FIRST COMPARISON OF IONIZATION AND METALLICITY IN TWO LINES OF SIGHT TOWARD HE 1104—1805 AB AT \(z = 1.66\)^1

SEBASTIAN LOPEZ AND DIETER REIMERS
Hamburger Sternwarte, Universität Hamburg, Gojenbergsweg 112, 21029 Hamburg, Germany; slopez@hs.uni-hamburg.de

MICHAEI RAOCH^2 AND WALLACE L. W. SARAN
Astronomy Department, 105-25 California Institute of Technology, 1200 E. California Boulevard, Pasadena, CA 91125; mr@astro.caltech.edu

AND

ALAIN SMEITE^3
Kapteyn Astronomical Institute, PO Box 800, NL-9700 AV Groningen, The Netherlands

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ABSTRACT
Using new Hubble Space Telescope Faint Object Spectrograph, the New Technology Telescope ESO Multi Mode Instrument, and Keck HIRES spectra of the gravitationally lensed double QSO HE 1104—1805 AB (\(z_{\text{em}} = 2.31\)) and assuming UV photoionization by a metagalactic radiation field, we derive physical conditions (ionization levels, metal abundances, and cloud sizes along the lines of sight) in five C IV + Mg II absorption systems clustered around \(z = 1.66\) along the two lines of sight. Three of these systems are associated with a damped Ly\(\alpha\) (DLA) system with log \(N(\text{H} I) = 20.85\), which is observed in the UV spectra of the bright QSO image, A. The other two systems are associated with a Lyman-limit system with log \(N(\text{H} I) = 17.57\) seen in the fainter image, B. The C IV and Mg II line profiles in A resemble those in the B spectra and span \(\Delta v \approx 360\) km s\(^{-1}\). The angular separation, \(\theta = 3.195\)^\(^{-\circ}\), between A and B corresponds to a transverse proper separation of \(S_{\text{ab}} = 8.3\ h_{50}^{-1}\) kpc for \(d_0 = 0.5\) and a lens at \(z = 1\). Assuming that the relative metal abundances in these absorption systems are the same as those observed in the DLA system, we find that the observed \(N(\text{C} IV)/N(\text{Mg} II)\) ratios imply ionization parameters of \(\log \Gamma = -2.95\) to \(-2.35\). Consequently, these clouds should be small (0.5—1.6 kpc with a hydrogen density of \(n_{\text{H}} \leq 0.01\) cm\(^{-3}\)) and relatively highly ionized. The absorption systems to B are found to have a metallicity 0.63 times lower than the metallicity of the gas giving rise to the DLA system, \(Z_{\text{DLA}} \approx 1/10\ Z_\odot\). We detect O VI at \(z = 1.66253\) in both QSO spectra but no associated N v. Our model calculations lead us to conclude that the C IV clouds should be surrounded by large (\(\sim 100\) kpc), highly ionized low-density clouds (\(n_{\text{H}} \sim 10^{-4}\) cm\(^{-3}\)) in which O VI, but only weak C IV, absorption occurs. In this state, \(\log \Gamma \geq -1.2\) reproduces the observed ratio of \(N(O\ VI)/N(N\ v) > 60\). These results are discussed in view of the disk/halo and hierarchical structure formation models.

Subject headings: galaxies: abundances — gravitational lensing — quasars: absorption lines — quasars: individual (HE 1104—1805 AB)

1. INTRODUCTION
The physical nature of the ionized gas observed in high-redshift QSO absorption systems has not been clearly determined so far. One possible mechanism capable of ionizing this gas is UV photoionization by the background field of distant active galactic nuclei (AGNs) and of local sources associated with the absorption systems. In this model, two gas phases with different ionization parameters \(\Gamma\) (the ratio of hydrogen ionizing photon density to total hydrogen density, \(n_{\text{H}}\)) are commonly invoked to explain the presence of low- and high-ionization species, e.g., Mg II, C IV, and O VI (Bergeron et al. 1994; Lu & Savage 1993). As \(\Gamma\) is defined by \(n_{\text{H}}\) for a given ionizing field, one can also estimate the spatial extent of the ionized clouds along the line of sight (LOS) if the total hydrogen column density \(N(\text{H})\) is known. In general, the reliability of these models strongly depends on a good knowledge of the metal abundances involved. On the other hand, double LOSs toward background QSOs offer a unique possibility to resolve such clouds geometrically and determine transverse sizes. For instance, Smette et al. (1992) report lower limits of \(D = 0.7—2.2\ h_{50}^{-1}\) kpc for the diameters of two metal systems at \(z \approx 2\) toward UM 673 AB from the analysis of the line strengths in both QSO spectra. A somewhat different result, but with large uncertainties, is achieved through statistical simulations by Smette et al. (1995, hereafter Paper I), who infer \(25 < D < 300\ h_{50}^{-1}\) kpc for the C IV clouds in the LOSs to HE 1104—1805 AB. At higher resolution, Rauch (1997) has recently shown that density gradients on subkiloparsec scales in gas associated with metal systems are not uncommon. These results suggest that C IV absorbers are composed of a large number of small cloudlets.

HE 1104—1805 AB \([z_{\text{em}} = 2.31, \ m_p(A) = 16.7, \ m_p(B) = 18.6, \text{and} \ \text{angular separation} \ \theta = 3.195^\circ\) was discovered in the course of the Hubble/ESO Survey (Wisotzki et al. 1993) and has been already studied at medium resolution by Smette et al. (Paper I). There is wide evidence for this QSO to be gravitationally lensed (Paper I; Wisotzki et al. 1995;
Courbin, Lidman, & Magain 1998), so the proper separation between LOSs will depend on the (hitherto not well established) redshift of the lensing agent. Two papers aimed at detecting the lensing galaxy of HE 1104–1805 with somewhat different results have recently appeared. Using IR–direct imaging observations, Courbin et al. (1998) estimate the lensing galaxy to be at $z_{\text{gal}} = 1.66$, while Remy et al. (1998) find that their Hubble Space Telescope (HST) and ground-based direct imaging observations are consistent with $z_{\text{gal}} = 1.32$. Neither of these results influences our ground-based direct imaging observations are consistent with $z_{\text{gal}} = 1.66$. Nevertheless, the small velocity differences and the similar line profiles between absorption lines in A and B at $z = 1.66$ (see § 5) probably exclude the damped Ly$\alpha$ (DLA) system observed in A as the lensing agent, thus excluding the $z_{\text{gal}} = 1.66$ result.

The primary aim of this study is to compare ionization conditions and metallicities in clouds at $z_{\text{abs}} = 1.66$ for the two LOSs toward HE 1104–1805. We use new HST Faint Object Spectrograph (FOS), ground-based New Technology Telescope (NTT), and Keck spectra. The C IV systems observed in the UV and optical spectra of A and B at redshifts close to $z_{\text{D}}$ are very well suited to determine whether this gas is indeed photoionized: it can be assumed that they are associated with the high-density gas giving rise to the DLA system observed in A at $z = 1.66162$ and therefore have a common chemical history. Consequently, the relative element abundances should be the same in all these systems. Since the DLA gas is expected to be opaque to the ionizing radiation, it is possible to derive these element abundances without ionization corrections.

To investigate the issue of ionization in the C IV systems, we have used the photoionization code CLOUDY (Ferland et al. 1996). We have assumed that this radiation field also ionizes the gas that gives rise to the strong O VI absorption observed along both LOSs. We have made a distinction between gas phases with different ionization states: a low-ionization phase, where both Mg II and C IV absorption occur, and a high-ionization phase, where O VI but weak C IV absorption occurs. The photoionization models for each of these two gas phases are constrained by the observed column density ratios $N$(C IV)/$N$(Mg II) and $N$(O VI)/$N$(N V), respectively.

Our paper is organized basically in two parts: estimation of the metal abundances in the DLA gas and photoionization models for the C IV systems. The spectra are described in § 2. In § 3 we describe the line-fitting method used and discuss the important role played by the continuum fitting to the HST spectra. Section 4 is devoted to the metal abundances determined for the DLA system observed in QSO component A. Section 5 presents possible physical scenarios for the C IV systems observed in A and B based on their association with the DLA system and on the line profiles. The CLOUDY models and the resulting physical parameters for the C IV and O VI absorbers are described in § 6. Finally, we outline our conclusions in § 7.

### 2. OBSERVATIONS AND DATA REDUCTION

An overview of the spectra used in this paper is displayed in Table 1. We now detail the observations.

#### 2.1. HST Spectra

UV spectra of HE 1104–1805 A and B were taken in 1995 November with the FOS on board the HST. Target acquisition and spectroscopy were done using Grating G270H with the red detector and the 3.7' $\times$ 3.7' aperture. This configuration yields a spectral resolution of FWHM = 2 Å and a wavelength coverage from 2222 to 3277 Å (Schneider et al. 1993). Total integration times of 1790 and 6690 s for QSO component A and B, respectively, resulted in variance weighted spectra of maximum signal-to-noise ratios S/N = 20 (A) and 17 per $\sim$0.5 Å pixel.

#### 2.2. Keck HIRES Spectra

Optical spectra of HE 1104–1805 A and B were taken in 1997 January and February with the Keck High Resolution Spectrograph (HIRES; Vogt et al. 1994) and an 0:86 slit at FWHM = 6.6 km s$^{-1}$. They range from 3620 to 6080 Å. A full description of the observations and extraction method, as well as the spectra themselves, will be presented elsewhere. In short, an image rotator was used to keep the slit off the second image and as close as possible to the parallactic angle. The continua were matched by using the brighter A image continuum as a template, i.e., the continuum points of the B image spectrum were, in a sense, “stapled” to the A image continuum. This was done using polynomial fits in such a way that differences between the continua on scales larger than at average 300 km s$^{-1}$ are divided out, but regions smaller than that retain their differences between the LOSs. The typical absorption line or absorption complexes between the spectra (which were omitted from the fit anyway) are not affected, as can be seen from the strong differences in the metal lines despite the very similar Ly$\alpha$.

### Table 1: Journal of Observations

| Object         | ID*   | UT date   | Coverage (Å) | Signal-to-Noise Ratio$^b$ | FWHM (Å)  |
|----------------|-------|-----------|--------------|--------------------------|-----------|
| HE 1104–1805 A | HST   | 1995 Nov  | 2222–3277    | 20                       | 2.0       |
| HE 1104–1805 B |       |           |              | 17                       |           |
| HE 1104–1805 A | AAT   | 1993 May  | 3170–7570    | 82                       | 1.2       |
| HE 1104–1805 B |       |           |              | 30                       |           |
| HE 1104–1805 A | NTT   | 1996 Feb  | 3910–8290    | 77                       | 0.8–1.0   |
| HE 1104–1805 B |       |           |              | 27                       |           |
| HE 1104–1805 A | Keck  | 1997 Jan  | 3620–6080    | 61                       | 0.08–0.13 |
| HE 1104–1805 B |       |           |              | 42                       |           |

$^a$ HST: Hubble Space Telescope; AAT: Anglo-Australian Telescope; NTT: New Technology Telescope.

$^b$ Maximum S/N per pixel.

$^c$ See Paper I.
forest. We have also taken special care to omit the metal absorption-line complexes from the continuum points, in order to be sure that we do not wipe out the differences. One sigma arrays were derived from the Poissonian photon error and rebinned onto the 0.04 Å pixel$^{-1}$ constant wavelength scale.

2.3. NTT Spectra
Optical spectra of HE 1104–1805 A and B were obtained in 1996 February with the echelle spectrograph of EMMI on the ESO NTT in the red medium dispersion mode under subarcsecond seeing conditions. The wavelength coverage is 3910–8290 Å. Both images were simultaneously centered in a 1” slit. Grating 9, grism 3 as cross disperser, a F/5.2 camera, and a TEK 2048$^2$ CCD were used. This CCD provides 24 µm pixels, corresponding to 0.27 in the sky. The total integration time was 16 hr. The echelle orders were optimally extracted with a version of the extraction algorithm used in Paper 1, modified to extract cross-dispersed spectra. The algorithm attempts to reduce the statistical noise in the extracted spectra to a minimum and allows the correct separation of the two seeing profiles.

