, and multiphase distribution) of absorbing gas in three galaxies at $z = 0.9254$, 0.9276, and 0.9343 along the line of sight to PG 1206+459. The chemical and ionization species covered in the FOS/HST spectra are H I, Si ii, C ii, N ii, Fe iii, Si iii, Si iv, N iii, C iii, C iv, S vi, N v, and O vi, with ionization potentials ranging from 13.6 to 138 eV. The multiple Mg II clouds exhibit complex kinematics and the C iv, N v, and O vi are exceptionally strong in absorption. We assumed that the Mg II clouds are photoionized by the extragalactic background and determined the allowed ranges of their physical properties as constrained by the absorption strengths in the FOS spectra. A main result of this paper is that the low-resolution spectra can provide meaningful constraints on the physical conditions of the Mg II clouds, including allowed ranges of cloud-to-cloud variations within a system. We find that the Mg II clouds, which have a typical size of approximately 100 pc, give rise to the Si iv, the majority of which arises in a single, very large (~5 kpc), highly ionized cloud. However, the Mg II clouds cannot account for the strong C iv, N v, and O vi absorption. We conclude that the Mg II clouds are embedded in extended (10–20 kpc), highly ionized gas that gives rise to C iv, N v, and O vi; these are multiphase absorption systems. The high-ionization phases have near-solar metallicity and are consistent with Galactic-like coronae surrounding the individual galaxies, as opposed to a very extended common "halo" encompassing all three galaxies.

Key words: galaxies: abundances — galaxies: evolution — galaxies: halos — galaxies: structure — quasars: absorption lines

1. INTRODUCTION

An ultimate goal of the study of quasar (QSO) absorption lines is to develop a comprehensive understanding of the kinematic, chemical, and ionization conditions of gaseous structures in early-epoch galaxies and to chart their cosmic evolution. For a comprehensive physical picture of any given absorption system, both high-resolution spectra of a wide range of chemical and ionization species and the empirically measured properties of the associated galaxies are required. For $z \sim 1$, shortly following the epoch of peak star formation, the association between Mg II $\lambda 2796$, 2803 absorption and galaxies is well established (Bergeron & Boissé 1991; Steidel 1995), and their kinematics, though complex and varied, are consistent with being coupled to the galaxies themselves (Churchill, Steidel, & Vogt 1996; Charlton & Churchill 1998). It is unfortunate, however, that for $z \sim 1$, the spectroscopic data are not of uniform high quality because of the need for large amounts of space-based telescope time to observe ultraviolet wavelengths. Presently, any comprehensive analyses of low-redshift systems for which the low-ionization species (i.e., Mg II, Fe ii, Mg i) have been observed at high resolution with HIRES/Keck (see Churchill, Vogt, & Charlton 1999b) must incorporate low-resolution Hubble Space Telescope (HST) Faint Object Spectrograph (FOS) spectra of the intermediate- and high-ionization species, especially the strong C iv $\lambda\lambda 1548, 1550, N v \lambda\lambda 1238, 1242$, and O vi $\lambda\lambda 1031, 1037$ doublets, and of several other important low-ionization species.

Presently, it is not clear if these low-resolution data can be used to place meaningful constraints on the chemical and ionization conditions of the clouds in Mg II selected absorbers. For this paper, we investigated this issue in a pilot study, since an affirmation would imply that a larger sample could be studied using existing data from the Hubble Data Archive. We would then be able to address the broader implications for galaxy formation scenarios based upon the inferred metallicities, abundance patterns, and inferred relative spatial distribution of the low- and high-ionization absorbing gas clouds.

Under the assumptions of photoionization and/or collisional ionization equilibrium, we developed a technique in which it was assumed that the number of clouds and their kinematics are obtained by Voigt profile decomposition of the high-resolution Mg II spectra. We then used the lower resolution profiles from the FOS data to place constraints on the range of chemical and ionization conditions in these clouds. We also explored the idea that the Mg II could arise in relatively low-ionization clouds embedded in a higher ionization and more extended medium (see Bergeron et al. 1994; Churchill 1997a). More specifically, we set out to

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1 Some of the data presented here were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. Based in part on observations obtained with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under NASA contract NAS 5-26555.

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answer three questions: (1) Assuming the Mg II clouds measured with HIRES are photoionized, can we construct model clouds that are consistent with the many low- and intermediate-ionization species captured in the FOS data? (2) If so, are we required to infer an additional (presumably low-density and diffuse) component to account for higher ionization absorption from C IV, N V, and O VI? (3) If so, can this diffuse component be made consistent with photoionized only, collisionally ionized only, or photo-plus collisionally ionized gas?

For this paper, we chose the three systems at z_{abs} = 0.9254, 0.9276, and 0.9342 along the line of sight toward PG 1206 + 459 (z_{em} = 1.16) because they are exceptionally rich in low-, intermediate-, and high-ionization ultraviolet transitions (Burles & Tytler 1996; Churchill 1997b; Jannuzi et al. 1998). The HIRES/Keck Mg II profiles are illustrated in Figure 1. Two of the systems are kinematically “complex” and are separated by about 300 km s^{-1}. The third system is more isolated, being approximately +1000 km s^{-1} from the other two. This system is classified as a “weak” Mg II absorber [defined by W_{lambda}(2796) < 0.3 Å; Churchill et al. 1999a]. The highest ionization transitions, C IV, N V, and O VI, are seen to have a total kinematic spread of approximately 1000 km s^{-1} coincident with the three systems seen in Mg II absorption (Churchill 1997b).

In the QSO field, Kirhakos et al. (1994) found three bright galaxies with angular separations from the quasar of 5.6', 8.6', and 9.0' and g magnitudes 21.1, 21.5, and 22.3, respectively (see note added in proof). The 8.6' galaxy has detected [O II] lambda 3727 with flux 9 \times 10^{-17} ergs cm^{-2} s^{-1} at z = 0.93 (Thimm 1995). At this redshift, the QSO-galaxy impact parameters are 29, 45, and 47 h^{-1} kpc (g_0 = 0.05). There are approximately 10 galaxies with 21 \leq g \leq 22 within 100' of the QSO (Kirhakos et al. 1994). This is an overdensity by a factor of about 3 compared to field galaxies (Tyson 1988). Thus, it is of interest to entertain the possibility of a group environment for these absorbers.

In §2 we describe the data and their analysis. In §3 we outline our modeling technique and simplifying assumptions. A synopsis of the model results are given in §4. Details on how the data were used to constrain the models and how various ionizing spectral energy distributions modify these models are given in Appendices A and B. In §5 we compare and contrast the system properties, and in §6 we discuss what might be inferred about the relative spatial distribution of the low- and high-ionization gas. We summarize in §7.

2. DATA AND ANALYSIS

2.1. HIRES/Keck

The optical data were obtained with the HIRES spectrometer (Vogt et al. 1994) on the Keck I Telescope on 1995 January 23 UT under clear and stable conditions with a seeing of approximately 0.6'. The spectral resolution is approximately 6.6 km s^{-1} (R = 45,000), with a sampling of 3 pixels per resolution element. The signal-to-noise ratio (S/N) is approximately 50 per resolution element. The Fe II lambda 2344, 2374, 2383, 2587, and 2600 transitions were captured at similar S/N.

The HIRES spectrum was reduced with the IRAF4 APEXTRACT package for echelle data. The detailed steps for the reduction are outlined in Churchill (1995). The spectrum was extracted using the optimized routines of Horne (1986) and Marsh (1989). The wavelengths were calibrated to vacuum using the IRAF task ECIDENTIFY, which models the full two-dimensional echelle format. The absolute wavelength scale was then corrected to heliocentric velocity. The continuum normalization was performed using the IRAF SFIT task. Objective and unbiased identification of absorption features (without regard to their association with the studied systems) was performed as described in Churchill et al. (1999b), using the methodology of Schneider et al. (1993).

4 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by AURA, Inc., under cooperative agreement with the NSF.
Three systems, which we hereafter call A, B, and C, are observed at redshifts $z_A = 0.92540$, $z_B = 0.92760$, and $z_C = 0.93428$. In Figure 1 we present the Mg II doublet profiles. The doublets are marked by the labeled bar above the normalized continuum. The solid curve through the data is a model spectrum generated using Voigt profile (VP) decomposition. The free parameters are the number of VP components ("clouds") and, for each, its redshift, column density, and Doppler b parameter. We have used the program MINFIT (Churchill 1997c), which performs a $\chi^2$ minimization while minimizing the number of clouds using a specified confidence level and the standard F-test. The adopted VP decomposition had six clouds in system A, five clouds in system B, and a single cloud in system C.

The HIRES data and the VP decompositions are shown in Figure 2, with the profiles aligned in rest-frame velocity. In Table 1, we present the cloud properties, including individual redshifts, velocities with respect to $z = 0.92760$, column densities, b parameters, and the ratios $\log \left[ N(\text{Fe II})/N(\text{Mg II}) \right]$. Only system B was found to have measurable Fe II. The 1 $\sigma$ upper limits on Fe II were obtained for each cloud from the equivalent width limits of the $\lambda 2600$ transition. For Fe II in system A, we measured a mean 1 $\sigma$ column density upper limit of $N(\text{Fe II}) \leq 10^{11.1}$ cm$^{-2}$ for the six clouds using the technique of stacking (Norris, Hartwick, & Peterson 1983).

2.2. FOS/HST

The ultraviolet data were obtained with the FOS on HST as part of the QSO Absorption Line Key Project. The data acquisition, their reduction, and the objective absorption-line lists are presented in Jannuzi et al. (1998). Their fully reduced G190H and G270H spectra have kindly been made available for this study. The spectra have a resolution of $R = 1300$ ($\sim 230$ km s$^{-1}$) and cover the approximate wavelength intervals 1600 to 2313 Å and 2225 to 3280 Å for the G190H and G270H settings, respectively.

For the most part, we have adopted the Key Project continuum fits and line identifications. Some refinement was needed near the Si IV $\lambda 1393$, 1402 doublet (2680 Å $\leq \lambda_{\text{obs}} \leq 2715$ Å on G270H), which lies on the red wing of the broad Ly$\alpha$ emission line, and near the Si II $\lambda \lambda 1190, 1193$ doublet (2290 Å $\leq \lambda_{\text{obs}} \leq 2310$ Å on G190H), which lies at the spectrum edge. We have refitted the continuum across these regions.

A Lyman limit break is present at approximately 1760 Å (however, see Stengler-Larrea 1995; Jannuzi et al. 1998). We extrapolated the continuum fit of Jannuzi et al. below the break starting at the break shoulder ($\lambda = 1895$ Å). This technique preserved the measured optical depth, or the break ratio, $F_\nu/F_\nu$ (Schneider et al. 1993), while yielding a reasonable approximation to the shape of the recovery (see

![Figure 2](image_url)
Fig. 3a). Because of the high density of lines, the Jannuzi et al. continuum may have been systematically low by 5%–10% in the region 1790 to 1820 Å, and our extrapolation may have propagated this systematic offset. Nonetheless, this error has a negligible effect on the measured break ratio of 2.5 ± 0.4, which we obtained from the unnormalized as well as the normalized spectrum. This ratio implies τ_{Lyα} ≈ 0.9 and a total neutral hydrogen column density of N(H I) ≈ 10^{21.2} cm^{-2}.

Out of the roughly 70 QSOs analyzed by the QSO Absorption Line Key Project, PG 1206+459 is one of eight for which the line identifications (IDs) were subject to greater uncertainty (the Lyz forest is ubiquitous blueward of 2623 Å and at least four metal systems are present). Using the HIRES data for cross-checks with the Jannuzi et al. line IDs in the FOS spectrum, we have made a table of transitions, including those detected and those used for constraining the models. In Table 2, we have listed the observed wavelengths, line IDs, ionization potentials, and notes on any blending. For example, we identified the Lyman series down to Lyα, beyond which the three systems blend together. The FOS spectrum provides a large number of chemical and ionization species, including Lyz, Lyβ, Lyγ, Lyδ, Lyε, C II λ1036 and λ1334, C III λ977, C IV λ1548, 1550, N II λ1295, N III λ989, N v λ1238, 1242, O VI λ1031, 1037, Si II λ1190, 1193 and λ1260, Si III λ1206, Si IV λ1393, 1402, and S VI λ2933, 944. These species represent a wide range of ionization potentials from 13.6 eV for H I to 138.1 eV for O VI.

3. MODELS

Assuming the Mg II clouds are photoionized, our goal was to determine if we can obtain useful constraints on their range of chemical and ionization conditions using the FOS/HST spectra. Within this context, we also explored the possibility of a high-ionization (C IV, N v, and O vi), presumably diffuse, component. In principle, this high-ionization phase could be photoionized, collisionally ionized, or photo-plus collisionally ionized gas (a spatially segregated two-phase high-ionization component).

For both the Mg II and the high-ionization phase, the extragalactic ultraviolet ionizing background spectrum of Haardt & Madau (1996) for z = 1 was assumed. Using the [O II] λ3727 detection and constraints measured by Thimm (1995), we explored the range of allowed contributions (modifications to the Haardt & Madau background) from various galactic spectral energy distributions. We find that galactic contributions, within the allowed ranges explored, do not modify general conclusions based upon the assumption of a pure Haardt & Madau background (see Appendix B).

3.1. Mg II Clouds

We used the photoionization code CLOUDY (version 90.4; Ferland 1996). The free parameters are the neutral hydrogen column density, N(H I), the metallicity, Z, the abundance pattern, and the ionization “parameter” U, which is defined as the ratio of the number of hydrogen-ionizing photons to the hydrogen number density, n_H (including ionized, neutral, and molecular forms). For the Haardt & Madau spectrum and normalization, a simple relation between ionization parameter and hydrogen number density, log U = −5.2 − log n_H, holds.

For a given abundance pattern, the ratio N(Fe II)/N(Mg II) uniquely determines the ionization parameter, U. Once U is determined, the measured N(Mg II) fixes log N(H I) + Z ≈ C_1 for a cloud in photoionization equilibrium. For a given Z, the constant C_1 is constrained by the Lyman series transitions in the FOS data. Throughout, we assume Z ≤ 0. To characterize the abundance pattern, we used the ratio of z-group species to Fe-group species, [z/Fe]. Abundance ratios measured in Galactic stars show a clear range of 0 ≤ [z/Fe] ≤ +0.5 (Lauroesch et al. 1996), which we adopt as a reasonable range for the studied systems. Since all clouds have measured N(Mg II), an z-group element, it follows that [z/Fe] + Z ≈ C_2. Thus, for clouds with measured N(Fe II)/N(Mg II), the only arbitrarily chosen free parameter is the abundance pattern. One selects a Z and [z/Fe] (fixes C_2), determines N(H I) by constraining the photoionization models with the Lyman series tran-

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TABLE 1

| SYSTEM | CLOUD | z_{abs} (km s^{-1}) | e | log N (cm^{-2}) | b (km s^{-1}) | log N^a (cm^{-2}) | b (km s^{-1}) | Fe II/Mg II (log) |
|--------|-------|-------------------|---|----------------|-------------|----------------|-------------|-----------------|
| A ...... 1 0.92501 | -403.5 | 11.92 ± 0.03 | 5.98 ± 0.55 | < 11.47 | ... | < -0.5 |
| A ...... 2 0.92535 | -350.7 | 12.16 ± 0.02 | 2.89 ± 0.26 | < 11.48 | ... | < -0.7 |
| A ...... 3 0.92550 | -327.7 | 12.12 ± 0.02 | 2.98 ± 0.28 | < 11.48 | ... | < -0.6 |
| A ...... 4 0.92595 | -256.8 | 12.35 ± 0.01 | 4.77 ± 0.20 | < 11.48 | ... | < -0.9 |
| A ...... 5 0.92639 | -188.0 | 12.01 ± 0.02 | 3.10 ± 0.37 | < 11.49 | ... | < -0.5 |
| A ...... 6 0.92648 | -174.2 | 11.60 ± 0.05 | 3.69 ± 0.89 | < 11.49 | ... | < -0.1 |
| B ...... 7 0.92720 | -62.8 | 11.72 ± 0.07 | 16.19 ± 3.54 | < 11.47 | ... | < 0.3 |
| B ...... 8 0.92742 | -29.0 | 13.44 ± 0.04 | 5.67 ± 0.15 | 12.75 ± 0.02 | 6.19 ± 0.27 | < 0.7 |
| B ...... 9 0.92764 | 6.0 | 13.29 ± 0.01 | 7.38 ± 0.14 | 12.21 ± 0.06 | 8.52 ± 1.26 | < 1.1 |
| B ...... 10 0.92780 | 30.4 | 12.60 ± 0.01 | 12.70 ± 0.49 | < 11.45 | ... | < 1.2 |
| B ...... 11 0.92803 | 66.0 | 12.82 ± 0.01 | 5.08 ± 0.10 | 12.07 ± 0.05 | 2.85 ± 0.76 | < 0.8 |
| C ...... 12 0.93428 | 1038.3 | 12.05 ± 0.02 | 7.52 ± 0.52 | < 11.41 | ... | < -0.6 |

*a The mean upper limit on log N(Fe II) is 11.1 cm^{-2} for the six clouds in system A based upon the technique of stacking the Mg II clouds.
Fig. 3.—Normalized FOS/HST spectrum (histogram) and the tuned model predictions (not fits). The ticks mark locations of the constraint transitions identified for systems A, B, and C. Three models are shown. The thick solid spectrum includes the photoionized Mg II clouds, the photoionized diffuse component for systems B and C, and the photo-plus collisionally ionized diffuse component for system A. The narrow solid spectrum includes the Mg II clouds and the photoionized diffuse components for each system. The dotted-line model includes the Mg II clouds only and is shown to illustrate the required high-ionization phases. (a) Lyman break and Lyman series. See text regarding the continuum fit, which is probably low in the region of 1760 to 1820 Å. Note the N II j 916 in system B and the S VI j 933, 944 in systems A and B. (b) Lyβ, C III j 977, and N III j 989 predictions. Note the sensitivity of C III to the model components. (c) Lyβ, O VI j 1031, 1037, and C IV j 1036 predictions. The wavelength calibration may be shifted blueward in the region from approximately 1980 to 2005 Å. Virtually no O VI resides in the Mg II clouds, but must arise in a higher ionization phase. (d) Si III j 1206, Lyα, and N V j 1242 predictions. Note the sensitivity of Lyα and N V to the model components. The Si III arises primarily in the Mg II clouds. (e) Si II j 1190, 1193 doublet. The Si II also arises primarily in the Mg II clouds. (f) Si II j 1260 prediction. A blend (Lyα?) must be present in the red wing. (g) C III j 1334 prediction. As with Si II and Si III, the C II arises primarily in the Mg II clouds. Note the strong blend (Lyα?) in the red wing. (h) Si IV j 1400 doublet predictions. Since the Si IV also arises primarily in the Mg II clouds, the Si II, Si III, and Si IV ratios placed tight constraints on the cloud ionization conditions. (i) (Self-blending) C IV j 1548, 1550 doublet predictions. For systems A and B, note that a fair fraction of the C IV arises in the Mg II clouds, but the majority must arise in a higher ionization phase.

sitions, and thus determines C_1 (an example of this process is given in Appendix A).