It basically consists of the following steps. (1) A variance (Poisson statistics, readout noise, and cosmics) is assigned to each pixel. For each flat-fielded two-dimensional spectrum, two Gaussian curves of common width are simultaneously fitted to the profiles at each wavelength channel along the previously defined echelle orders using the Levenberg-Marquardt method (Press et al. 1986). (2) The variation of the width and the position of the brighter component with respect to the orders in the dispersion direction is then fitted with low-order polynomials. (3) Step 1 is repeated, this time with the fixed width and position given by the Gaussian fit. For each flat-fielded two-dimensional spectrum, two Gaussian curves of common width are simultaneously fitted to the profiles at each wavelength channel along the previously defined echelle orders using the Levenberg-Marquardt method (Press et al. 1986).

2.4. AAT Spectra
Additional FWHM = 1.2 Å resolution spectra of both QSO images taken with the 3.9 m Anglo-Australian Telescope (AAT) and covering the wavelength range 3170–7570 Å were also used. They have already been presented in Paper I.

2.5. Wavelength Calibration of the HST Spectra
Special care has been taken to redefine the absolute zero point of the wavelength scale in the HST spectra. An off-center position of the targets in the aperture of the FOS may cause differences in the wavelength scale between the A and B spectra. By measuring wavelength positions of the galactic MgII λ2796, 2803 lines and assuming that this absorption takes place in the same cloud along both LOSs, we found an offset of Δλ(A–B) = −0.42 Å. This correction was applied to the B spectrum. Additionally, an overlapping 100 Å wide spectral region around λ = 3220 Å in the HST and AAT spectra allowed for a correction of the FOS wavelength scale to vacuum-heliocentric values. This was done by comparing the central wavelength differences of absorption lines in the A spectrum thought not to be blended. A relatively small correction of Δλ(AAT – HST) = + 0.04 Å was then applied to both HST spectra.

3. ABSORPTION-LINE ANALYSIS
3.1. Continuum Definition in the HST Spectra
Owing to the low FOS resolution, line blending introduces a serious problem when performing continuum fitting. This is particularly marked in the Ly$\alpha$ forest because of the lack of spectral regions free of absorption lines. For this reason, we decided to first determine the absorbed continuum, which is clearly dominated by two optically thin Lyman-limit systems (LLS) at z = 2.20 and 2.30 and the DLA system (A) and a LLS at z = 1.66 (B), before describing the intrinsic QSO continuum. Both spectra were corrected for galactic extinction (Seaton 1979) with $E(B-V) = 0.09$ (Reimers et al. 1995). The Lyman edges, arising from the superposition and blending of corresponding high-order H I Lyman series lines, were modeled with Voigt profiles convolved with a FWHM = 2 Å Gaussian curve describing the instrumental profile. The optical depth $\tau$ at each Lyman break, given by the ratio of the extrapolated continuum to the Lyman one, determined $N$(HI), whereas $b$ was mainly constrained by the shape of the edge. These parameters are listed in Table 2. The total optical depth at each LLS is given by the Lyman continuum and the lines of the Lyman series. Note that the flux for $\lambda < 2200$ Å in the B spectrum is not completely absorbed (see Fig. 1).

The intrinsic QSO continuum of HE 1104–1805 A and B in the HST spectra for $\lambda_{\text{obs}} < 3277$ Å was found to be very well represented by two power laws ($\lambda \propto \lambda^p$) with a break at $\lambda = 2917$ Å. To determine the power-law parameters, a maximum likelihood fit was performed, matching simultaneously the intrinsic and the H I absorption continuum with the observed flux at selected absorption-free spectral regions, including some regions dominated by significant H I absorption lines. This led to the best-fit spectral indices $\alpha = -0.8, -1.5$ for A and $-0.8, -0.9$ for B (see Fig. 1). We believe this continuum estimation is a good one, since an extrapolation to longer wavelengths fits the scaled AAT spectra to well within 1σ in regions of low Ly$\alpha$ line density. Moreover, expected emission lines by Ly$\beta$, N v, and O vi stand out well against the continuum, as can be seen in Figure 1. Division of the flux by this continuum resulted in the normalized HST spectra shown in Figure 2.

The different continuum slopes of A and B, already pointed out in the discovery paper, might be a consequence of QSO component A being microlensed (Wisotzki et al. 2004).

| Component | $z_{\text{LLS}}$ | $\tau$ | $\log N$(HI) (cm$^{-2}$) | $b$ (km s$^{-1}$) |
|-----------|-----------------|--------|-------------------------|-----------------|
| A         | 1.66162          | ...    | 20.84$^a$               | 27              |
| 2.20016   | 0.29 ± 0.08     | 16.67 ± 0.12 | 35              |
| 2.29880   | 0.14 ± 0.07     | 16.36 ± 0.23 | 40              |
| B         | 1.66184          | 2.34 ± 0.51 | 17.57 ± 0.10 | 30              |
| 2.20099   | 0.63 ± 0.11     | 17.00 ± 0.08 | 40              |
| 2.29877   | 0.21 ± 0.11     | 16.53 ± 0.23 | 35              |

$^a$ Optical depth $\tau = \ln \left( \frac{f_r}{f_r^0} \right)$, where $f_r^0$ is the extrapolated continuum redward of 912 × (1 + $z_{\text{obs}}$) and $f_r$ is the absorbed continuum.

$^b$ Column density constrained by the DLA wings.
Fig. 1.—HST FOS spectra of HE 1104–1805 A and B and their 1σ errors. Fluxes have been corrected for galactic extinction (Seaton 1979) with $E(B - V) = 0.09$ (Reimers et al. 1995). Also shown are the AAT spectra, which have been scaled to the HST flux levels, smoothed, and rebinned to the FOS resolution and plotted for $i \geq 3277$ Å. Metal absorption lines lying longward of Ly$\alpha$ emission were covered by the NTT and Keck spectra. The power law and the QSO continuum derived as described in the text have been overplotted. Expected positions of emission lines by Ly$\alpha$, Ly$\beta$, N$\nu$, O$\nu$, and S$\nu$ are indicated.

Fig. 2.—Sections of the normalized HST FOS (FWHM $\sim$ 2 Å) and AAT (FWHM $\sim$ 1.2 Å) spectra of HE 1104–1805 A (upper panels) and B, showing synthetic Voigt profiles of the high-order H i Lyman series lines (top) and most relevant metal lines belonging to the DLA system (A) and LLS (B) at $z = 1.66$. Tick marks (upper panel to right lower panel) indicate the positions of H i $\lambda\lambda$918–949, C ii $\lambda\lambda$1036, 1334, N ii $\lambda 1083$, and O i $\lambda\lambda$7898, 1302.
Furthermore, we find the spectrum of A blueward of Lyα emission to be softer than that of B, which is in agreement with the variability in the spectral slopes reported by Wisotzki et al. (1995) from the analysis of low-resolution observations in the optical range made 1 and 2 yr before ours. However, an alternative explanation for the different slopes might be differential reddening by dust grains in the DLA system observed in A, a possibility recently considered.
for the gravitationally lensed QSO 0957+561 (Zuo et al. 1997).

3.2. Line Profile Fitting

In this section we describe the line-fitting procedures used to obtain column densities of lines associated with the $z = 1.66$ absorption systems in A and B. In general, this is a nontrivial task because of the limited resolution of our spectra other than Keck HIRES, so assumptions concerning line widths must be made. The lines were modeled with Voigt profiles. We distinguish between maximum likelihood fits, performed to lines in the Keck and NTT spectra, and "interactive" fits, performed to lines in the AAT and HST spectra (aside from H I lines).

3.2.1. Keck Spectra

To determine column densities $N$ and Doppler parameters $b$ of lines in the Keck HIRES spectra, we $\chi^2$ fitted Voigt profiles convolved with the instrumental profile using the MIDAS program FITLYMAN (Fontana & Bal- Lester 1995). These lines lie longward of Ly$\alpha$ emission. Line parameters, i.e., rest frame vacuum wavelengths, damping constants, and oscillator strengths, were taken from Morton (1991) and Verner, Barthel, & Tytler (1994) for lines with revised $f$-values.

Most of the column density errors $\sigma_{\log N}$ range from 0.01 to 0.10 dex; however, the smoothing introduced by rebinning the $\sigma$ arrays sometimes underestimates the true flux uncertainties, making $\sigma_{\log N}$ systematically too low. Thus we made the following correction to the fit errors: for each line we measured the amount of smoothing by calculating the ratio of the flux standard deviation from 41 pixel-wide, featureless regions in the data to the sigma from the error array. In the (few) cases where this ratio was larger than one, $\sigma_{\log N}$ was corrected by this factor. Clearly, this applies only to unsaturated, resolved lines; a similar treatment to nonresolved complexes is less obvious because the $\sigma_{\log N}$ values for adjacent lines, as a result of a more complicated Hessian matrix, are correlated. We did not allow for this effect.

Special attention must be given to the fits of lines associated with the DLA system observed in the spectrum of QSO component A, because they will determine the metal abundances. To look for possible hidden saturation, we used the apparent optical depth method to compare apparent column densities $N_{\text{app}}(v)$ of different transitions of a given ion in velocity space (e.g., eq. [1] in Lu et al. 1996; Savage & Sembach 1991 for a description of the method). Although some lines are probably saturated (e.g., Al II $\lambda 1670$), in most of the cases where more than one transition is available we do not find significantly saturated structures, and the agreement between the fit and integration results is remarkable (see Table 4).

3.2.2. NTT Spectra

In the NTT spectrum, the Mg II profiles at $z_{\text{DLA}}$ are slightly asymmetric, suggesting that this system will also split into more components at higher resolution. Consequently, we fitted four-component Voigt profiles to these lines, with $b$-parameters fixed at values found for the Si II lines in the Keck spectra.
3.2.3. HST and AAT Spectra

At even lower resolution, one cannot expect to recognize the line profiles properly; hence, to derive column densities of lines in the HST and AAT spectra, turbulence-dominated line broadening was considered. Voigt profiles were interactively created and superposed to the spectra using XVOIGT (Mar & Bailey 1995), while attempting to minimize the residuals. The redshift and Doppler widths used to create such line profiles were those found in a second fit with FITLYMAN of lines present both in the AAT and Keck spectra. Lines with asymmetric profiles were considered to be single, and the total column densities were fixed to the known Keck values. In this fashion, the low- and high-ionization species were distinguished using “low-resolution” Doppler parameters determined by the fits to Fe II λ1608 (b = 20 km s\(^{-1}\)) and C IV λ1548 (b = 44 km s\(^{-1}\)) lines in A, respectively. For B, the lines used were Al II λ1670 (b = 20 km s\(^{-1}\)) and C IV λ1548 (b = 37 km s\(^{-1}\)).

To estimate the uncertainties of our column densities, we smoothed and rebinned lines observed in the NTT spectra to HST FOS resolution and recomputed column densities with the procedure described above. The new column densities showed deviations of the order 0.1−0.2 dex from the original, better determined values. Another source of error is our limited ability to deblend metal lines from Ly\(\alpha\) forest lines. On the other hand, most column densities of transitions in the UV that contribute to the metal abundances are based on one line in the HST spectra and another in the AAT ones, e.g., C II λ1036, 1334 and O I λλ988, 1302 (see Fig. 2). If these two effects compensate, we think that taking \(\sigma_{\log N} = 0.2\) dex for these ions is appropriate.