By exploring a large range of Z and [α/Fe], we verified the above relationships. When only an upper limit is available on N(Fe II)/N(Mg II) for a given cloud, one has two arbitrarily chosen parameters, [α/Fe] and N(Fe II)/N(Mg II), which together uniquely determine the ionization parameter. The constraints on the Mg II cloud ionization param-
| Number | \( \lambda \) (Å) | Ion \( \lambda \) (Å) | IP (eV) | System | Notes |
|--------|------------------|-----------------|--------|--------|-------|
| 1a     | 1762.92          | N II 915.61     | 29.6   | A      |       |
| 2a     | 1765.03          | N II 915.61     |        | B      | Matches depression at Lyman limit |
| 3a     | 1770.98          | N II 915.61     |        | C      |       |
| 4a     | 1797.13          | S VI 933.38     | 88.0   | A      | C-fit? |
| 5a     | 1799.19          | S VI 933.38     |        | B      | Bl-Ly6 from system C; C-fit?; note* |
| 6a     | 1805.42          | S VI 933.38     |        | C      | Bl-7a; C-fit? |
| 7a     | 1805.65          | Lyβ 937.80      | 13.6   | A      | Bl-6a; C-fit? |
| 8a     | 1807.80          | Lyβ 937.80      |        | B      |       |
| 9a     | 1813.90          | Lyβ 937.80      |        | C      |       |
| 10a    | 1818.58          | S VI 944.52     | 88.0   | A      |       |
| 11a    | 1820.66          | S VI 944.52     |        | B      |       |
| 12a    | 1826.97          | S VI 944.52     |        | C      | Bl-13a |
| 13a    | 1828.64          | Lyβ 949.74      | 13.6   | A      | Bl-12a |
| 14a    | 1830.82          | Lyβ 949.74      |        | B      |       |
| 15a    | 1836.99          | Lyβ 949.74      |        | C      |       |
| 16a    | 1872.52          | Lyγ 972.54      |        | A      |       |
| 17a    | 1874.76          | Lyγ 972.54      |        | B      |       |
| 18a    | 1881.08          | Lyγ 972.54      |        | C      | Bl-19b; Bl-Lyγ |
| 19a    | 1881.15          | C III 977.02    | 47.9   | A      | Bl-18b |
| 20a    | 1883.40          | C III 977.02    |        | B      |       |
| 21a    | 1889.75          | C III 977.02    |        | C      |       |
| 22a    | 1905.76          | N III 989.80    | 47.4   | A      | Bl-Ly or Lyβ? |
| 23a    | 1908.04          | N III 989.80    |        | B      |       |
| 24a    | 1914.47          | N III 989.80    |        | C      |       |
| 25a    | 1974.93          | Lyβ 1025.72     | 13.6   | A      |       |
| 26a    | 1977.28          | Lyβ 1025.72     |        | B      |       |
| 27a    | 1983.95          | Lyβ 1025.72     |        | C      |       |
| 28a    | 1986.87          | O VI 1031.93    | 138.1  | A      |       |
| 29a    | 1989.25          | O VI 1031.93    |        | B      |       |
| 30a    | 1995.36          | C II 1036.33    | 24.3   | A      | Bl-31c; Bl-Lyβ? |
| 31a    | 1995.95          | O VI 1031.93    | 138.1  | C      | Bl-30c; Bl-Lyβ? |
| 32a    | 1997.75          | C II 1036.34    | 24.3   | B      | Bl-33c |
| 33a    | 1997.83          | O VI 1037.62    | 138.1  | A      | Bl-32c |
| 34a    | 2000.21          | O VI 1037.62    |        | B      | Bl-Lyβ? |
| 35c    | 2004.48          | C II 1036.34    | 24.3   | C      |       |
| 36c    | 2006.96          | O VI 1037.62    | 138.1  | C      |       |
| 37e    | 2292.03          | Si II 1190.42   | 16.3   | A      |       |
| 38e    | 2294.76          | Si II 1190.42   |        | B      |       |
| 39e    | 2297.56          | Si II 1193.29   |        | A      |       |
| 40e    | 2300.31          | Si II 1193.29   |        | C      |       |
| 41e    | 2302.50          | Si II 1190.42   |        | B      |       |
| 42e    | 2308.06          | Si II 1193.29   |        | C      |       |
| 43d    | 2323.00          | Si II 1206.50   | 33.5   | A      |       |
| 44d    | 2325.77          | Si III 1206.50  |        | B      |       |
| 45d    | 2333.61          | Si III 1206.50  |        | C      |       |
| 46d    | 2340.65          | Lyα 1215.67     | 13.6   | A      |       |
| 47d    | 2343.45          | Lyα 1215.67     |        | B      |       |
| 48d    | 2351.35          | Lyα 1215.67     |        | C      |       |
| 49d    | 2385.23          | N v 1238.82     | 97.9   | A      | Bl-Galactic Fe II |
| 50d    | 2388.08          | N v 1238.82     |        | B      |       |
| 51d    | 2392.89          | N v 1242.80     |        | A      |       |
| 52d    | 2395.75          | N v 1242.80     |        | B      | Bl-53d |
| 53d    | 2396.13          | N v 1238.82     |        | C      | Bl-52d |
| 54d    | 2403.83          | N v 1242.80     |        | C      |       |
| 55f    | 2426.82          | Si II 1260.42   | 16.3   | A      |       |
| 56f    | 2429.72          | Si II 1260.42   |        | B      | Bl-Lyα? |
| 57f    | 2437.91          | Si II 1260.42   |        | C      |       |
| 58g    | 2565.51          | C II 1334.53    | 24.4   | A      |       |
| 59g    | 2572.58          | C II 1334.53    |        | B      | Bl-Lyα? |
| 60g    | 2581.25          | C II 1334.53    |        | C      | Bl-Lyα? |
| 61h    | 2683.54          | Si IV 1393.76   | 45.1   | A      | Note* |
| 62h    | 2686.74          | Si IV 1393.76   |        | B      |       |
eters, abundance pattern, and metallicities are fairly tight and robust; even when \( N(\text{Fe} II)/N(\text{Mg} II) \) was an upper limit, the Si \( \Pi \), Si \( \III \), and Si \( \IV \) ratios were key for constraining the ionization parameter, independent of the abundance pattern (see Appendix A). In a given system, for clouds in which \( N(\text{Fe} II)/N(\text{Mg} II) \) was only an upper limit, we assumed that they were identical vis-à-vis their Mg \( \II \) column densities (had identical metallicities and abundance patterns). This yielded model clouds with identical \( Z \) and \( [\alpha/\text{Fe}] \), but unique \( N(H \ I) \), because of their unique \( N(\text{Mg} II) \). The allowed range of cloud-to-cloud variations within a system, if desired, can be obtained from the two relations giving \( C_1 \) and \( C_2 \) [as long as the total \( N(H \ I) \) is held constant].

To narrow parameter space, we began with a grid of photoionization models with CLOUDY, where the grid was defined for (1) \( \log [N(\text{Fe} II)/N(\text{Mg} II)] \) from \( -1 \) to \( -4 \) in intervals of 0.5 dex (this provides the ionization parameter \( U \)), (2) \( N(H \ I) \) from \( 10^{14} \) to \( 10^{18} \) cm\(^{-2} \) in 1 dex intervals, (3) \( Z \), from \( -2.0 \) to \( +0.4 \) in intervals of 0.2 dex, and (4) solar and \( [\alpha/\text{Fe}] = +0.5 \) abundance pattern. Once the parameter space was narrowed, we ran CLOUDY in its optimized mode tuned to the Mg \( \II \) column densities to obtain the adopted models.

Model clouds are drawn from the grid, and a synthetic FOS spectrum is generated from the model column densities for the transitions listed in Table 2. The simulated FOS spectrum is generated by modeling the absorption from each transition by Voigt profiles convolved with the FOS instrumental spread function. The Doppler parameters of the modeled transitions are determined from the observed Mg \( \II \) \( b \) parameters and the kinetic temperature, \( T \), output by the CLOUDY models, typically 5000 to 30,000 K. The CLOUDY temperature is used to estimate the thermal component of \( b(\text{Mg} \ II) \), from which the turbulent \( b \) parameter is computed from the relation \( b^2 = b^2_\text{thermal} + b^2_\text{turb} \). The total \( b \) parameter of any transition can then be estimated from its CLOUDY thermal \( b \) and the turbulent \( b \). The synthetic spectrum is then superposed on the observed FOS spectrum and the \( \chi^2 \) is calculated pixel by pixel in regions of interest as an indicator of the goodness of the model.

3.2. High-Ionization Gas

As will be shown, the model Mg \( \II \) clouds could not account for even a small fraction of the absorption strengths of the higher ionization species (i.e., C \( \IV \), S \( \VI \), N \( \V \), and O \( \VI \)). Thus, we postulated a high-ionization diffuse component not seen in Mg \( \II \) absorption. A maximal diffuse scenario provides the low-ionization limit of the Mg \( \II \) clouds such that their contribution to the moderate- and high-ionization species is minimized. A minimal diffuse scenario provides the high-ionization limit of the Mg \( \II \) clouds such that their contribution to the moderate- and high-ionization species is maximized.

For a postulated high-ionization component, we used C \( \IV \) and O \( \VI \) to constrain model cloud properties for both a solar abundance pattern \( [\text{C}/\text{O}] = 0 \) and an oxygen to carbon enhancement of \( [\text{C}/\text{O}] = -0.5 \). For constraints on the models from S \( \VI \), we use \( [\text{S}/\text{H}] = 0 \), but note that sulfur is enhanced by approximately 0.5 dex for \( [\text{Fe}/\text{H}] < 0 \). We avoid using N \( \V \) as a primary constraint because the chemical enrichment processes for nitrogen can lead to wide variations in its abundance (Wheeler, Sneden, & Truran 1989). We adopt \( [\text{N}/\text{O}] = 0 \) for this work, but occasionally discuss possible variations in this ratio.

To examine the range of properties of a diffuse component, we did the following systematic explorations. For each system, we first assumed that any required high-ionization gas is in a single, broad component. The adopted models of the high-ionization components are obtained using the same techniques illustrated in Appendix A, but the primary constraints are the residual strengths of the C \( \IV \) and O \( \VI \) absorption unaccounted by the Mg \( \II \) clouds. Also, consistency with any unaccounted C \( \III \), Si \( \III \), Si \( \IV \), S \( \VI \), and N \( \V \) is required. We then explored the possibility that the C \( \IV \) arises in a few “C \( \IV \)–only” clouds, while the O \( \VI \) arises in a diffuse low-density high-ionization phase that is separate from the C \( \IV \) clouds, which are separate from the Mg \( \II \) clouds. The N \( \V \) and S \( \VI \) absorption profiles were critical for constraining these “C \( \IV \) cloud” models.

We systematically explored whether contributions from both photoionization and collisional ionization are consistent with the data. For collisional ionization, we have drawn from the equilibrium models of Sutherland & Dopita (1993) with solar abundances. In these models, the relative column densities of various species, including that of neutral hydrogen, are a unique function of temperature for a given metallicity. Thus, under the model assumptions, the remaining free parameter is the temperature. We located the

### Table 2—Continued

| NUMBER | \( \lambda \) (Å) | LINE ID | \( \lambda \) (Å) | IP (eV) | SYSTEM | NOTES |
|--------|-----------------|---------|-----------------|------|--------|-------|
| 63h….. | 2695.80         | Si iv   | 1393.76         | C    |        |       |
| 64h….. | 2700.89         | Si iv   | 1402.77         | A    |        |       |
| 65h….. | 2704.12         | Si iv   | 1402.77         | B    |        |       |
| 66h….. | 2713.24         | Si iv   | 1402.77         | C    |        |       |
| 67i….. | 2980.89         | C iv    | 1548.20         | 64.5 | A      |       |
| 68i….. | 2984.46         | C iv    | 1548.20         | B    | Bl-69i |       |
| 69i….. | 2985.85         | C iv    | 1550.77         | A    | Bl-68i |       |
| 70i….. | 2989.42         | C iv    | 1550.77         | B    |        |       |
| 71i….. | 2994.52         | C iv    | 1548.20         | C    |        |       |
| 72i….. | 2999.50         | C iv    | 1550.77         | C    |        |       |

Note—The letter component to the line number gives the Fig. 5 panel designation. “C-fit?” indicates that the continuum fit is somewhat uncertain. “Bl-X” indicates an identified line blend.

*The clear presence of Ly6 from system C at 1799.2 Å and of Si iv 21393 from system A at 2683.5 Å casts doubt upon the reality of the O vi–selected system at \( z = 0.7338 \) reported by Burles & Tytler 1996.*
lowest ionization level of a photoionized diffuse component consistent with the intermediate and moderately high ionization species, after taking into account the Mg II clouds. A collisional ionization model was then tuned to any unaccounted absorption in N V and O VI.

4. MODEL RESULTS

Our intent is to present a general picture of both the Mg II cloud and high-ionization diffuse component properties within the context of our modeling. The adopted model properties are presented in Tables 3, 4, and 5. In Table 3, we list the physical parameters of the 12 Mg II clouds for the scenarios of a maximal or minimal diffuse component. Typical model parameters for each system are given in Table 4. The tabulated values serve as a guide; in the following discussion we quote allowed ranges in the cloud properties based upon § 3. The diffuse component properties are listed in Table 5. The results described below are for Appendix B, we describe our explorations with several galactic/starburst radiation fields (representing both some- properties based upon Table 4. The tabulated values serve as a guide; in the following discussion we quote allowed ranges in the cloud properties based upon § 3. The diffuse component properties are listed in Table 5. The results described below are for the Haardt & Madau (1996) extragalactic background. In Figure 3, we present the synthetic spectrum of our models superposed upon the FOS spectrum. The model transitions are labeled with three-point ticks, which give the locations of systems A, B, and C, from blue to red, respectively. Three synthetic spectra are shown. The dotted spectrum is of the 12 photoionized Mg II clouds. The thin solid spectrum includes both the Mg II clouds and the single-phase photoionized diffuse components. The thick solid-line spectrum includes a two-phase photo-plus collisionally ionized component in system A.

4.1. System A (z = 0.9254)

Since N(Fe II)/N(Mg II) was not measured in any of the system A clouds, the clouds were assumed identical vis-a-vis their N(Mg II). The Si II–to–Si IV ratio tightly constrains the ionization level of these six clouds. There is only a very small range of allowed ionization conditions, with log U ≈ −2.3. To avoid supersolar metallicity, the mean [α/Fe] ranges from +0.3 to +0.5, which corresponds to 0.0 ≤ Z ≤ −0.2, respectively.

### Table 3

| System | Cloud | N(Mg II) | U (1) | Z (2) | Fe II/Mg II (3) | N(H I) (4) | N(C IV) (5) | S (pc) (6) |
|--------|-------|----------|-------|-------|----------------|------------|------------|-----------|
| A***** | 1     | 11.92    | −2.5  | −0.2  | −3.0           | 15.0       | 13.3       | 90        |
| A...... | 2     | 12.16    | −2.5  | −0.2  | −3.0           | 15.2       | 13.5       | 150       |
| A...... | 3     | 12.12    | −2.5  | −0.2  | −3.0           | 15.2       | 13.5       | 140       |
| A...... | 4     | 12.35    | −2.5  | −0.2  | −3.0           | 15.4       | 13.7       | 230       |
| A...... | 5     | 12.35    | −2.5  | −0.2  | −3.0           | 15.1       | 13.4       | 110       |
| A...... | 6     | 11.60    | −2.5  | −0.2  | −3.0           | 14.7       | 13.0       | 40        |
| B....... | 7     | 11.72    | −4.0  | −0.6  | −0.7           | 15.7       | 6.7        | 1         |
| B....... | 8     | 13.44    | −3.2  | 0.0   | −0.7           | 16.7       | 13.2       | 110       |
| B....... | 9     | 13.29    | −3.4  | 0.0   | −1.1           | 16.5       | 13.6       | 210       |
| B....... | 10    | 12.60    | −3.1  | −0.6  | −1.6           | 16.2       | 12.6       | 60        |
| B....... | 11    | 12.82    | −3.2  | 0.0   | −0.8           | 16.1       | 12.7       | 30        |
| C....... | 12    | 12.05    | −3.1  | −1.0  | −1.1           | 16.3       | 12.3       | 100       |

**Note:** Systems A and B are α-group enhanced by 0.5 dex, whereas system C has solar abundance ratios. Col. (1) is the log of the ionization parameter (see text). The number density of hydrogen is given by log n_H = −(log U + 5.2). Col. (2) is the metallicity, [Z/Z⊙]. Col. (3) is the ratio of the Fe II and Mg II column densities, log N(Fe II) − log N(Mg II).Cols. (4) and (5) are the log of the H I and C IV column densities in atoms cm⁻². Col. (6) is the linear depth of the cloud in parsecs.

a. Note that the low- and high-ionization “limits” of system A are presented to be identical. In fact, the limits are very narrow because of the constraints provided by the Si II and Si IV profiles (see text).

b. The Fe II/Mg II ratio of this cloud is fixed by measurement. The cloud abundance ratio pattern is assumed solar, not α-group enhanced (see text).
density increases rapidly with decreasing $b$ and is effectively constant for $b > 70$ km s$^{-1}$ in the relevant range of equivalent width. Based upon exploration of the allowed range of $b$ parameters, an upper limit on the size of the diffuse component is approximately 30 kpc for $b = 50$ km s$^{-1}$. However, the best models, incorporating both a $\chi^2$ fit to the C IV profile and matching to the N V, S VI, and O VI profiles, had $b \geq 65$ km s$^{-1}$, which yielded sizes of about 10–20 kpc.