3.2.4. Detection Limits

We defined 3 \(\sigma\) detection limits for metal lines in the HST and AAT spectra according to the formula (Caulet 1989)

\[
\sigma_w = \frac{\text{FWHM}}{\langle S/N \rangle},
\]

where FWHM is the width of the spectral point spread function and \(\langle S/N \rangle\) is the mean local signal-to-noise ratio.
### TABLE 3

Line Parameters for $z_{\text{abs}} = 1.66$ Absorption Systems toward HE 1104—1805 A

| Species | Lines | $z$   | $W_{\lambda}^a$ (Å) | $b$ (km s$^{-1}$) | $\sigma_b$ | log $N$ (cm$^{-2}$) | $\sigma_{\log N}$ | Spectrum$^e$ |
|---------|-------|-------|---------------------|-------------------|------------|---------------------|------------------|--------------|
| H I      | 1215  | 1.661620 | 19.05              | 26.90             | 0.30       | 20.85              | 0.01             | 4            |
|         | 1025  | 2.99   |                     |                   |            |                     |                  |              |
|         | ...   | ...    |                     |                   |            |                     |                  |              |
|         | 918   | ...    |                     |                   |            |                     |                  |              |
|         | 1215  | 1.664490 | 28.50              | 0.90              | 16.59      | 0.07               | 4                |              |
|         | 1025  |        |                     |                   |            |                     |                  |              |
|         | ...   |        |                     |                   |            |                     |                  |              |
|         | 918   |        |                     |                   |            |                     |                  |              |
| C I      | 1548  | 1.661620 | <0.02              | 20.00             | 0.00       | <12.80             | ...              | 4            |
|         | 1036  | 0.46   |                     |                   |            |                     |                  |              |
| C II     | 977   | 1.661430 | 1.62               | 44.00             | 0.00       | 15.68              | 0.20             | 4            |
|         | 977   | 1.662800 | 13.10              | 0.00              | 13.15      | 4                  |                  |
| C III    | 1509  | 0.361  | 15.88              | 1.89              | 13.31      | 0.16               | 4                |              |
|         | 1500  | 1.661186 | 0.361              | 15.88              | 1.89      | 13.31              | 0.16             |              |
| N I      | 1199  | 1.661640 | 0.29               | 20.00             | 0.00       | 14.00              | 0.20             | 4            |
|         | 1200.2| 1.661640 | 0.29               | 20.00             | 0.00       | 14.00              | 0.20             |              |
| N II     | 1083  | 1.661640 | 0.53               | 20.00             | 0.00       | 15.00              | 0.20             | 4            |
|         | 989   | 0.44   | 44.00               | 0.00              | 13.60      | 0.20               | 4                |              |
| N III    | 1238  | 1.662530 | <0.034             | ...               | ...       | <13.20             | ...              | 4            |
| O I      | 988   | 1.661640 | ...                | 20.00             | 0.00       | 16.80              | 0.20             | 4            |
|         | 1302  | 0.75   |                     |                   |            |                     |                  |              |
| O VI     | 1031  | 1.662530 | 0.93               | 180.00            | 0.00       | 14.95              | 0.20             | 4            |
|         | 1037  |        |                     |                   |            |                     |                  |              |
| Mg I     | 2852  | 1.661523 | 0.25               | 14.20             | 0.00       | 12.33              | 0.03             | 2            |
|         | 2852  | 1.661793 | 24.30              | 11.65             | 0.09       | 2                  |                  |
| Mg II    | 2796  | 1.661370 | 0.96               | 3.61              | 0.00       | 10.44              | 0.06             | 2            |
|         | 2803  | 0.90   |                     |                   |            |                     |                  |              |
|         | 2796  | 1.661549 | 16.69              | 0.00              | 15.09      | 0.03               | 2                |              |
|         | 2803  |        |                     |                   |            |                     |                  |              |
|         | 2796  | 1.661710 | 7.31               | 0.00              | 15.21      | 0.18               | 2                |              |
|         | 2803  |        |                     |                   |            |                     |                  |              |
|         | 2796  | 1.661982 | 8.70               | 0.00              | 13.30      | 0.02               | 2                |              |
|         | 2803  |        |                     |                   |            |                     |                  |              |
|         | 2796  | 1.662760 | <0.03              | 10.00             | 0.00       | <11.80             | ...              | 2            |
|         | 2803  |        |                     |                   |            |                     |                  |              |
|         | 2796  | 1.664650 | 0.06               | 7.70              | 0.00       | 12.19              | 0.03             | 2            |
|         | 2803  |        |                     |                   |            |                     |                  |              |
| Al I     | 1765  | 1.661620 | <0.02              | 20.00             | ...       | <12.10             | ...              | 1            |
| Al II    | 1670  | 1.661382 | 0.404              | 3.21              | 0.47       | 14.66              | 0.31             | 1            |
|         | 1670  | 1.661485 | 12.29              | 3.33              | 12.97      | 0.17               | 1                |              |
|         | 1670  | 1.661698 | 12.77              | 0.92              | 13.12      | 0.06               | 1                |              |
|         | 1670  | 1.661990 | 7.18               | 0.51              | 12.21      | 0.02               | 1                |              |
| Species | Lines | $z$ | $W_{\lambda}^*$ (Å) | $b$ (km s$^{-1}$) | $\sigma_b$ | $\log N$ (cm$^{-2}$) | $\sigma_{\log N}$ | Spectrum$^a$ |
|---------|-------|----|-------------------|----------------|-----------|-----------------|----------------|-----------|
| Al III  | 1854  | 1.661378 | 0.153 | 2.99 | 0.42 | 12.34 | 0.02 | 1 |
|         | 1862  | 0.092  |       |     |     |      |      |     |
|         | 1854  | 1.661531 | 19.79 | 1.51 | 12.85 | 0.03 | 1 |
|         | 1862  |       |       |     |     |      |      |     |
|         | 1854  | 1.661727 | 7.34  | 1.04 | 12.27 | 0.09 | 1 |
|         | 1862  |       |       |     |     |      |      |     |
|         | 1854  | 1.661981 | 5.32  | 1.93 | 11.58 | 0.08 | 1 |
|         | 1862  |       |       |     |     |      |      |     |
| Si I    | 1845  | 1.661620 | <0.01 | 20.00 | ... | <12.90 | ... | 1 |
| Si II   | 1808  | 1.661371 | 0.103 | 3.61 | 0.19 | 15.13 | 0.02 | 1 |
|         | 1526  | 0.430  |       |     |     |      |      |     |
|         | 1808  | 1.661538 | 16.69 | 0.39 | 14.97 | 0.01 | 1 |
|         | 1526  |       |       |     |     |      |      |     |
|         | 1808  | 1.661773 | 7.31  | 1.08 | 13.96 | 0.09 | 1 |
|         | 1526  |       |       |     |     |      |      |     |
|         | 1808  | 1.661984 | 8.70  | 0.59 | 13.66 | 0.02 | 1 |
|         | 1526  |       |       |     |     |      |      |     |
| Si III  | 1206  | 1.66430  | 0.60  | 44.00 | 0.00 | 14.00 | 0.20 | 4 |
|         | 1206  |       |       |     |     |      |      |     |
| Si IV   | 1393  | 1.661640 | <0.09 | ... | ... | <14.08 | ... | 1 |
|         | 1402  | <0.34   |       |     |     |      |      |     |
|         | 1393  | 1.662800 | ...   | ... | ... | <12.58 | ... | 1 |
|         | 1402  | <0.017  |       |     |     |      |      |     |
|         | 1393  | 1.664650 | 0.170 | ... | ... | 13.11 | 0.07 | 1 |
|         | 1402  | 0.044   |       |     |     |      |      |     |
| Ti II   | 1910.6| 1.661389 | 0.007 | 2.81 | 1.16 | 12.28 | 0.05 | 1 |
|         | 1910.9|       |       |     |     |      |      |     |
| Cr II   | 2056  | 1.661381 | 0.051 | 3.94 | 0.22 | 12.86 | 0.01 | 1 |
|         | 2062  |       |       |     |     |      |      |     |
|         | 2066  |       |       |     |     |      |      |     |
|         | 2056  | 1.661705 | 1.75  | 0.74 | 11.68 | 0.12 | 1 |
|         | 2062  |       |       |     |     |      |      |     |
| Mn I    | 2795  | 1.661420 | 0.06  | 14.20 | 0.00 | 11.80 | 0.20 | 2 |
| Mn II   | 2576  | 1.661469 | 0.05  | 14.20 | 0.00 | 12.66 | 0.06 | 2 |
|         | 2594  |       |       |     |     |      |      |     |
|         | 2606  |       |       |     |     |      |      |     |
| Fe I    | 2484  | 1.661620 | <0.02 | 20.00 | ... | <12.30 | ... | 2 |
| Fe II   | 1608  | 1.661376 | 0.280 | 4.80 | 0.16 | 14.49 | 0.01 | 1 |
|         | 2249  |       |       |     |     |      |      |     |
|         | 2260  |       |       |     |     |      |      |     |
|         | 1608  | 1.661549 | 8.49  | 0.70 | 14.29 | 0.03 | 1 |
|         | 2249  |       |       |     |     |      |      |     |
|         | 2260  |       |       |     |     |      |      |     |
|         | 1608  | 1.661709 | 8.83  | 1.11 | 13.85 | 0.06 | 1 |
|         | 2249  |       |       |     |     |      |      |     |
|         | 2260  |       |       |     |     |      |      |     |
| Ni II   | 1709  | 1.661382 | 0.052 | 3.05 | 0.35 | 13.07 | 0.02 | 1 |
|         | 1741  |       |       |     |     |      |      |     |
|         | 1751  |       |       |     |     |      |      |     |
|         | 1709  | 1.661559 | 11.52 | 1.38 | 12.98 | 0.04 | 1 |
|         | 1741  |       |       |     |     |      |      |     |
|         | 1751  |       |       |     |     |      |      |     |
|         | 1709  | 1.661716 | 0.52  | 0.19 | 12.29 | 0.27 | 1 |
|         | 1741  |       |       |     |     |      |      |     |
|         | 1751  |       |       |     |     |      |      |     |
|         | 1709  | 1.661921 | 21.67 | 7.71 | 12.47 | 0.12 | 1 |
|         | 1741  |       |       |     |     |      |      |     |
expected at the position of the line (measured as the inverse standard deviation of the normalized flux in small featureless stretches adjacent to the line). They range between \( W_{\text{obs}} = 0.13 \) and 1.00 Å in the B spectra.

3.2.5. H I Column Densities at \( z \equiv 1.66 \)

To derive more accurate column densities for H I, we used the normalized HST spectra. Because they completely cover the rest frame spectral range down to 912 Å for the \( z = 1.66 \) systems, it is possible to measure \( N(\text{HI}) \) in both spectra more accurately than in previous studies on damped systems by using higher Lyman series transitions. We simultaneously fitted two-component Voigt profiles to 11 resolved H I lines in the normalized spectra of A and B using FITLYMAN. The fit solutions to lines in B were constrained by \( \tau = 2.34 \) at the Lyman edge. We estimate the neutral hydrogen column density of the DLA gas (spectrum A) to be \( \log N(\text{HI}) = 20.85 \pm 0.01 \); for the LLS (B) we obtained \( \log N(\text{HI}) = 17.57 \pm 0.10 \). Notice that these values are independent of the ones estimated for placing the continuum and shown in Table 2.

4. THE DLA SYSTEM TOWARD HE 1104—1805 A AT \( z_{\text{DLA}} = 1.66162 \)

Table 3 displays the fit results for lines associated with the DLA system toward HE 1104—1805 A at \( z_{\text{DLA}} = 1.66162 \). A wide variety of singly and doubly ionized species is observed in this DLA system, but C IV and Si IV are also present. We now describe the Keck HIRES line profiles, referring to the left panels of Figures 3, 4, and 5 throughout this section.

4.1. Low Ion Profiles

The left panel of Figure 3 shows the line profiles of strongest low-ionization species in velocity space, relative to \( v = 0 \) at \( z = 1.66164 \), the redshift of Mg II in the DLA system. These lines lie redward of the Ly\( \alpha \) forest. In each line complex we have fitted four Voigt profiles with independent \( z, b, \) and \( N \) values. The Ni II and Fe II results are based on simultaneous fits to three transitions, the Si II and Al III fits on two transitions, the Al II fit on one transition, and the Mg II fit on two transitions (see Table 3). We fitted four components to the Mg II lines in the NTT spectra, with \( z \) and \( b \) tied to the values found for Si II. Only the three bluestmost components show associated Zn II and Cr II (see § 4.3.1).

From the high-resolution plots, we see that the low ions track each other quite closely, suggesting that they occur in the same gas clouds. The whole profile is characterized by one cloud at \( v \equiv -30 \) km s\(^{-1} \) with the strongest absorption, one cloud at \( v \equiv +40 \) km s\(^{-1} \) with the smallest column densities, and two clouds with intermediate column density clouds lying in between. This “edge-leading asymmetry” seems to be a common feature of low-ionization absorption lines associated with DLA systems. It has been variously interpreted as a consequence of absorption by rotating gaseous disks (e.g., Wolfe et al. 1995) or as the signature of merging protogalactic clumps in hierarchical structure formation (Rauch, Haehnelt, & Steinmetz 1997). The different column density ratios at each velocity indicate clouds with different physical conditions (gas density, metallicity, or even ionization) within 70 km s\(^{-1} \).