### TABLE 5

**Diffuse Component Cloud Properties**

| Property | System A | System B | System C |
|----------|----------|----------|----------|
|..........| Single-Phase | Two-Phase | Single-Phase | Single-Phase |
| $z_{abs}$ | Photo. | Photo. | Coll. | Photo. | Photo. | Unit |
|..........| 0.92572 | 0.92572 | 0.92572 | 0.92768 | 0.93428 |
| $Z$ | 0 | 0 | 0 | 0 | -0.4 |
| [C/O] | 0 | 0 | 0 | 0 | 0 |
| $b$ | 70 | 70 | 70 | 70 | 40 km s$^{-1}$ |
| $N$(Si IV) | 11.3 | 12.1 | 12.0 | 12.8 | 10.3 cm$^{-2}$ |
| $N$(N III) | 13.3 | 13.7 | 12.5 | 14.3 | 12.8 cm$^{-2}$ |
| $N$(C III) | 13.8 | 14.2 | 11.8 | 14.8 | 13.4 cm$^{-2}$ |
| $N$(C IV) | 14.5 | 14.5 | 13.5 | 15.2 | 13.9 cm$^{-2}$ |
| $N$(S VI) | 12.7 | 13.1 | 13.4 | 13.7 | 12.1 cm$^{-2}$ |
| $N$(N V) | 14.2 | 13.8 | 14.2 | 14.5 | 13.6 cm$^{-2}$ |
| $N$(O VI) | 15.0 | 14.3 | 15.0 | 14.9 | 14.5 cm$^{-2}$ |
| $\log U$ | -1.2 | -1.6 | ... | -1.6 | -1.3 |
| $N$(H I) | 14.6 | 14.8 | 13.5 | 15.5 | 14.5 cm$^{-2}$ |
| $N$(H) | 18.7 | 18.5 | 19.2 | 19.1 | 18.6 cm$^{-2}$ |
| $N$(C IV)/$N$(N IV) | -4.0 | -3.6 | ... | -3.6 | -3.9 cm$^{-3}$ |
| $S'$ | 16.5 | 3.9 | 0.01/$n_H$ | 16.0 | 11.6 kpc |
| $N$(C IV)/$N$(O IV) | 0.3 | 1.6 | 0.03 | 1.6 | 0.3 |
| $N$(C IV)/$N$(Si IV) | 1320 | 250 | 30 | 220 | 4000 |

* For a fiducial density range of $-3 \leq \log n_H$(cm$^{-3}$) $\leq -4$ for the collisionally ionized phase of system A, the inferred size is $10 \leq S \leq 100$ kpc.
4.2. System B (z = 0.9276)

A range of ionization conditions (−3.2 ≤ log \( U \) ≤ −2.7) for the clouds is found for this system, primarily based upon the observed Fe II to Mg II ratios in clouds 8, 9, and 11, and upon Si II, Si IV and the other low-ionization species for clouds 7 and 10. However, the low-ionization limits (maximal diffuse scenario) are ruled out because the Si IV, N III and a large fraction of the C III must arise in the Mg II clouds. The Lyman limit break is primarily produced by clouds 8 and 11. For these clouds, the metallicity must be \( Z \geq -0.2 \), even for an \( x\)-group enhanced abundance pattern, or else the Lyman limit break would be too large. In clouds 7 and 10, the allowed abundance-pattern range is \( 0.0 \leq [z/Fe] \leq +0.5 \), corresponding to \( -0.1 \leq Z \leq -0.6 \) (the lower limit is constrained by the Lyman series). The Si IV arises primarily in cloud 10, the most highly ionized, lowest density, and extended (≈ 5 kpc) Mg II cloud of the five. Even for the minimal diffuse scenario (high-ionization limit), the predicted C IV absorption is still well below the observed strength.

Thus, an additional high-ionization component, not seen in Mg II absorption, is required to account for the C IV, N V, and O VI absorption. This component is consistent with a single-phase photoionized diffuse medium (\( b \approx 70 \) km s\(^{-1}\), based upon the simulations of the C IV profile) with a solar abundance pattern and near-solar metallicity. The bulk of the C IV, N V, and O VI absorption arises in this component, whereas the N III and Si IV absorption arise primarily in cloud 10. The C III arises in both the Mg II clouds and the diffuse component. In Figure 3a, we point out the N II \( \lambda 916 \) absorption, which accounts for the reduced flux in the Lyman break. We also point out the weak S VI \( \lambda 933, 944 \) absorption, which arises in the diffuse component (the \( \lambda 933 \) transition is blended with Ly\( \alpha \) from system C). It is not possible for a collisionally ionized phase to substantially contribute.

As with system A, we obtained a maximum line-of-sight size, \( S \), of 30 kpc for the highly ionized diffuse component, but found a preferred size range of 10–20 kpc. For \( b \leq 50 \) km s\(^{-1}\), the larger cloud size elevated absorption in all high-ionization species such that, in particular, \( S \) \( \geq \) was significantly overproduced. A reduced [S/H] would yield reduced sulfur absorption, but is unlikely because sulfur is usually enhanced relative to solar, and it is known not to suffer dust depletion (Lauroesch et al. 1996).

4.3. System C (z = 0.9343)

Although system C is a single weak Mg II cloud, it is best described by two photoionized phases. This inference is based upon a self-consistent match to the Lyman series, which is obtained when both a narrow and a broad component are included. The narrower low-ionization Mg II cloud accounts for the \( \mathrm{H} \) \( I \) in the \( \mathrm{L} \) \( \gamma \), \( \mathrm{L} \) \( \delta \), and \( \mathrm{L} \) \( \epsilon \) absorption, whereas the broader high-ionization diffuse component contributes significantly to the \( \mathrm{L} \) \( \alpha \) and \( \mathrm{L} \) \( \beta \) profiles.

The lower ionization phase produces the narrow Mg II, Si III, and Si IV in a smaller cloud. We obtained log \( U \approx -2.6 \) and the range \( -1.0 \geq Z \geq -1.5 \) for \( 0.0 \leq [x/Fe] \leq +0.5 \). The higher ionization phase, with log \( U \approx -1.3 \), has \( b \approx 40 \) km s\(^{-1}\), which yields a size \( S \approx 10 \) kpc. It is not possible for this high-ionization component to be strictly collisionally ionized, nor is it possible for it to be a two-phase photo-plus collisionally ionized component; any contribution from a collisionally ionized phase is insignificant.

5. DISCUSSION

As shown in Figure 2, system A is composed of six distinct Mg II clouds with a total velocity spread of approximately 200 km s\(^{-1}\) and is about 300 km s\(^{-1}\) from system B, which has five clouds spread over about 100 km s\(^{-1}\). System C is approximately +1000 km s\(^{-1}\) from system B and is composed of a single, resolved Mg II cloud. In Figure 3, we show the normalized FOS spectrum with simulated spectra superposed. These low-resolution data reveal that each system is rich in multiple chemical species covering a wide range of ionization potentials and that the chemical and ionization conditions differ from system to system.

One motivation for our study was simply to ascertain if a multiphase medium was required to explain the strong C IV, N V, and O VI absorption lines. In all three systems, we were required to postulate a higher ionization component that is not seen in Mg II absorption. We emphasize that (1) the overall Mg II cloud properties are well constrained by the data and modeling and (2) the allowed cloud-to-cloud variations are constrained tightly enough that no scenario even remotely modifies the requirement for a C IV–N V–O VI high-ionization phase to explain the data. To the accuracy afforded by the FOS spectrum, each of these high-ionization phases is well described by a single component with \( b \approx 70 \) km s\(^{-1}\) (based upon simulations). Given the large \( b \) parameters and the range of sizes derived from the models (Table 5), this high-ionization gas is likely to have a line-of-sight extent of 10 kpc ≤ \( S \) ≤ 20 kpc and thus may be a surrounding medium in which the roughly 0.1 kpc Mg II clouds are embedded.

5.1. Comparison of System Properties

Consider the cloud-to-cloud variations in system B, which is a Lyman limit system. The line-of-sight velocity spread of the Mg II clouds is about 100 km s\(^{-1}\), which implies that they are bound within a galactic potential. If the clouds are equally illuminated by the extragalactic background, then the presence of Fe II in three of the clouds (8, 9, and 11) implies that they are more dense, more shielded from the ionizing flux, and/or iron-group enriched relative to the other two clouds (7 and 10). This suggests that clouds 8, 9, and 11 may be spatially contiguous (relatively speaking), in that they may share similar histories of iron-group enrichment from Type Ia supernovae. In the Galaxy, the association of Type Ia explosions with the kinematically old disk implies that some events take place at large scale heights, so there is uncertainty in how much iron-rich gas is driven into galactic halos (Wheeler et al. 1989).

The unique cloud in system B is cloud 10, which gives rise to a broader absorption profile (\( b \approx 13 \) km s\(^{-1}\)) and has no detectable Fe II. It has a higher ionization condition and gives rise to the majority of the Si IV absorption (see Fig. 4). It also has the largest \( N(\text{Mg II}) \). Models show that it is extended (≈ 5 kpc) and has lower metallicity. This leads us to speculate conservatively that cloud 10 is more akin to a halolike cloud or to a so-called Galactic high-velocity cloud. The ratio \( N(\text{Si IV})/N(\text{Mg II}) \) may be a useful indicator of the differing local environments of clouds in higher redshift systems.

System C classifies as a “weak” Mg II absorber, defined by \( W_c(2796) < 0.3 \) Å (Churchill et al. 1999a). From a sample
Fig. 4.—Selection of predicted high-resolution profiles for systems A and B based upon our models. This simulated STIS/HST spectrum has $R = 30,000$ ($v \sim 10 \text{ km s}^{-1}$) and S/N of 30. Short ticks mark the velocities based upon the HIRES Mg II clouds and long ticks mark the diffuse component centroids. For system A, the three-phase model (photoionized Mg II clouds and photo-plus collisionally ionized diffuse component) is shown, and for system B, the two-phase model (photoionized clouds and diffuse component) is shown. The dotted curves are the profiles of the blended individual Mg II clouds. The solid curves are the photoionized diffuse component profiles and the dash-dotted curves are of the collisionally ionized diffuse component.
of 30 such systems over the redshift range $0.4 < z < 1.4$, Churchill et al. found a wide range of $W_r(^{12}\text{Fe II})/W_r(^{24}\text{Mg II})$ and $W_r(^{24}\text{Si IV})/W_r(^{24}\text{Mg II})$, presumably because of variations in abundance pattern and ionization conditions, including single-phase and multiphase. These $\text{Mg II}$ absorbers are sub-Lyman limit systems with $Z \geq -1$ and (some with $Z > 0$; Churchill & Le Brun 1998). Apart from its line-of-sight proximity ($<500$ km s$^{-1}$) to system B, system A would classify as a weak $\text{Mg II}$ absorber. The approximately 200 km s$^{-1}$ kinematic spread of the six clouds in system A and the large $N(\text{Si IV})/N(\text{Si IV})$ ratio in the diffuse component are suggestive of lower ionization clouds moving within a high-ionization galactic corona, or halo, where the ratio $N(\text{C IV})/N(\text{Si IV})$ is expected to be large (Savage, Sembach, & Lu 1997). Is it possible that the system C $\text{Mg II}$ cloud arises in a similar environment as the six system A clouds, but that the line of sight happens to sample only one cloud? If so, the C IV absorption strength in system C would be comparable to that of system A, and it is significantly weaker. For weak systems, it may be that strong, broad C IV absorption implies a larger number of $\text{Mg II}$ clouds with a larger kinematic spread.

5.2. Profile Anatomy: Model Predictions

In Figure 4, we present simulated STIS/HST spectra with $R = 30,000$, 2 pixels per resolution element, and an S/N of 30 for the first four transitions in the Lyman series, and for the Si IV, C IV, N v, and O vi profiles of systems A and B. These spectra were generated assuming Voigt profiles with the properties listed in Tables 4 and 5. These model profiles can be compared directly with observed data (from STIS/HST) and thus provide a direct test of the models. We show the contributing components as smooth curves. The dotted curves are the $\text{Mg II}$ clouds, with their velocity centroids marked with the short tick marks above the continuum. The solid curves are from the photoionized diffuse component and the dash-dotted curves in system A represents the collisionally ionized diffuse component.

5.2.1. Lyman Series

Here we emphasize the importance of the Lyman series. For all three systems, the Lyz and $\text{Ly}^\beta$ profiles in the FOS spectra were significantly broader than could be fully accounted by the H I obtained solely from the model $\text{Mg II}$ clouds. However, the narrower Ly$\gamma$, Ly$\delta$, and Ly$\epsilon$ profiles were fully accounted by the H I in these clouds. Based upon the curve of growth behavior of the Lyman series, we found that the addition of a very broad ($b > 50$ km s$^{-1}$), lower $N(\text{H I})$ component naturally explained the deeper and broader Lyz and $\text{Ly}^\beta$ profiles, without overproducing the narrower Ly$\gamma$, Ly$\delta$, and Ly$\epsilon$ profiles (or modifying the Lyman limit break).

Such behavior of the Lyman series in low-resolution data is likely to be a strong indication that a broad, perhaps highly ionized diffuse component is present. In Figure 4, we illustrate this behavior as it would be seen in higher resolution spectra. Note that the widths of Lyz and $\text{Ly}^\beta$ are dominated by a broad, high-ionization component, whereas the higher order transition widths are dominated by the $\text{Mg II}$ clouds. In high-resolution spectra, a diffuse component gives rise to a broadened, shallow wing when the profiles are saturated (see Lyz and $\text{Ly}^\beta$ in system B) and/or suppresses the recovery of the flux to the continuum level between clouds in the profile centers (see Ly$\beta$ and Ly$\gamma$ in system A).

5.2.2. High-Resolution Metal Lines

In system A the C IV profiles have structure because of the lower ionization $\text{Mg II}$ clouds. The Si IV absorption predominantly arises in the $\text{Mg II}$ clouds, and thus closely traces the $\text{Mg II}$ kinematics. Together, these profiles are tantamount similar to those observed by Savage, Sembach, & Cardelli (1994) along the line of sight to HD 167756 in the Galaxy. We quote, "The sight line contains at least two types of highly ionized gas. One type gives rise to a broad N v profile, and the other results in a more structured Si IV profile. The C IV profile contains contributions from both types of highly ionized gas." We also find similarities between the model C IV profiles and those in the damped Ly$\alpha$ systems at $z_{\text{abs}} = 3.3901$ toward Q0000$-262$ and $z_{\text{abs}} = 2.2931$ toward Q0216$+080$ (Lu et al. 1996, Figs. 2 and 3).

In system B, cloud 10 is clearly unique among the $\text{Mg II}$ clouds. This cloud has the largest ionization parameter and accounts for the majority of the Si IV absorption, which was clearly constrained to arise in the $\text{Mg II}$ clouds. Since the ionization conditions of clouds 8, 9, and 11 were set by their measured $N(\text{Fe II})/N(\text{Mg II})$, the ionization condition in cloud 10 was well constrained by the ratio $N(\text{Si II})/N(\text{Si IV})$; there was no alternative but for cloud 10 to dominate the Si IV absorption. The point is that this cloud may arise in a spatially distinct environment and have a unique formation history from the other clouds in system B (see § 5). The C IV profile is dominated by a diffuse higher ionization phase, whereas the Si IV is predominantly due to higher density clouds. Some lines of sight through the Galaxy also exhibit narrow Si IV profiles and broad C IV profiles (for examples, see Sembach, Savage, & Jenkins 1994; Savage & Sembach 1994). In contrast, the Si IV and C IV profiles in the $z_{\text{abs}} = 2.8268$ damped Ly$\alpha$ system toward Q1425$+063$ (Lu et al. 1996) appear to arise in the same phase.

A synthetic STIS/HST spectrum for system C (not shown) reveals a narrow Si IV profile and broad C IV, N v, and O vi profiles. The C IV profile exhibits a slightly deep, narrow core because of the low-ionization phase. However, this contribution would be lost for the expected noise levels in observed data unless this narrow component was off-center by about 40 km s$^{-1}$ relative to the broad component (within the uncertainty of our modeling such an offset is not ruled out).

6. ON THE NATURE OF THE HIGH-IONIZATION PHASE

Within 100" of the QSO, Kirhakos et al. (1994) identified 10 galaxies with $21 \leq g \leq 22$. Compared with field galaxies, this is a slight overdensity by a factor of a few to several (Tyson 1988). Identified within 10" of the QSO are three bright galaxies with impact parameters 29, 45, and 47 h$^{-1}$ kpc, respectively ($q_0 = 0.05$) (see note added in proof). At $z = 0.93$, Thimm (1995) detected a [O II] $\lambda 3727$ flux of $9 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ from the galaxy at 45 h$^{-1}$ kpc.

Given these facts, we entertain the possibility that the $\text{Mg II}$ absorption systems arise in individual galaxies either in a small group or possibly in a cluster. Such a possibility would have interesting implications in view of the types of mechanisms that could give rise to highly ionized gas in such environments.
6.1. Intragroup Corona?

Mulchaey et al. (1996) predicted that poor groups that are rich in spiral galaxies have hot, diffuse coronae that are cooler than the X-ray coronae surrounding poor groups dominated by E/S0 galaxies. This high-ionization intragroup material is predicted to have $T \sim 2 \times 10^6$ K and to give rise primarily to strong O vi, whereas any C iv or N v absorption is predicted to arise in the proximity of the galaxies themselves (Mulchaey et al. 1996). As such, the O vi profiles would be broader than the N v and C iv. The same would hold for the Lyman series (Verner, Tytler, & Barthel 1994).