4.1.1. Line Widths

Remarkably, and despite the independent fits performed to each ion profile, we obtain fit solutions that uniquely characterize each cloud in redshift and broadening parameter (see Table 3 and Fig. 3). For instance, for the clouds at \( v \sim -30, -10, 10, \) and \( 40 \) km s\(^{-1} \), we find respective mean widths and standard deviations of \( \langle b \rangle = 3.5 \pm 0.7, 12.6 \pm 2.7, 9.1 \pm 2.2, \) and \( 7.6 \pm 1.8 \) km s\(^{-1} \) (the fourth Ni II component is excluded because of large \( b \)-uncertainties, and the fits to Zn II, Cr II, and Ti II lines are not included). Thus we find a similar line-broadening mechanism in each of these absorption systems and, based on the small Doppler-parameter dispersions, cautiously favor turbulent gas motions as the dominant line-broadening mechanism.

4.2. High Ion Profiles

The left panel of Figure 4 shows the C IV \( \lambda \lambda 1548, 1550, \) Si IV \( \lambda \lambda 1393, 1402, \) and, in comparison, Al II \( \lambda 1670 \) velocity profiles associated with the DLA system. For the C IV absorption lines between \([-80,+80]\) km s\(^{-1} \), only four-component Voigt profile fits succeeded. Unfortunately, the poor S/N at the position of the Si IV lines and contamination by Ly\( \alpha \) forest lines do not allow a clear comparison with the C IV profiles. We decided not to fit these Si IV lines. Instead we give upper limits for column densities based on the apparent optical depth method. The high ion profiles do not exactly track the low ion profiles: the data rather suggest that at least part of the C IV absorption (velocity component 1) occurs in clouds without low-ionization species. On the other hand, C IV velocity components 2–4 show a certain resemblance to the edge-leading asymmetry of the low ion profiles; however, our fit solution yields relatively large \( b \)-values, suggesting that C IV, regardless of which line broadening mechanism dominates, thermal or turbulent gas motion, occurs in hotter gas regions than the low ion clouds.

### Table 3—Continued

| Species | Lines | \( z \) | \( W/\lambda^a \) (Å) | \( b \) (km s\(^{-1} \)) | \( \sigma_b^b \) | \( \log N \) (cm\(^{-2} \)) | \( \sigma_{\log N} \) | Spectrum\(^c \) |
|---------|-------|------|-----------------|--------|---------|-----------------|-----------------|-----------|
| Zn II   |      |      |                 |        |         |                 |                 |           |
| 1751    |      | 2062 | 1.661373        | 0.026  | 3.04    | 0.24            | 12.37           | 0.01      | 1         |
| 2026    |      |      |                 |        |         |                 |                 |           | 1         |
| 2026    | 2062 | 1.661560 | 7.64          | 1.21   | 11.82   | 0.04            | 12.37           | 0.01      | 1         |

\( ^a \) Rest frame equivalent widths. For blends, the total equivalent width is given. Upper limits (3 \( \sigma \)) represent nondetections.

\( ^b \) \( \sigma_b = 0 \) indicates fixed \( b \) parameter.

\( ^c \) (1) Keck; (2) NTT; (3) AAT; (4) HST.
4.3. Abundances

Metal abundances in the DLA system, normalized to solar values and defined by

\[ [M/H] = \log \left[ \frac{N(M)}{N(H)} \right] - \log \left[ \frac{N(M)}{N(H)} \right]_{\odot} \],

were computed using the column densities integrated between \([-50, 60]\) km s\(^{-1}\). They are listed in Table 4. Solar abundances were taken from Verner et al. (1994). Singly ionized species provide the bulk of the total element column densities, except for O I, which is assumed to be the dominant ionization stage of oxygen.

4.3.1. Zn, Cr, and Ti Abundances and Dust

Figure 5 shows the Keck velocity profiles of the most outstanding Zn II and Cr II transitions. The fit solutions lead to three-component profiles for the Cr II complex at \(v = -29.1, -7.3,\) and 7.4 km s\(^{-1}\) and two-component profiles for Zn II at \(v = -30.0\) and \(-9.0\) km s\(^{-1}\), relative to \(z = 1.66164\). The column density ratios relative to solar vary from \(N(Zn II)/N(Cr II) = 3.47\) (bluemost component) to 1.73. If the Zn and Cr abundances as well as the ionization level were the same in these clouds (which is very probable), then this variation would indicate that the dust-to-gas ratio in this DLA gas is inhomogeneous within 20 km s\(^{-1}\), with a higher dust content in the higher density Zn II component.

The variation of the abundance ratios of refractory elements among different clouds associated with the DLA gas provides insights into the presence of dust in the disk of DLA galaxies (Lu et al. 1996), because dust grains can be locally destroyed by passage of supernova shocks (Sembach & Savage 1996 and references therein). We can extend our analysis of elemental abundance ratios to iron and nickel, which are also expected to be depleted into dust. The column density ratios Zn II/Fe II and Zn II/Ni II relative to solar are, respectively, Zn/Fe = 5.5 and Zn/Ni = 7.9 for velocity component 1 and Zn/Fe = 2.5 and Zn/Ni = 2.8 for velocity component 2, and are thus in concordance with what one observes for Cr in the corresponding clouds (we estimate the corresponding uncertainties to be no larger than 0.4). Although these variations are small, 0.3–0.4 dex, it seems that in the \(v \sim -30\) km s\(^{-1}\) cloud, the effect of dust depletion is more important than in the cloud at \(v \sim -10\) km s\(^{-1}\). On the other hand, as was pointed out in § 4.1.1, the bluemost component is characterized by narrower lines than component 2 in all the ions considered (including Zn II and Cr II). It would be of great interest to discern whether such line width differences have a thermal origin (contrary to what was stated in § 4.1.1), because it would give evidence for dust depletion being more effective in cooler gas.

Lu et al. (1996) have presented arguments for a pure nucleosynthetic origin of the elemental abundance pattern observed in DLA systems at low metallicity. These arguments are: the low N/O ratio, which we also find in this DLA system (see next section); the \(\alpha\)-element-overabundance relative to Fe peak elements, also observed for the abundance ratios of Si to Fe, Cr, Mn, and Ni in our Keck HIRES data; and the underabundance of Al relative to Si and Mn relative to Fe (see Lu et al. 1996 for details), which we do not find in this DLA system. Instead, we derive \([\text{Al}/\text{Si}] = +0.25 \pm 0.15\) and \([\text{Mn}/\text{Fe}] = -0.02 \pm 0.14\) (see Table 4), although we recall that the Al abundance is only based on the Al \(\lambda 1670\) line. Given the high Mn/Fe ratio and the argument given in the

| Species | \(\log N_d(X)\) | \(\sigma_{\log N}\) | \(\log N_{\text{sys}}(X)\) | \(\sigma_{\log N}\) | \(\log N_d(X)\) | \(\sigma_{\log N}\) | \(\log N(X)\) | \(\sigma_{\log N}\) | \([X/H]^a\) | \(\sigma_{[X/H]}\) |
|---------|-----------------|----------------|------------------|----------------|-----------------|---------------|-----------------|----------------|-----------------|-----------------|
| H I      | 20.85           | 0.01           | ...              | ...             | 20.85           | 0.01           | ...             | ...             | ...             | ...             |
| C I      | <12.80          | ...            | ...              | ...             | <12.80          | 16.50         | 0.20            | -0.91           | 0.20            |
| C II     | 16.50           | 0.20           | ...              | ...             | 16.50           | 0.20           | ...             | ...             | ...             |
| C III    | 15.70           | 0.20           | ...              | ...             | 15.70           | 0.20           | ...             | ...             | ...             |
| C IV     | 14.13           | 0.05           | 14.13            | 0.01            | 14.13           | 0.05           | ...             | ...             | ...             |
| N I      | 14.00           | 0.20           | ...              | ...             | 14.00           | 0.20           | ...             | ...             | ...             |
| N II     | 15.00           | 0.20           | ...              | ...             | 15.00           | 0.20           | ...             | ...             | ...             |
| N III    | 13.60           | 0.20           | ...              | ...             | 13.60           | 0.20           | ...             | ...             | ...             |
| N IV     | <13.20          | ...            | ...              | ...             | <13.20          | ...            | ...             | ...             | ...             |
| O I      | 16.80           | 0.20           | ...              | ...             | 16.80           | 0.20           | ...             | ...             | ...             |
| O VI     | 14.95           | 0.20           | ...              | ...             | 14.95           | 0.20           | ...             | ...             | ...             |
| Mg I     | 12.41           | 0.09           | ...              | ...             | 12.41           | 0.09           | ...             | ...             | ...             |
| Mg II    | 15.46           | 0.09           | ...              | ...             | >15.46          | 0.09           | ...             | ...             | ...             |
| Al I     | <12.10          | ...            | ...              | ...             | <12.10          | 14.56         | 0.15            | -0.77           | 0.15            |
| Al II    | 14.55           | 0.24           | 13.43            | 0.16            | 14.55           | 0.24           | ...             | ...             | ...             |
| Al III   | 13.06           | 0.02           | 13.08            | 0.01            | 13.06           | 0.02           | ...             | ...             | ...             |
| Si I     | <12.90          | ...            | ...              | ...             | <12.90          | 15.38         | 0.02            | -1.02           | 0.02            |
| Si II    | 15.38           | 0.02           | 15.26            | 0.01            | 15.38           | 0.02           | ...             | ...             | ...             |
| Si III   | 14.00           | 0.20           | ...              | ...             | 14.00           | 0.20           | ...             | ...             | ...             |
| Si IV    | ...             | ...            | <14.08           | ...             | <14.08          | ...            | ...             | ...             | ...             |
| Ti I     | 12.28           | 0.05           | 12.28            | 0.07            | 12.28           | 0.07           | ...             | ...             | ...             |
| Cr II    | 13.07           | 0.01           | 13.05            | 0.01            | 13.07           | 0.01           | ...             | ...             | ...             |
| Mn I     | 11.80           | 0.20           | ...              | ...             | 11.80           | 0.20           | 12.77           | 0.14            | -1.61           |
| Mn II    | 12.72           | 0.18           | ...              | ...             | 12.72           | 0.18           | ...             | ...             | ...             |
| Fe I     | <12.30          | ...            | ...              | ...             | <12.30          | 14.77         | 0.01            | -1.59           | 0.02            |
| Fe II    | 14.77           | 0.01           | 14.68            | 0.02            | 14.77           | 0.02           | ...             | ...             | ...             |
| Ni II    | 13.42           | 0.03           | 13.43            | 0.02            | 13.42           | 0.03           | 13.42           | 0.03            | -1.68           |
| Zn II    | 12.48           | 0.01           | 12.45            | 0.01            | 12.48           | 0.01           | 12.48           | 0.01            | -1.02           |

\({}^a\) Relative to solar element abundances compiled by Verner et al. (1994).
last paragraph, we suggest that stellar nucleosynthesis alone is not likely to produce the relative abundance pattern observed in this DLA gas.

Based on the total zinc abundance \([Zn/H] = -1.02 \pm 0.01\) relative to the solar value, we derive a metallicity of \(Z_{DLA} \approx 1/10 Z_{\odot}\) for this system. This zinc abundance is somewhat lower than the value \([Zn/H] = -0.8\) reported by Pettini et al. (1997; same data as in Paper I), who also used \(\log (Zn/H)_{\odot} = -7.35\), which is more accurate, as it is based on a simultaneous fit to two \(Zn\) lines.\(^4\)

Additionally, we deduce from \([Cr/H] = -1.46 \pm 0.02\) a dust-to-gas ratio of \(-0.11\), using the definition given by Vladilo (1998)'s eq. (19) and considering that most of the chromium should be incorporated into dust grains in the interstellar medium (ISM) of galaxies showing damped H I absorption (e.g., Pettini, Boksenberg, & Hunstead 1990). Furthermore, titanium, another refractory element, is found to have \([Ti/H] = -1.50 \pm 0.07\) based on the unsaturated Ti II \(\lambda 1910.6, 1910.9\) lines. This is in full agreement with the incorporation of Ti and Cr into a dust phase in the neutral ISM of this DLA galaxy. Thus, based on these abundances, we conclude that (1) this DLA system does not differ too much from other ones at higher redshifts, given the scatter observed in \([Zn/H]\) (see Fig. 3 in Pettini et al. 1997); and (2) there is evidence for the presence of dust.