Our models can fully explain the O vi, N v, and C iv in a single component of $T \sim 3 \times 10^4$ K gas (the possible collisional component in system A has $T \sim 3 \times 10^5$ K). The observed O vi or H i widths are not broader than those of the C iv and N v, and their approximately 70 km s$^{-1}$ $b$ parameters are not suggestive of gas that is kinematically akin to the roughly 200 km s$^{-1}$ dispersion of a galaxy group. Furthermore, the O vi, N v, and C iv profiles are clearly aligned with the three Mg ii absorption redshifts, suggesting that the high-ionization material is spatially coincident with the individual Mg ii systems. The upper limit on the size of the photoionized diffuse components is $S \leq 30$ kpc (assuming photoionization equilibrium), and the inferred $Z \sim 0$ metallicities suggest that the high-ionization material surrounds the galaxies and has been enriched by them. Significantly lower metallicities are expected if the gas was intragroup material left over from the formation processes. We do not favor an interpretation of the data in which the high-ionization material arises in an intragroup or common halo.

6.2. Galactic Coronae?

The highly ionized material in these three $z \sim 1$ galaxies may be more akin to galactic coronae (see Spitzer 1956, 1990; Savage et al. 1997) material stirred up by energetic mechanical processes, such as galactic fountains. In this scenario, the gas is concentrated around individual galaxies, which presumably provide a source of support, heating, and chemical enrichment.

In the Galaxy, $b \approx 60$ km s$^{-1}$ was measured for C iv and was observed to increase slightly with the ionization level of the transition (Savage et al. 1997). Simulations of the allowed range of $b$ parameters for systems A and B yielded similar Doppler widths, with $b \approx 70$ km s$^{-1}$ providing a good match to the C iv, N v, and O vi profiles for both systems. If the high-ionization diffuse components in these systems are arising in coronae analogous to that surrounding the Galaxy, they may have similar turbulent processes supporting their scale heights.

The radial extent of the Galactic corona is unknown, but for local galaxies, radio maps reveal that H i extends to tens of kiloparsecs (Corbelli, Schneider, & Salpeter 1989; van Gorkom et al. 1993), beyond which the hydrogen becomes optically thin and a highly ionized extension is expected (Maloney 1993; Corbelli & Salpeter 1993; Dove & Shull 1994). The impact parameters of the candidate galaxies are approximately 30–50 h$^{-1}$ kpc, with the orientation of the line of sight through each galaxy unknown. Absorption, even from nonspherical absorbers, is not unexpected at an impact parameter of about 50 kpc (see Fig. 1 of Charlton & Churchill 1996). For the Galaxy, Savage et al. (1997) measured the effective scale heights of 5.1, 4.4, and 3.9 kpc for Si iv, C iv, and N v, respectively. We find a preferred size of 10–20 kpc for the size of the high-ionization gas at $z \sim 0.93$, with an upper limit of approximately 30 kpc. Since these “sizes” (or the path length through an oriented structure) are comparable to twice the Galactic scale height, the distribution of high ionization is consistent with Galactic-like coronae.

A scenario in which the high-ionization gas arises in individual galactic coronae is in contrast to that proposed by Lopez et al. (1998) for a system at $z \sim 1.7$ in the spectra of HE 1104–1811, B. In a double line-of-sight study, Lopez et al. found O vi profiles consistent with $110 \leq b \leq 180$ km s$^{-1}$ and that the extent of the highly ionized gas was approximately 100 kpc. These inferences also differ from those of Bergeron et al. (1994), who found that the O vi phase in the $z_{abs} \sim 0.8$ Mg ii absorber toward PKS 2145 +064 was at least 50 kpc in extent.

7. Conclusions

We have studied the kinematic, chemical, and ionization conditions of three metal-line absorption systems at $z \sim 1$ seen in the PG 1206+459 spectrum. The systems were selected by the presence of Mg ii absorption in a high-resolution spectrum and were chosen as a pilot study for a larger program designed to chart the physical conditions and evolution of absorbing gas in galaxies. The Mg ii profiles are shown in Figure 1, with the respective systems designated A, B, and C. Rich absorption-line data from FOS/HST (Jannuzi et al. 1998) revealed strong C iv, N v, and O vi absorption, as well as H i and many other species and transitions covering a wide range of ionization potentials. Ground-based imaging data (Kirhakos et al. 1994) revealed three candidate absorbing galaxies within 10" of the QSO and possibly a group of galaxies within 100" of the QSO (see note added in proof).

The main goals of the study were to see if multiphase gas was required to explain the strong high-ionization absorption-line data and to infer some level of information on the gas metallicities and spatial distributions. Assuming the Mg ii clouds are photoionized, we found the range of chemical and ionization conditions consistent with both the high- and low-resolution data. We then postulated the presence of high-ionization components not seen in Mg ii absorption to explain the unaccounted C iii, C iv, N v, and O vi absorption.

We briefly summarize the main results of our study:

1. For systems A and B, we were required to postulate a high-ionization phase in addition to the lower ionization Mg ii clouds. System C could be made marginally consistent with a single-phase absorber, though a two-phase absorber is strongly preferred because of the nature of the Lyman series absorption. We infer that, in these systems, the lower ionization Mg ii clouds arise in high-ionization diffuse gas; each of these absorption systems is composed of a multiphase gaseous medium. We find that the high-ionization phase of system A could arise in multiple, narrower “C iv clouds.” For system B, such C iv clouds are ruled out.

2. The absorbing gas in both the Mg ii clouds and the high-ionization components are consistent with photoionized clouds. In systems B and C, a collisionally ionized phase is ruled out. Only in system A could the data be made...
consistent with a three-phase absorber, incorporating the photoionized Mg II clouds, a highly photoionized diffuse component, and a collisionally ionized component. This three-phase model provided a more consistent match to the N v absorption in this system. In this three-phase scenario, the C IV could arise in a few narrower components. However, [N/O] ≈ 0.15 in the highly photoionized component, instead of the assumed [N/O] = 0, would remove the need for the collisionally ionized gas and rule out the three-phase absorber.

3. We find no evidence that the O vi gas is in a separate and very highly ionized diffuse phase that encompasses the C IV and N v absorption. Based upon the b ∼ 70 km s\(^{-1}\) profile widths, inferred Z ∼ 0 metallicities, 3 × 10\(^4\) K temperatures, inferred S ≤ 30 kpc sizes, and the clear redshift alignment of the high-ionization transitions with the Mg II systems, we suggest that the high-ionization gas is analogous to the Galactic corona in that it traces the galaxies themselves and does not appear to exhibit the characteristics predicted for intragroup or intracluster material. The O vi likely arises in the same phase as the C IV and N v. The Si IV is constrained to arise in the same phase as the Mg II clouds, whereas C III arises in both the clouds and the high-ionization phase.

4. We have found cloud-to-cloud variations in the chemical and ionization conditions in the five Mg II clouds of system B. Three of the clouds are likely to be iron-group enriched and have higher densities and low-ionization conditions. The majority of the neutral hydrogen giving rise to the Lyman break in the FOS spectrum is from these clouds. A lower metallicity Mg II cloud giving rise to a broader absorption profile is interspersed in velocity with these clouds, likely has a z-group enhanced abundance pattern, and gives rise to the majority of the Si IV absorption. We speculate that this cloud may be similar to a halo-like cloud, and suggest that the ratio N(Si iv)/(Mg II) may be a useful indicator for discriminating between clouds in different parts of high-redshift galaxies.

The most compelling reason why we favor the scenario in which the high-ionization diffuse material is coupled to the galaxies is the clear kinematic separation of the O vi profiles corresponding to systems A and B. Each of the inferred diffuse components must be centered (at least roughly) on the systems, and they must be distinct from one another in velocity space. There are additional, if less compelling, arguments. The inferred b parameters in the model diffuse components are in the same regime as those found for the Galactic corona (Savage et al. 1997), further suggesting that the material is galaxy-associated. The inferred metallicities are high, Z ∼ 0, which is best understood if the material had been enriched by its host galaxy and further suggests that the origin and source of enrichment of the diffuse gas is related to star-forming parts of galaxies. The enrichment could be due to in situ star formation as gas clouds collide and cool in the galactic halos (Steidel & Sargent 1992), or it could be due to galactic fountain processes from the galactic disks (Spitzer 1990).

As a speculative aside, we ask if Galactic-like coronae O vi absorbers are likely to be a common form of O vi systems at z ≲ 1, as opposed to group halos. Burles & Tytler (1996) have shown that absorbers selected by the presence of O viI have the same redshift path density as Lyman-limit Mg II absorbers at z = 0.9. As we have found here, O viI can be associated with a Lyman limit system when the absorbing gas is segregated into multiple ionization phases. If multiphase absorption is common in Mg II absorbers, some O vi might arise in Galactic-like corona.