4.3.2. The Abundance Ratio \(O/N\)

The crucial abundance ratios in this work are \([O/N]\) and \([C/Mg]\).

Based on the O I \(\lambda 7988, 1302\) lines, we find \([O/H] = -0.98 \pm 0.20\), which is in very good agreement with the abundance ratio of Zn. This supports O I as a very good tracer of H I, as can be expected from its ionization potential, 13.62 eV, and suggests that O is not depleted into dust in the ISM of this DLA galaxy, which is in agreement with observations in the local ISM (Cardelli, Savage, & Ebbets 1991). Moreover, since both O and Si have been observed to have solar abundance ratios in Galactic halo stars and in metal-poor dwarf galaxies, one would expect \([Si/O] \approx 0\) in DLA systems (Lu et al. 1996 and references therein). We do obtain the same abundance ratios for O and Si within the errors, and \([Si/H]\) is based on reliable column density measurements of two Si II lines (observed in the Keck HIRES spectrum), making our oxygen abundance estimation yet more confident. Concerning the abundance ratio of nitrogen, the bulk of \([N/H]\) is provided by the column density of N II \(\lambda 12083\). This line is very probably not contaminated by a Ly\(\alpha\) forest interloper, given the absence of absorption at the same wavelength in the spectrum of B (see Fig. 2). In addition, nitrogen, as well as oxygen, is also expected not to be depleted in the ISM (Cardelli et al. 1991). In consequence, we are confident of an abundance ratio of \([O/N] = 0.88\) in this DLA gas; that is, \(O/N\) is 8 times greater than the solar ratio. This is in qualitative agreement with observations of damped Ly\(\alpha\) galaxies at higher redshifts (Pettini, Lipman, & Hunstead 1995; Lu et al. 1996) and with galactic chemical evolution models, because these two elements have different nucleosynthetic origins, oxygen being produced in much shorter timescales than nitrogen.

4 However, our 40 km s\(^{-1}\) resolution NTT spectra yield Zn and Cr abundances completely consistent with the Keck results, thus validating abundance studies of Zn at medium resolution.

4.3.3. The Abundance Ratio \(C/Mg\)

The carbon abundance is based on the fits to the C II \(\lambda 1304, 1334\) lines. C/Mg is found to have the solar value within the errors, but \(N(Mg)\) might be underestimated through saturation of the Mg II lines in A.

5. GEOMETRY OF THE ABSORBERS AT \(z = 1.66\)

Figure 6 shows the velocity profiles of the C IV \(\lambda 1548, 1550\) and Mg II \(\lambda 2796, 2803\) doublets (at 7 and 40 km s\(^{-1}\) resolution, respectively) toward HE 1104 – 1805 A (left) and B. In both panels, \(v = 0\) km s\(^{-1}\) corresponds to \(z = 1.66164\), which is the redshift of Mg II in the DLA system. We have arbitrarily numbered the C IV complexes at \(z = 1.66143 (1), 1.66280 (2), 1.66465 (3)\) in the A spectra and at \(z = 1.66184 (4), 1.66284 (5), 1.66493 (6)\) in the B spectra, so they will be referred to as systems 1–6 throughout the following sections. Also shown in Figure 6, covering a larger range of velocities, are the profiles of the Ly\(\alpha\), Ly\(\beta\), and Ly\(\gamma\) H I lines. Note that H I presents (at least) two components both in A and B.

C IV systems 1–4 show associated Mg II, although shifted in velocity, as is more evident in systems 1 and 4 (the line shapes suggest that either of these systems will probably split into more components at even higher resolution). However, most of the Mg II seen in A at \(v = 0\) is due to the DLA system. In B, system 4 is identified with the LLS. The presence of Mg II in absorption systems 2 and 6 is less evident at this S/N, so only upper limits can be derived. C IV system 5 will not be considered here.

Do C IV and Mg II occur in the same clouds? Although the present data show a correspondence in velocity, there might not be a physical association between both ions. However, we will show in the next section that photoionization simulations of these clouds do indeed predict the presence of both ions in a common gas phase, in agreement with our observations. Furthermore, we know from studies at high resolution that line profiles of low and high ions do track one another in LLSs (Prochaska & Wolfe 1996). As is discussed in § 6.2, it is also possible that part of the C IV arises in the same highly ionized gas that gives rise to O vi. In any case, the velocity profiles of system 4 (LLS) show that if a physical association of both ions is correct, at least part of the C IV arises in clouds where no Mg II is present (see also Fig. 4, right panel).

From inspection of Figure 6, it seems likely that LOSs A and B cross common absorbers. This is suggested by the similar line profile pattern in both spectra. If a common absorption complex gives rise to systems 1 (A) and 4 (B), then the different equivalent widths of the Mg II lines in A and B, in contrast to the more similar C IV equivalent widths, suggest gas inhomogeneities on spatial scales smaller than the linear separation between LOSs \(S_z = 8.3\) h\(^{-1}\) kpc for \(q_0 = 0.5\) and a lens at \(z = 1\), thus suggesting that C IV arises in a more extended region than Mg II. However, we find that the velocity difference between the C IV clouds in A and B is \(<\Delta v> = -11 \pm 2 \text{ km s}^{-1}\), while \(<\Delta v> = -1 \pm 1 \text{ km s}^{-1}\) for the corresponding Mg II clouds. If these velocity differences are a consequence of peculiar cloud motions, then a physical association of C IV and Mg II is still compatible with the data. Since it is not the aim of this study to determine the origin of both this velocity difference and the \(\sim 360 \text{ km s}^{-1}\) velocity span of the C IV absorbers along both LOSs, we have analyzed each system separately.
Fig. 6.—Bottom: Velocity profiles of the \text{C IV} \lambda\lambda 1548, 1550 (at 6.6 km s\(^{-1}\) resolution) and \text{Mg II} \lambda\lambda 2796, 2803 (at 40 km s\(^{-1}\) resolution) doublets in A (left) and B. In both panels \( v = 0 \) km s\(^{-1}\) corresponds to \( z = 1.66164 \). In the \text{Mg II} \lambda 2796 plot, the feature at \( -100 \) km s\(^{-1}\) is identified with Mn \text{I} \lambda 2795. Top: HST velocity profiles of the corresponding Ly\(\alpha\), Ly\(\beta\), and Ly\(\gamma\) H I lines (note the different velocity scales).
There are two alternative interpretations for the \( \text{H} \) column densities in A and B: (1) the DLA system arises in a disk-type galaxy (Wolfe 1995) with the LOS to A passing through the gas in the halo and the disk and LOS B passing through the halo gas only, or (2) in models of hierarchical structure formation the DLA system arises in the central region of a protogalactic clump, and LOS B crosses the surrounding less dense gas at an impact parameter of a few kpc (Rauch et al. 1997). Our data do not allow us to discriminate between these two models. Consequently, in the following we will simply consider that \( \text{C} \ IV \) absorption systems 2–6 arise in clouds in the extended halo of the cloud giving rise to the DLA system (system 1), giving explicit references to one of these models.

6. IONIZATION STATE AND CHEMICAL COMPOSITION

We have used the photoionization code CLOUDY (version 84.12a; Ferland 1993) to investigate the ionization state and metallicity in the LLS observed in the B spectra of HE 1104–1805 (system number 4 in Fig. 6) and in three further \( \text{C} \ IV-\text{Mg} \ II \) systems observed in A (systems 2 and 3) and B (system 6). The clouds giving rise to these systems are represented by parallel slabs illuminated on one side by the radiation field \( J_{\nu} \) proposed by Haardt & Madau (1996), consisting of the background flux contributed by QSOs and AGNs, which is attenuated by H and He absorption in LLSs and Lya forest clouds. This radiation field also has a diffuse component due to recombination continuum radiation. Our model assumes \( J(912) = 0.37 \times 10^{-21} \text{ergs s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \text{sr}^{-1} \) at \( z = 1.66 \). Although this geometry does not perfectly describe a cloud being illuminated by an isotropic incident radiation field, it should not introduce errors larger than a factor of \( \sim 2 \) (Bergeron & Stasinska 1986). In particular, cloud sizes along the LOSs resulting from this model need to be considered upper limits, because considering slabs illuminated only on one side underestimates the true ionizing radiation field.

As we argue below, the wide variety of low- and high-ionization states present in these systems makes it necessary to model the gas clouds with two zones of different ionization levels: (1) a “low-ionization phase,” where absorption by singly, doubly, and also triply ionized atoms occurs;\(^5\) and (2) a “high-ionization phase,” where \( \text{O} \ IV \) absorption occurs. However, we will also discuss the possible existence of a third “intermediate-ionization phase.”

The CLOUDY simulations predict column densities of the expected ionization stages suitable to be compared with the observations. As a general strategy we attempt to reproduce the observed ionic column density ratios \( N(\text{C} \ IV)/N(\text{Mg} \ II) \) in systems 2, 3, 4, and 6 and the ratio \( N(\text{O} \ IV)/N(\text{N} \ IV) \) in the high-ionization phase by varying the ionization parameter \( \Gamma \). We assume that both gas zones are ionized by the Haardt & Madau radiation field and have the same relative abundances as found in the DLA gas. Since the column density ratios are quite insensitive to the metallicity of the gas \([\text{M}/\text{H}]\) for a wide range of ionization parameters, we can constrain \([\text{M}/\text{H}]\) using the individual observed column densities.

Clearly, the assumption of same relative abundances in A and B must not hold for gas-phase abundances of elements known to be depleted by condensation into dust grains. If

\(^5\) The term “low” specifically has the purpose to distinguish both gas phases.
| Species | Lines | $z$ | $W_{\lambda}^*$ (Å) | $b$ (km s$^{-1}$) | $\sigma_s$ | $\log N$ (cm$^{-2}$) | $\sigma_{\log N}$ | Spectrum$^a$ |
|---------|-------|-----|---------------------|-------------------|-----------|----------------------|-----------------|-------------|
| H I      | 1215  | 1.661840 | 1.690             | 30.00             | 0.00      | 17.57                | 0.00            | 4           |
|          | 1025  |       | 0.790              |                   |           |                      |                 |             |
|          | 918   |       |                    |                   |           |                      |                 |             |
|          | 912   |       |                    |                   |           |                      |                 |             |
|          | 912   |       |                    |                   |           |                      |                 |             |
| C I      | 1656  | 1.661650 | <0.09             | 20.00             | 0.00      | <13.50               |                | 3           |
| C II     | 1025  | 1.661650 | ...               | 20.00             | 0.00      | 14.50                | 0.20            | 4           |
| C III    | 977   | 1.664480 | 0.95              | 37.00             | 0.00      | 15.50                | 0.20            | 4           |
| C IV     | 1548  | 1.661130 | 0.630             | 19.93             | 2.33      | 13.24                | 0.04            | 1           |
|          | 1550  | 0.361   |                    |                   |           |                      |                 |             |
| N I      | 1199  | 1.661650 | <0.11             | 20.00             | ...       | <14.00               | ...             | 4           |
| N II     | 1083  | 1.661650 | <0.13             | 20.00             | ...       | <13.70               | ...             | 4           |
| N III    | 989   | 1.661830 | 0.27              | 37.00             | 0.00      | 14.00                | 0.20            | 4           |
| N IV     | 1238  | 1.662530 | <0.19             | ...               | ...       | <14.00               |                | 4           |
| O I      | 988   | 1.661650 | <0.13             | 20.00             | ...       | <14.10               | ...             | 4           |
| O II     | 1302  | 1.662530 | 0.86              | 110.00            | 0.00      | 14.95                | 0.20            | 4           |
| Mg I     | 2853  | 1.661650 | <0.10             | 20.00             | ...       | <11.90               | ...             | 2           |
| Mg II    | 2796  | 1.661557 | 0.343             | 7.83              | 0.00      | 13.14                | 0.13            | 2           |
|          | 2083  | 0.239   |                    |                   |           |                      |                 |             |
|          | 2796  | 1.661783 |                | 26.52             | 0.00      | 12.73                | 0.09            | 2           |
|          | 2083  |        |                    |                   |           |                      |                 |             |
|          | 2796  | 1.664930 | <0.09             | 10.00             | ...       | <12.40               | ...             | 2           |
|          | 2083  |        |                    |                   |           |                      |                 |             |
| Al I     | 1765  | 1.661650 | <0.10             | 20.00             | ...       | <12.60               | ...             | 1           |
| Al II    | 1670  | 1.661556 | 0.097             | 7.70              | 0.00      | 12.26                | 0.03            | 1           |
|          | 1670  | 1.661781 |                | 14.10             | 0.00      | 11.80                | 0.06            | 1           |
|          | 1670  | 1.661990 |                | 8.10              | 0.00      | 11.45                | 0.10            | 1           |
| Al III   | 1854  | 1.661564 | 0.041             | 7.75              | 1.29      | 12.08                | 0.11            | 1           |
|          | 1862  | 0.036   |                    |                   |           |                      |                 |             |
|          | 1854  | 1.661784 |                | 14.07             | 13.05     | 11.98                | 0.35            | 1           |
|          | 1862  |        |                    |                   |           |                      |                 |             |
|          | 1854  | 1.661956 |                | 8.15              | 11.22     | 11.81                | 0.46            | 1           |
|          | 1862  |        |                    |                   |           |                      |                 |             |
| Si I     | 1845  | 1.661650 | <0.08             | 20.00             | ...       | <13.20               | ...             | 1           |
| Si II    | 1526  | 1.661552 | 0.076             | 8.30              | 0.94      | 13.29                | 0.03            | 1           |
|          | 1526  | 1.661747 |                | 7.72              | 3.94      | 12.80                | 0.15            | 1           |
|          | 1526  | 1.661941 |                | 8.99              | 3.69      | 12.89                | 0.12            | 1           |
| Si III   | 1206  | 1.661830 | 0.55              | 37.00             | 14.10     | 14.10                | 0.20            | 4           |
| Si IV    | 1393  | 1.661840 | 1.166             | ...               | ...       | <14.28               | ...             | 1           |
is shown by smoothed particle hydrodynamics simulations (Rauch et al. 1997; Haehnelt, Steinmetz, & Rauch 1996b). Thus the hydrogen recombination timescale in this regime, ~6 Myr, is short enough to allow line cooling to balance photoheating processes. Consequently, we believe the CLOUDY sizes derived for this LLS to be reliable.

6.1.1.1. Gas Metallicity in the LLS

The photoionization models described above are quite independent of the gas metallicity, [M/H], over the whole range of possible gas densities; therefore, [M/H] can be determined by matching predicted and observed column densities. We find that regardless of which model is assumed, \([M/H]_{\text{LLS}} = [M/H]_{\text{DLA}} - 0.2\) represents the best prediction for nine ions observed in this system (Al II, Al III, and Fe II are not considered). In particular, \(N(C\ II), N(C\ IV), N(Mg\ II),\) and \(N(Si\ III)\) are simultaneously very well reproduced if \(Z_{\text{LLS}} = 0.63Z_{\text{DLA}}.\) This is an upper limit for \(Z_{\text{LLS}}\), because, due to saturation of the Mg II lines in A, we obtain only a lower limit for \([\text{Mg/H}]\); hence, to reproduce \(N(Mg\ II)\) in B, a larger Mg content would require an even lower metallicity in the LLS relative to the DLA gas. Varying the relative abundances within the observational errors in the column densities leads us to estimate that this result is significant at the 2 \(\sigma\) level (for comparison, considering solar relative abundances in the LLS leads to \([M/H]_{\text{LLS}} = -1.5\).

Studies of our galaxy halo gas show no systematic differences in the gas-phase abundances within galactocentric distances of 7–10 kpc in various directions, suggesting uniform physical properties over these radii. In addition, warm disk clouds show gas abundances that are 0.2–0.6 dex lower than those in warm halo clouds (Sembach & Savage 1996 and references therein; Savage & Sembach 1996; but see Cardelli, Sembach, & Savage 1995). If we assume that the LLS observed at \(z = 1.66184\) in HE 1104–1805 B arises in the halo of the \(z = 1.66162\) DLA galaxy seen in A, a negative gradient in metallicity from DLA to halo gas implies that this halo gas has not yet been fully enriched with metals. This might be a consequence of different star formation rates, in which case LOS B would be probing gas

### Table 5—Continued

| Species | Lines | \(z\) | \(W^a\) (Å) | \(b\) (km s\(^{-1}\)) | \(\sigma_b\) | \(\log N\) (cm\(^{-2}\)) | \(\sigma_{\log N}\) | Spectrum\(^{c}\) |
|---------|-------|------|---------|-------------|-----------|----------------|--------------|----------------|
| 1402    |       |      | 0.580   |             |           |                |              | 1              |
| 1393    |       |      | 1.664930| ...         | ...       | <12.86         | ...          | 1              |
| 1402    |       |      | <0.033  |             |           |                |              | 1              |
| Fe II   | 2344  | 1.661578| 0.012   | 7.86        | 4.30      | 12.47          | 0.08         | 2              |
|         | 2382  |      | 0.030   |             |           |                |              | 2              |
|         | 2600  |      | 0.045   |             |           |                |              | 2              |

\(^a\) Rest frame equivalent widths. For blends, the total equivalent width is given. Upper limits (3 \(\sigma\)) represent nondetections.

\(^b\) \(\sigma_b = 0\) indicates fixed \(b\) parameter.

\(^c\) (1) Keck; (2) NTT; (3) AAT; (4) HST.

### Table 6

| Species | \(\log N_{\text{ad}}(X)\) | \(\sigma_{\log N}\) | \(\log N_{\text{app}}(X)\) | \(\sigma_{\log N}\) | \(\log N_{\text{ad}}(X)\) | \(\sigma_{\log N}\) | MODEL 1\(^a\) | MODEL 2\(^b\) |
|---------|----------------|---------------|----------------|---------------|----------------|---------------|----------------|----------------|
| H I     | 17.57          | 0.10          | ...            | ...           | 17.57          | 0.10          | 17.57          | 17.57          |
| H II    | ...            | ...           | ...            | ...           | ...            | ...           | 19.89          | 19.82          |
| C I     | <13.50         | ...           | ...            | ...           | <13.50         | ...           | 11.87          | 12.14          |
| C II    | 14.50          | 0.20          | ...            | ...           | 14.50          | 0.20          | 14.47          | 14.75          |
| C III   | 15.50          | 0.20          | ...            | ...           | 15.50          | 0.20          | 15.25          | 15.24          |
| C IV    | 14.41          | 0.05          | 14.40          | 0.01          | 14.00\(^{a}\)  | 0.06          | 13.99          | 13.99          |
| N I     | <14.00         | ...           | ...            | ...           | <14.00         | ...           | 10.55          | 10.97          |
| N II    | <13.70         | ...           | ...            | ...           | <13.70         | ...           | 13.00          | 13.31          |
| N III   | 14.00          | 0.20          | ...            | ...           | 14.00          | 0.20          | 13.79          | 13.77          |
| N V     | <14.00         | ...           | ...            | ...           | <14.00         | ...           | 11.30          | 10.87          |
| O I     | <14.10         | ...           | ...            | ...           | <14.10         | ...           | 12.52          | 12.84          |
| O VI    | 14.95          | 0.20          | ...            | ...           | 14.95          | 0.20          | 11.54          | 10.76          |
| Mg II   | <11.90         | ...           | ...            | ...           | <11.90         | ...           | 11.61          | 11.68          |
| Mg III  | 13.28          | 0.09          | ...            | ...           | 13.28          | 0.09          | 13.23          | 13.29          |
| Al II   | <12.60         | ...           | ...            | ...           | <12.60         | ...           | 10.69          | 11.00          |
| Al III  | 12.44          | 0.03          | 12.44          | 0.01          | 12.44          | 0.03          | 12.98          | 13.26          |
| Si I    | <13.20         | ...           | ...            | ...           | <13.20         | ...           | 10.29          | 10.48          |
| Si II   | 13.52          | 0.05          | 13.52          | 0.01          | 13.52          | 0.05          | 13.30          | 13.47          |
| Si III  | 14.10          | 0.20          | ...            | ...           | 14.10          | 0.20          | 14.06          | 14.12          |
| Si IV   | ...            | ...           | <14.28         | ...           | <14.28         | ...           | 13.43          | 13.25          |
| Fe II   | 12.47          | 0.08          | 11.78          | 0.12          | 12.47          | 0.08          | 11.45          | 11.08          |

\(^a\) MODEL 1: Haardt & Madau, \(\log \Gamma = -2.95, \log n_H = -1.8, Z = 0.63Z_{\text{DLA}}, \) and \(S = 1.6\) kpc.

\(^b\) MODEL 2: Power Law \(\Gamma = -2.0, \log \Gamma = -3.02, \log n_H = -1.91, Z = 0.79Z_{\text{DLA}}, \) and \(S = 1.8\) kpc.

\(^c\) Sum of fit components 2 and 3.
regions of lower star formation rate than LOS A. Alternatively, such an abundance gradient could also be explained by a disk-to-halo gas (and dust) transfer yet in early stages, if gas in the halo originates in the disk.

6.1.1.2. Fe and Al Abundances in the LLS

Singly ionized iron is the most outstanding outlier in our model, yielding an Fe II abundance 1 order of magnitude lower than observed (see Table 6). We conclude that this difference can only be due to different iron gas abundances between A and B, which is qualitatively consistent with the absence of dust in the halo of this DLA galaxy. This situation resembles that in our Galaxy, where the degree of dust depletion in halo clouds is smaller than in disk clouds (Sembach & Savage 1996). Further CLOUDY simulations show that the observed log N(Fe ii) = 12.47 can be reproduced if [Fe/H]_LS = -0.8 (Haardt & Madau 1996) or -1.0 (f_c ∝ v^2). An opposite effect is found for aluminum, where our model reproduces Al III only if [Al/H] = -1.0; that is, if the Al overabundance is limited to the DLA gas (but such overabundance might be a consequence of a saturated Al II λ1670 line in A; see also § 3.2.1).

6.1.1.3. A Third Ionization Phase?

N(C iv)/N(Mg ii) = 5.3 also requires N(C iii) to be lower by 1.5 σ than observed. This suggests that there might in fact be a third “intermediate-ionization gas phase,” where part of the C iv, C iii, N iii, and Si iv but no singly ionized species occur (neither does Si iii, whose ionizing potential of 33.5 eV is considerably lower than that of C iii). We would thus be observing blends of lines arising in two phases at similar redshifts. The existence of such a gas phase is fully consistent with the model predictions for Si iii and Al iii in the low-ionization phase (provided the Al relative abundance is lower than in the DLA gas) and with the C iv line profiles, showing a much wider velocity span than the low ions (Fig. 4). Unfortunately, the HST spectral resolution does not allow an appropriate analysis of the C iii and N iii line profiles.

6.1.2. The C iv Systems at z = 1.66280 and z = 1.66465 toward HE 1104—1805 A

The N(C iv)/N(Mg ii) ratios in the C iv systems at z = 1.66280 and z = 1.66460 in A (systems 2 and 3 in Fig. 6) are relatively well constrained by the observations, so we basically repeated the procedure described in the previous section, i.e., we searched for CLOUDY solutions that reproduce these ratios by varying Γ and Z. Since only the total neutral hydrogen column density is known, N(H i) was distributed according to the N(Mg ii) ratios.

Table 7 displays the column densities predicted by CLOUDY for system 3. Again assuming DLA gas-phase abundances and the Haardt & Madau metagalactic radiation field, we find for this system that the observed log N(C iv)/N(Mg ii) = 70.8 can be well reproduced if log n_H = -2.21 cm^{-3} (or log Γ = -2.54 for this radiation field), implying a cloud size along the LOSs of S < 0.9 kpc, where the inequality stands for [Mg/H] > -0.97. This size estimate assumes that both C iv and Mg ii arise from the same density region in photoionization equilibrium.