It would seem that this pilot study has shown that wholesale study of the kinematic, chemical, and ionization conditions of Mg II absorbers, using high-resolution Mg II profiles and the available low-resolution HST spectra, would yield a improved understanding of galactic gas at early epochs. In order to assess the robustness of our modeling, we have synthesized high-resolution STIS/HST spectra of the ultraviolet transitions (presented in Fig. 4). The modeling techniques applied in this paper can be directly tested by comparing these predicted profiles with those observed with STIS/HST. If our approach proves to yield an accurate description of the gas, then wholesale modeling can be embarked upon for roughly 50 Mg II systems without requiring large amounts of space-based telescope time to acquire high-resolution spectra of high quality.

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APPENDIX A
APPLICATION OF OBSERVED CONSTRAINTS

In this appendix, we demonstrate our modeling methodology for constraining the ionization parameters, metallicities, and overall Mg II cloud properties, using the FOS/HST data.

In Figure 5, we present an example of how the data are used to constrain the ionization parameter U. In Figure 5a the synthetic FOS spectrum of the Si ii λ1190, 1193 doublet is superposed on the FOS data for the 1 σ upper limits on log [N(Fe II)/N(Mg II)], and for the set ratios −3.0, −3.5, and −4.0. The Si iv λ1393, 1402 doublet is shown in Figure 5b. The assumed abundance pattern is solar. Clouds 8, 9, and 11 have their U constrained by the observed log [N(Fe II)/N(Mg II)]. The ratio of Si ii to Si iv can uniquely determine U for the remaining clouds. For system A, the best match is provided by log U = −2.3 (which corresponds to log [N(Fe II)/N(Mg II)] = −3.0). Lower ionization clouds are not possible because they overproduce Si ii, whereas higher ionization clouds overproduce Si iv. For system B, a reasonable
match to the observed Si II and Si IV is achieved if clouds 7 and 10 (dominated by its larger Mg II column density) are assigned log $U = -2.0$, which corresponds to log $[N(Fe\ II)/N(Mg\ II)] = -4.0$. Less ionized clouds are possible, but an additional more highly ionized component would then be required to produce Si IV.

In Figure 6, we present an example of how the Lyman series and limit are used to constrain the metallicity for the ionization parameters determined in the above illustration. We have assumed $[\alpha/Fe] = 0$ for this illustration. Three metallicities are shown, $Z = -0.4, 0.0$, and $+0.4$, to illustrate the strength variations in the Lyman series and limit. At low metallicity, a large $N(H\ I)$ is needed to produce the observed metal lines with low and intermediate ionization levels. Such a large $N(H\ I)$ can be inconsistent with the observed Lyman series lines and Lyman limit break. As described in § 2, the Lyman limit break implies a total $N(H\ I)$ of $10^{17.2}$ cm$^{-2}$. For system A, the best match to the Lyman series lines is given by $Z = +0.2$, supersolar metallicity. For system B, the best match also has high metallicity; clouds 8, 9, and 11 must have $Z = 0.0$, and cloud 10 must also have near solar metallicity in order that there not be too large an $N(H\ I)$. It is important to point out that the assumed abundance pattern directly affects the inferred metallicities. If the abundance pattern is $\alpha$-group enhanced, $[\alpha/Fe] = +0.5$, the illustrated metallicities would proportionally drop by approximately 0.5 dex. This is because the cloud properties are tuned to the $N(Mg\ II)$, and magnesium is an $\alpha$-group element (see § 3).

APPENDIX B

GALACTIC IONIZING PHOTONS?

Given the $[O\ II] \lambda 3727$ emission measured by Thimm (1995), it is reasonable to assume that high-energy photons could be escaping the galaxies (e.g., Bergeron et al. 1994). The Thimm measurement of an $[O\ II]$ flux from one galaxy (and limits for the others) constrains the contribution of galactic ionizing photons to be greater than $7 \times 10^5$ cm$^{-2}$ s$^{-1}$ under the assumption that 50% of the photons escape from the galaxy. This is a factor of 5 to 50 times greater than that estimated for the Galaxy (Bland-Hawthorn & Maloney 1999) and for external galaxies (Deharveng et al. 1997), respectively. Keeping this generous upper limit in mind, we consider the effect a change in spectral shape could have on our main results. Several contrasting starburst models from Bruzual & Charlot (1993) were explored. In all cases, the galaxy spectra were normalized relative to the Haardt & Madau (1996) flux, $F_{\text{HI}}$, at 1 ryd. Depending on the spectral shape, the above limit corresponds to $F_{\text{sb}}/F_{\text{HI}} < 4$–10, where $F_{\text{sb}}$ is the flux of the starburst galaxy model at 1 ryd.

First we consider a $10^7$ yr instantaneous burst model because of its prominent He I edge (see Fig. 4 of Bruzual & Charlot 1993). As the ratio $F_{\text{sb}}/F_{\text{HI}}$ is increased, the hydrogen becomes more ionized and it is possible to decrease the cloud metallicities without overproducing H I. However, only a modest decrease of 0.4 dex is possible for $F_{\text{sb}}/F_{\text{HI}} \leq 10$. For these models, there are relatively fewer photons capable of ionizing C III and thus there is even less C IV produced in the Mg II clouds. Similarly, in order to maintain the observed Si II–Si IV ratio, it is necessary to slightly increase the cloud ionization parameter by a few tenths of a dex from the pure Haardt & Madau case. We also consider the effect of the change in spectral shape upon the diffuse phase that produces C IV and O VI. Similar conclusions hold for the metallicity, which can decrease by at most 0.5 dex from the pure Haardt & Madau case; the diffuse phase still must have relatively high metallicity ($>0.32Z$). For energies greater than the He II edge, this overall spectrum is unchanged relative to Haardt & Madau, and therefore the balance between C IV and O VI, and other high-ionization energy transitions is unaltered.

In order to explore a severe H I edge, we considered another extreme model, a $10^8$ yr instantaneous burst. In this case the measured $[O\ II]$ constraint also forces the upper limit $F_{\text{sb}}/F_{\text{HI}} \leq 10$. Interestingly, the Mg II cloud metallicity cannot be reduced (relative to pure Haardt & Madau) because $N(H\ I)$ actually increases relative to $N(Mg\ II)$ as the galaxy contribution is increased. Because of similar behavior, the metallicity of the required diffuse component is constrained to be solar or
Fig. 6.—Illustration of how the Lyman series was used for tuning metallicity, $Z$, and neutral hydrogen column density, $N(H\,\text{i})$, for set ionization conditions. Only the photoionized Mg $\text{ii}$ clouds are shown. For these clouds, the ionization conditions were tightly constrained by the Si $\text{ii}$, Si $\text{iii}$, and Si $\text{iv}$ data. The ticks mark systems A, B, and C, from left to right. A solar abundance pattern is assumed. The thick solid model has $Z = 0$ (solar); the dotted-line model with stronger $N(H\,\text{i})$ absorption has $Z = -0.4$; and, the dotted-line model with the weaker absorption has $Z = +0.4$. Note that the series is not fitted self-consistently for any value of $Z$ (see § 5.2).
supersolar. The change in spectral shape has the effect of increasing Si iv and S vi, but decreasing C iii. The bulk of the Si iv still arises in the Mg ii clouds, but S vi in the diffuse phase is overproduced, and the required supersolar metallicity seems implausible.

Finally, we consider a later-type galaxy model with a 16 Gyr stellar population and with exponentially decreasing but persistent, star formation (the $\mu = 0.01$ model; Bruzual & Charlot 1983). This model has 1% of the total star-forming mass in stars after 1 Gyr. The star formation longevity of this relatively quiescent galaxy is more plausible than an instantaneous burst. As the galactic flux is incrementally increased relative to the extragalactic background, the metallicity constraints are unchanged, but the ratio $N$(C iv)/$N$(Mg ii) decreases because of the drop in flux at the He ii edge. Thus, the requirement for a diffuse component in these absorbers is strengthened if galactic flux is contributing. We also found that it is increasingly difficult to produce the required $N$(O vi)/$N$(C iv) ratio as the galactic flux is increased, unless the ionization parameter is significantly increased. This results in the destruction of Si iv. Thus, our conclusion that the Si iv must arise in the Mg ii clouds is also strengthened if such a galactic flux is contributing to or dominating the ionizing spectrum. Likewise, our conclusion holds that any collisionally ionized diffuse component in system B must be negligible. As with the extragalactic background scenario, the C iii becomes too large and inconsistent with the data if one lowers the ionization condition in the photoionized diffuse component.

Although some starburst galaxy spectra can somewhat decrease the constraint on the cloud and diffuse component metallicities, this effect is limited to less than 0.5 dex because of constraints on [O ii] emission. These galaxies are not strong starbursts, though they could have modest galaxy contribution to the spectral shape. Thus, we find that our general conclusions with regard to the requirement of highly ionized diffuse components and relatively high-metallicity clouds are not sensitive to the assumed spectral shape of the ionizing flux, although the details of the adopted models would be somewhat modified.

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Note added in proof.—In a deep WIYN image with subarcsecond seeing, we did not confirm the galaxy with the 5.6 impact parameter reported by Kirhakos et al. (1994). However, we did discover two additional fainter galaxies (redshifts unconfirmed) with impact parameters less than 20°.