In system 2 the detection of Mg ii is uncertain, and we can only derive N(C iv)/N(Mg ii) > 117.5, which requires that log n_H < -2.30 (log Γ > -2.45) or S < 0.5 kpc for N(H i) = 16.05. Predicted column densities for system 2 are shown in Table 8. The disagreement for N(C iii) arises as a consequence of a bad fit to the C iii λ977 line.

TABLE 7

| Species | log N(Fe ii) | σ_{log N} | log N(Al iii) | σ_{log N} | log N(Si iv) | σ_{log N} | MODEL^a |
|---------|--------------|-----------|---------------|-----------|-------------|-----------|----------|
| H I      | 16.59        | 0.07      | ...           | ...       | 16.44       | 0.07      | 16.44    |
| H II     | ...          | ...       | ...           | ...       | ...         | ...       | 19.22    |
| C III    | 14.04        | 0.03      | 14.03         | 0.01      | 14.04       | 0.03      | 14.06    |
| N III    | <13.20       | ...       | ...           | <13.20    | <13.20      | ...       | 13.29    |
| Mg II    | 12.19        | 0.03      | ...           | ...       | 12.19       | 0.03      | 12.20    |
| Si III   | 13.70        | 0.20      | ...           | ...       | 13.70       | 0.20      | 13.42    |
| Si IV    | 13.11        | 0.07      | <13.11        | 0.07      | 13.11       | 0.07      | 13.19    |

^a MODEL: Haardt & Madau, log Γ = -2.54, log n_H = -2.21, Z = Z_{DLA}, and S = 0.9 kpc.

^b N(H i) distributed according to the N(Mg ii) ratios.

TABLE 8

| Species | log N(Fe ii) | σ_{log N} | log N(Al iii) | σ_{log N} | log N(Si iv) | σ_{log N} | MODEL^a |
|---------|--------------|-----------|---------------|-----------|-------------|-----------|----------|
| H I      | 16.59        | 0.07      | ...           | ...       | 16.05       | 0.07      | 16.05    |
| H II     | ...          | ...       | ...           | ...       | ...         | ...       | 18.92    |
| C III    | 13.15        | 0.20      | ...           | ...       | 13.15       | 0.20      | 14.42    |
| C IV     | 13.87        | 0.10      | 13.85         | 0.01      | 13.87       | 0.10      | 13.84    |
| N III    | <13.00       | ...       | ...           | <13.00    | <13.00      | ...       | 12.97    |
| Mg II    | <11.80       | ...       | ...           | <11.80    | <11.80      | ...       | 11.76    |
| Si IV    | ...          | <12.58    | ...           | <12.58    | ...         | <12.58    | 12.88    |

^a MODEL: Haardt & Madau, log Γ = -2.45, log n_H = -2.30, Z = Z_{DLA}, and S = 0.5 kpc.

^b N(H i) distributed according to the N(Mg ii) ratios.
None of these photoionization models necessarily requires that $Z < Z_{\text{DLA}}$.

6.1.3. The C\textsc{iv} Systems at $z = 1.66493$ toward HE 1104–1805 B

Observed and predicted column densities for the C\textsc{iv} system at $z = 1.66493$ in B (system 6) are shown in Table 9. Because the detection of Mg\textsc{ii} is very uncertain, our model was required to reproduce C\textsc{iv} assuming $Z = 0.63 Z_{\text{DLA}}$. We arrived at $\log n_H = -2.40$ (or $\log \Gamma = -2.35$), implying $S_{\|} \approx 0.6 \, \text{kpc}$.

6.2. O\textsc{vi} Phase

Possibly the most interesting result of this study is the significant detection of strong O\textsc{vi} absorption at $z = 1.66$ in both LOSs toward HE 1104–1805. Figure 7 shows the corresponding section of the HST spectra of the A and B images with tick marks above the spectrum indicating the O\textsc{vi} $\lambda \lambda 1031, 1037$ doublet at $z = 1.66253$ and the C\textsc{ii} $\lambda \lambda 1036$ lines associated with the DLA and LLSs. Tick marks below the flux level indicate lines identified with other systems. The O\textsc{vi} $\lambda \lambda 1031$ lines at $\lambda = 2747 \, \AA$ have similar rest frame equivalent widths of $W_E = 0.93 \pm 0.07 \, \AA$ (A) and $0.86 \pm 0.10 \, \AA$. Besides Si\textsc{iii} $\lambda 1206$ at $z = 1.28$, neither further metal lines nor a Ly$\beta$ line has been identified at this wavelength, but contamination by a weak Ly$\alpha$ line is not ruled out.$^6$ Voigt profiles convolved with the instrumental profile have been overplotted in the spectra of A and B. They have Doppler parameters of $b = 180 \, \text{km} \, \text{s}^{-1}$ (A) and $110 \, \text{km} \, \text{s}^{-1}$ (B); obtained from Gaussian profile fits to the O\textsc{vi} $\lambda \lambda 1031$ lines and common column density, $\log N = 14.95$. $N$ shows little variation with $b$ within 110 and 180 $\text{km} \, \text{s}^{-1}$ in this region of the curve of growth. Clearly these large Doppler values do not necessarily represent the true line widths. Rather, the observed line profiles are probably made up of more than one O\textsc{vi} line (but see next paragraphs). For comparison, the dotted lines show the resulting profiles of 3 (A) and 2 (B) O\textsc{vi} doublets with common $b = 50 \, \text{km} \, \text{s}^{-1}$ and total column density $\log N = 15.1$ (A) and 15.0 (B). The doublets are placed at redshifts labeled 1, 2, and 3 (A) and 4 and 5 (B) in Fig. 6.

Although O\textsc{vi} has been shown to be relatively common in QSO absorption systems (Bahcall et al. 1993; Bergeron et al. 1994; Burles & Tytler 1996), its detection along the two LOSs to HE 1104–1805 at $z = 1.66$ allows us to directly prove for the first time that this ion does indeed arise in very extended gas clouds. There were indications of this for systems at lower redshift (e.g., Bergeron et al. 1994; Lu & Savage 1993) but no firm evidence. Large, low-density O\textsc{vi} gas clouds confirm the prediction by Rauch et al. (1997) based on simulations of protogalactic clumps (PGCs). In this model, PGCs with a few times $10^5 M_\odot$ (in baryons) are embedded in a filamentary, low density, and largely featureless O\textsc{vi} phase with a spatial extent of up to several hundred kiloparsecs at the N(O\textsc{vi}) $= 10^{13} \text{cm}^{-2}$ column density contour (see Fig. 3 in Rauch et al.). Detectable O\textsc{vi} is indeed expected to be more extended than C\textsc{iv}. The gas is photoionized and the lines are bulk motion broadened and wider than C\textsc{iv}, as they sample the peculiar velocities over a larger volume.

Observational evidence for the physical processes giving rise to O\textsc{vi}, collisional or photoionization, remain, however, debatable so far, basically because contamination by Ly$\alpha$ lines makes it difficult to resolve the O\textsc{vi} $\lambda \lambda 1032, 1036$ doublet profiles appropriately. In our case, a quantitative assessment of the nature of this gas phase is possible, since no N\textsc{v} is detected at this redshift (Fig. 8), and photoionization models can be well constrained under certain assumptions.

At the hydrogen density ($n_H \approx 0.01 \text{cm}^{-3}$) derived for the C\textsc{iv} + Mg\textsc{ii} clouds, the fraction of ionizing photons with the $E > 114 \, \text{eV}$ necessary to ionize enough O\textsc{v} into “observable” O\textsc{vi} is too small. Consequently, an additional, less dense phase is required to explain the strong O\textsc{vi} absorption observed in A and B. Since a unique interpretation of the line profiles is difficult with the present HST

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![Figure 7](image_url)

**Fig. 7.** Section of the HST spectra A and B showing the O\textsc{vi} $\lambda \lambda 1031, 1037$ doublet at $z = 1.66253$. Solid lines: Voigt profiles convolved with a FWHM = 2 $\AA$ Gaussian curve, with $b = 180 \, \text{km} \, \text{s}^{-1}$ (A) and $110 \, \text{km} \, \text{s}^{-1}$ (B) and column density $\log N = 14.95$. Dotted lines: Voigt profiles of three (A) and two (B) O\textsc{vi} lines with common $b = 50 \, \text{km} \, \text{s}^{-1}$ and total column density of $\log N = 15.1$ (A) and 15.0 (B). The lines are placed at redshifts labeled 1, 2, and 3 (A) and 4 and 5 (B) in Fig. 6.

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**Table 9**

| Species | $\log N_{\text{ad}}(X)$ | $\sigma_{\log N}$ | $\log N_{\text{app}}(X)$ | $\sigma_{\log N}$ | $\log N_{\text{ad}}(X)$ | $\sigma_{\log N}$ | MODEL$^*$ |
|---------|-------------------------|-------------------|--------------------------|-------------------|-------------------------|-------------------|-----------|
| H\textsc{i} | 15.90 | ... | ... | ... | ... | ... | 15.90 | 15.90 |
| H\textsc{ii} | ... | ... | ... | ... | ... | ... | ... | 18.90 |
| C\textsc{iii} | <12.90 | ... | ... | ... | ... | ... | <12.90 | 14.17 |
| C\textsc{iv} | 13.67 | 0.03 | 13.61 | 0.02 | 13.67 | 0.03 | 13.67 | 13.67 |
| N\textsc{iii} | <13.20 | ... | ... | ... | ... | ... | <13.20 | 12.71 |
| Mg\textsc{ii} | <12.40 | ... | ... | ... | ... | ... | <12.40 | 11.33 |
| Si\textsc{iv} | ... | <12.86 | ... | <12.86 | ... | ... | 12.58 |

$^*$ MODEL: Haardt & Madau, $\log \Gamma = -2.35$, $\log n_H = -2.40$, $Z = 0.63 Z_{\text{DLA}}$, and $S = 0.6 \, \text{kpc}$.
data, we made the following, simplifying assumptions: (1) both LOSs pass through a common phase giving rise to the O vi absorption lines, as is suggested by the similar equivalent widths and the zero velocity difference between lines in A and B; and (2) the absorption lines arise in one cloud, as is suggested by the line profile symmetry [this assumption may not be valid, but it is equivalent to integrating N(Ovi) over several line components]. A 3σ upper limit of Wc = 0.034 Å for the N v λ1238.8210 line (the stronger line of the N v doublet) measured in the AAT spectrum of A leads to a 3σ upper limit of log N(N v) < 13.2. The nondetection of N v places the stringent (but otherwise very conservative) lower limit of N(O vi)/N(N v) > 60. This ratio requires densities lower than log nH = −3.55 or a large ionization parameter, log Γ ≥ −1.2, if we assume the same relative abundances as found in the DLA gas. This is a striking result, given that a lower (closer to solar) [O/N] ratio would lead to even less dense O vi clouds. In this regard, we must bear in mind that the CLOUDY simulations above depend partly on the relative abundances assumed. For instance, variations of the [O/N] ratio within the estimated column density uncertainties will lead to differences in the predicted parameters.

It is not trivial to obtain an overall picture of this phase, because the total hydrogen column density is not known. As a consequence, photoionization models will not reproduce the individual observed column densities of N(O vi) and N(N v) uniquely, but both N(H) and the gas metallicity Z will determine them. This is shown in Figure 9, where we have plotted all the pairs [Z, N(H)] that reproduce log N(O vi) = 15.0 and log N(N v) = 13.2. We can see that in general a lower metallicity of the highly ionized gas relative to that of the DLA gas, say Z < 0.63Z_DLA, will be compatible with the observations if N(H) is large, log N(H) > 20.0. Additionally, we find that, regardless of the gas metallicity, the clouds where this phase occurs must be at least 1–2 orders of magnitude larger than the systems giving rise to Mg II absorption. These cloud sizes (St ∼ 100 kpc), if representative of transverse dimensions, are widely consistent with the detection of O vi of similar strength in both LOSs. Typical masses derived from these models are ∼ 10^6 M_☉.

To see whether C iv is expected in such a model, we performed further ionization simulations for larger ionization parameters, requiring that the assumed total hydrogen column density and metallicity always led to log N(O vi) = 15.0, i.e., curves departing from points on the Z versus N(H) curve in Figure 9. The predicted N(C iv) column densities in such models are shown in Figure 10 for the Haardt & Madau radiation field (solid line) and a power-law radiation field (dashed line). At the minimum value of Γ allowed by the observations logΓ = −1.2 and for a wide range of gas metallicities, CLOUDY predicts log N(C iv) ≈ 14.4, which is in agreement with the observed value. However, at higher ionization parameters, e.g., N(O vi)/N(N v) ≈ 90 or log Γ = −1.0 (corresponding to a 2σ significant nondetection of N v), N(C iv) becomes ∼ 40% smaller independently of Z. This result in turn indicates that at least part of

![Figure 9](image_url)

**Fig. 9.** Hydrogen column density vs. metallicity in the O vi phase for different CLOUDY models assuming the Haardt & Madau continuum (solid line) and a power law as ionizing background. The relative abundances are the same as in the DLA gas. These models yield throughout log N(O vi) = 15.0 and log N(N v) = 13.2.

![Figure 10](image_url)

**Fig. 10.** Column densities vs. ionization parameter Γ in the O vi phase for different CLOUDY models. Solid line: Haardt & Madau radiation field as ionizing background and Z = Z_DLA. Dotted line: Same radiation field, with Z = 0.4 Z_DLA. Dashed line: Power law and Z = Z_DLA. The relative abundances are the same as in the DLA gas. These models yield throughout log N(O vi) = 15.0.
the observed C IV arises in highly ionized gas, with the remaining contribution coming from the low-ionization gas phase. The present HST data do not enable us to quantitatively assess this issue, and we can only conclude that C IV is likely to occur in both phases.

Collisional ionization of gas in thermal equilibrium can also reproduce the observed N(O IV)/N(N v) ratio at $T = 10^{4.45}$ K if one assumes solar relative abundances (Sutherland & Dopita 1993), so we cannot rule out this process as responsible for ionizing O V into O VI. In such a case, the line broadening would be mostly due to macro-turbulence. Collisionally ionized O VI gas in a Lyman-limit system at $z \approx 3.4$ has been recently proposed by Kirkman & Tytler (1997), who detect both C IV and O VI at the same redshift in high-resolution data. These authors favor collisional ionization because of the high kinetic temperatures implied by the line widths of both ions. In the case of HE 1104−1805 AB, additional, higher resolution (R $\sim$ 23,000) UV spectra are needed to finally discriminate between collisional and photoionization as the dominant ionization mechanism in the O VI phase.

7. CONCLUSIONS AND FINAL REMARKS

We outline our conclusions as follows:

1. The DLA system observed at $z = 1.66162$ in the UV and optical spectra of HE 1104−1805 A has a neutral hydrogen column density of log $N$(H I) = 20.85 ± 0.01. The 6.6 km s$^{-1}$ resolution line profiles show that this high-density gas is distributed in four clouds spanning ~80 km s$^{-1}$. Since the low-ionization and Al III line profiles are observed to track fairly well, these ions are likely to arise in common clouds. Their b-values are consistent if the broadening mechanism is not purely thermal. The C IV line profiles show that at least some of C IV absorption occurs in clouds with no singly ionized species. We find a metallicity of $Z_{\text{DLA}} \approx 1/10 Z_{\odot}$ and a dust-to-gas ratio of $\sim 0.11$ based on $[\text{Zn}/\text{H}] = -1.02$ and $[\text{Cr}/\text{H}] = -1.46$. Other element abundances are $[\text{C}/\text{H}] = -0.91$, $[\text{N}/\text{H}] = -1.86$, $[\text{O}/\text{H}] = -0.98$, $[\text{Mg}/\text{H}] = -0.97$, $[\text{Al}/\text{H}] = -0.77$, $[\text{Si}/\text{H}] = -1.02$, $[\text{Ti}/\text{H}] = -1.50$, $[\text{Mn}/\text{H}] = -1.61$, $[\text{Fe}/\text{H}] = -1.59$, and $[\text{Ni}/\text{H}] = -1.68$. The O/N ratio, which is 8 times larger than the solar value, is consistent with galactic chemical evolution models. However, the observed elemental abundance pattern must be modified by condensation into dust grains given (1) the underabundance of Cr and Ti relative to Zn and (2) the variation of the abundance ratios of these and other refractory elements among different clouds associated with the DLA system.

2. Photoionization by the metagalactic radiation field proposed by Haardt & Madau (1996) implies that the LLS observed at $z = 1.66184$ in the spectra of HE 1104−1805 B and the three further C IV systems observed at similar redshifts in A and B all belong to the same category of absorbers, namely small (LOS sizes 0.5−1.6 kpc) and relatively dense ($n_H = 0.01$ cm$^{-3}$) clouds where both C IV and Mg II absorption occur.

3. We find evidence for the LLS and one further C IV absorption system observed in B to have lower metallicities than observed in the DLA gas, $Z = 0.63 Z_{\text{DLA}}$. This result is significant at the 2 $\sigma$ confidence level if the column density uncertainties are not underestimated.

4. In the context of galaxy formation, the observed H I column densities suggest that LOS B intercepts gas in the “halo” of a protogalaxy at $z = 1.66$, while LOS A crosses its denser, central gas regions. If this picture is correct, then we are observing metal-poor gas in the halo of such a galaxy, compared with the high-density gas (within a transverse separation of $\sim 8 h_50^{-1}$ kpc). This in turn suggests regions of different star formation rates or, alternatively, metal enrichment through gas transfer from the inner to the outer regions of the protogalaxy still in early stages.

5. The presence of a highly ionized gas phase giving rise to the observed O VI absorption of similar strength in both spectra is evident. If photoionization is assumed, the observed log $N$(O VI) = 15.0 and the nondetection of N v implies large ($\sim 100$−200 kpc), low-density ($\sim 10^{-4}$ cm$^{-3}$) clouds where strong O VI but weak C IV absorption occurs. On the basis of these results, we suggest that this highly ionized gas surrounds the clouds giving rise to the DLA system and the LLSs. Such an extended low-density O VI phase confirms the predictions of simulations of protogalactic clumps (Rauch et al. 1997).

Concerning the negative gradient in metallicity from gas crossed by LOS A to gas crossed by LOS B, it must be pointed out that such an effect, if real, does not necessarily support the disk/halo scenario. Indeed, it is still not clear whether present-day rotating, disklike galaxies should have had a similar appearance in their early stages of formation, nor is it well understood what we should define as protogalactic “halos.” A good deal of progress is being made to resolve this paradigm: a link between metallicity and kinematics can improve our understanding of DLA systems (Wolfe & Prochaska 1998); hydrodynamic simulations of merging protogalactic clumps are capable of explaining the large velocity spans seen in this class of absorption systems (Haehnelt et al. 1998). Here we have demonstrated the powerful tool that double LOSs can provide us. A convincing interpretation of our result, however, has to await a larger sample of such cases.

Finally, let us emphasize that the scenario of small and compact C IV clouds surrounded by extended O VI gas can indeed be theoretically understood and is in good agreement with the predictions of a cold dark matter–based model (Rauch et al. 1997). Furthermore, in a hierarchical structure-formation scenario, DLAs and LLSs can arise from relatively small ($M_{\text{baryon}} \sim 10^9 M_{\odot}$), merging protogalactic clumps. Even if the sizes derived using our photoionization models are not representative of transverse cloud sizes, the similar C IV line profiles and equivalent widths in A and B are still consistent with filamentary structures, which is also a prediction of hierarchical structure formation. Such a correlation between line profiles in A and B is, on the other hand, less evident for Mg II, implying gas inhomogeneities on spatial scales similar to the separation between LOSs and in concordance with Mg II arising in smaller regions than C IV and O VI.

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REFERENCES

Bahcall, J. N., et al. 1993, ApJS, 87, 1
Bergeron, J., et al. 1994, ApJ, 436, 33
Bergeron, J., & Stasinska, G. 1986, A&A, 169, 1
Burles, S., & Tytler, D. 1996, ApJ, 460, 584
Cardelli, J. A., Savage, B. D., & Ebbets, D. C. 1991, ApJ, 383, L23
Cardelli, J. A., Sembach, K. R., & Savage, B. D. 1995, ApJ, 440, 241
Caulte, A. 1989, ApJ, 340, 90
Courbin, F., Lidman, C., & Magain, P. 1998, A&A, 330, 57
Ferland, G. J. 1993, Univ. Kentucky, Phys. Dept. Internal Rep.
Fontana, A., & Ballester, P. 1995, ESO Messenger, 80, 37
Haardt, F., & Madau, P. 1996, ApJ, 461, 20
Haehnelt, M. G., Rauch, M., & Steinmetz, M. 1996a, MNRAS, 283, 1055
Haehnelt, M. G., Steinmetz, M., & Rauch, M. 1996b, ApJ, 465, L95
———. 1998, ApJ, 495, 647
Kirkman, D., & Tytler, D. 1997, ApJ, 489, L123
Lu, L., Sargent, W. L. W., Barlow, T. A., Churchill, C. W., & Vogt, S. S.
1996, ApJS, 107, 475
Lu, L., & Savage, B. D. 1993, ApJ, 403, 127
Mar, D. P., & Bailey, G. 1995, Proc. Astron. Soc. Australia, 12, 239
Morton, D. C. 1991, ApJS, 77, 119
Pettini, M., Boksenberg, A., & Hunstead, R. W. 1990, ApJ, 348, 48
Pettini, M., Lipman, K., & Hunstead, R. W. 1995, ApJ, 451, 100
Pettini, M., Smith, L. J., Kink, D. L., & Hunstead, R. W. 1997, ApJ, 486, 665
Press, W. H., Flannery, B. P., Teukolsky, S. A., & Vetterling, W. T. 1986,
Numerical Recipes (Cambridge: Cambridge Univ.)
Prochaska, J. X., & Wolfe, A. M. 1996, ApJ, 470, 403
Rauch, M. 1997, in Proc. 13th IAP Colloq. Structure and Evolution of the
IGM from QSO Absorption Lines, ed. P. Petitjean & S. Charlot (Paris: Editions Frontières), 109
Rauch, M., Haehnelt, M. G., & Steinmetz, M. 1997, ApJ, 481, 601
Reimers, D., Rodriguez-Pascual, P., Hagen, H.-J., & Wisotzki, L. 1995,
A&A, 293, L21
Remy, M., Claeskens, J.-F., Surdej, J., Hjorth, J.,Refsdal, S., Wucknitz, O.,
Sørensen, A. N., & Grundahl, F. 1998, NewA, 3, 379
Savage, B. D., & Sembach, K. R. 1991, ApJ, 379, 245
———. 1996, ApJ, 470, 893
Schneider, D. P., et al. 1993, ApJS, 87, 45
Seaton, M. J. 1979, MNRAS, 187, 73
Sembach, K. R., & Savage, B. D. 1996, ApJ, 457, 211
Smoltek, A., Robertson, J. G., Shaver, P. A., Reimers, D., Wisotzki, L., &
Köhler, T. 1995, A&AS, 113, 199 (Paper I)
Smoltek, A., Surdej, J., Shaver, P. A., Foltz, C. B., Chaffee, F. H., Weymann,
R. J., Williams, R. E., & Magain, P. 1992, ApJ, 398, 39
Sutherland, R. S., & Dopita, M. A. 1993, ApJS, 88, 253
Verner, D. A., Barthel, P. D., & Tytler, D. 1994, A&AS, 108, 287
Vladilo, G. 1998, ApJ, 493, 583
Vogt, S. S., et al. 1994, Proc. SPIE, 2198, 362
Wisotzki, L., Köhler, T., Ikonomou, M., & Reimers, D. 1995, A&A, 297, L59
Wisotzki, L., Köhler, T., Kayser, R., & Reimers, D. 1993, A&A, 278, L15
Wolfe, A. M. 1995, in Proc. ESO Workshop, QSO Absorption Lines, ed.
G. Meylan (Heidelberg: Springer), 13
Wolfe, A. M., Lanzetta, K. M., Foltz, C. B., & Chaffee F. H. 1995, ApJ, 454, 698
Wolfe, A. M., & Prochaska, J. X. 1998, ApJ, 494, L15
Zuo, L., Beaver, E. A., Burbidge, E. M., Cohen, R. D., Junkkarinen, V. T., &
Lyons, R. W. 1997, ApJ, 477, 568