First Comparison of Ionization and Metallicity in Two Lines of Sight Toward HE 1104–1805 AB at $z = 1.66$

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ABSTRACT

Using new Hubble Space Telescope Faint Object Spectrograph, New Technology Telescope EMMI, and Keck HIRES spectra of the gravitationally-lensed double QSO HE 1104–1805 AB ($z_{em} = 2.31$), 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 Lyα (DLA) system with $\log N(HI) = 20.85$, which is observed in the ultraviolet spectra of the bright QSO image (A). The other two systems are associated with a Lyman-limit system with $\log N(HI) = 17.57$, 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 $\theta = 3.195''$ between A and B corresponds to a transverse proper separation of $S_\perp = 8.3 \ h_{50}^{-1}$ kpc, for $q_0 = 0.5$ and a lens at $z = 1$.

Assuming that the relative metal abundances in these absorption systems are the same as observed in the DLA system, we find that the observed $N(C\ IV)/N(Mg\ II)$

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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 \( n_H \lesssim 0.01 \text{ cm}^{-3} \)) 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, \( Z_{\text{DLA}} \simeq 1/10 \) \( Z_{\odot} \).

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 (\( n_H \sim 10^{-4} \text{ cm}^{-3} \)), in which O\,vi, but only weak C\,iv absorption occurs. In this state, \( \log \Gamma \geq -1.2 \) reproduces the observed ratio of \( N(\text{O\,vi})/N(\text{N\,v}) > 60 \).

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 ultraviolet (UV) photoionization by the background field of distant active galactic nuclei and of local sources associated with the absorption systems. In this model, two gas phases with different ionization parameters \( \Gamma \) (ratio of hydrogen ionizing photon density to total hydrogen density \( n_H \)) are commonly invoked in order 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 \( n_H \) 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 \( N(H) \) 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 \( D = 0.7 \) to \( 2.2 \) \( h_{50}^{-1} \) 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, although 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 C\,IV clouds in the LOSs to HE 1104–1805 AB. At higher resolution, Rauch (1997b) has recently shown that density gradients on sub-kpc 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 (\( z_{\text{em}} = 2.31, \, m_B(A) = 16.7, \, m_B(B) = 18.6, \) angular separation \( \theta = 3.195'' \)) was discovered in the course of the Hamburg/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 $z_{\text{lens}} = 1.66$, while Remy et al. (1998) find that their Hubble Space Telescope (HST) and ground-based direct imaging observations are consistent with $z_{\text{lens}} = 1.32$. Neither of these results influences our photoionization models. 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 $z_{\text{lens}} = 1.66$ 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 HE1104–1805. We use new HST Faint Object Spectrograph (FOS), and ground-based New Technology Telescope (NTT) and Keck spectra. The C$\text{IV}$ systems observed in the UV and optical spectra of A and B at redshifts close to $z_{\text{DLA}}$ 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 have therefore 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$\text{IV}$ systems, we have used the photoionization code CLOUDY (Ferland 1993) and the ionizing radiation field proposed by Haardt & Madau (1996). We have assumed that this radiation field also ionizes the gas that gives rise to the strong O$\text{VI}$ absorption observed along both LOSs. We have made a distinction between two gas phases with different ionization states: a low ionization phase, where both Mg$\text{II}$ and C$\text{IV}$ absorption occur, and a high ionization phase, where O$\text{VI}$ but weak C$\text{IV}$ absorption occurs. The photoionization models for each of these two gas phases are constrained by the observed column density ratios $N(\text{CIV})$ to $N(\text{MgII})$ and $N(\text{OVI})$ to $N(\text{NV})$, respectively.

Our paper is organized basically in two parts: estimation of the metal abundances in the DLA gas, and photoionization models for the C$\text{IV}$ 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. § 4 is devoted to the metal abundances determined for the DLA system observed in QSO component A. § 5 presents possible physical scenarios for the C$\text{IV}$ 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$\text{IV}$ and O$\text{VI}$ 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 November 1995 with the Faint Object Spectrograph onboard the Hubble Space Telescope. Target acquisition and spectroscopy were done using Grating G270H with the red detector and the 3.7″ × 3.7″ aperture. This configuration yields a spectral resolution of FWHM = 2 Å and a wavelength coverage from 2222 Å to 3277 Å (Schneider et al. 1993). Total integration times of 1790 and 6690 seconds 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 ∼ 0.5 Å pixel.

2.2. Keck HIRES Spectra

Optical spectra of HE 1104–1805 A and B were taken in January and February 1997 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\(\alpha\) forest. We have also taken special care to omit the metal absorption line complexes from the continuum points, 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 constant wavelength scale.

2.3. NTT Spectra

Optical spectra of HE 1104–1805 A and B were obtained in February 1996 with the echelle spectrograph of EMMI on the ESO New Technology Telescope in the Red Medium Dispersion mode under subarcsecond seeing conditions. The wavelength coverage is 3910 to 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 CCD were used. This CCD provides 24µm pixels, corresponding to 0.
′′27 in the sky. The total integration time was 16 hours. The echelle orders were optimally extracted
with a version of the extraction algorithm used in Paper I, 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: (i) a variance (Poisson statistics, read-out noise and cosmics) is assigned
to each pixel. For each flat-fielded two-dimensional spectrum, two Gaussians 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); (ii) 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; (iii) step (i) is repeated, this time with fixed
width and position—given by the polynomial fits—thus allowing only the amplitudes to vary. The
final, variance-weighted coadded spectra have FWHM = 0.8 to 1.0 Å and maximum S/N ≃ 77 (A)
and ≃ 27 (B). The continuum level was estimated separately in each order—skipping corrections
for the blaze function—and for each QSO image. This was done by fitting low-order polynomials
and cubic splines to featureless spectral regions.

2.4. AAT Spectra

Additional FWHM = 1.2 Å resolution spectra of both QSO images taken with the 3.9m
Anglo-Australian Telescope and covering the wavelength range 3170 to 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 re-define 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 Mg II λλ 2796, 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 Lyα forest, because of the lack of spectral regions free of absorption lines. For this reason, we decided to first determine the absorbed continuum—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 \( \text{H}\alpha \) Lyman series lines, were modeled with Voigt profiles convolved with a FWHM = 2 Å Gaussian 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 \( N(\text{H}^\alpha) \), 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 \( \lambda_{\text{obs}} \leq 3277 \) Å was found to be very well represented by two power laws \( (f \propto \nu^\alpha) \) 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 \( \text{H}\alpha \) absorption continuum with the observed flux at selected absorption-free spectral regions including some regions dominated by significant \( \text{H}\alpha \) 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 Lyα line density. Moreover, the expected emission lines stand out well against the continuum as can be seen in Fig. 1. Division of the flux by this continuum resulted in the normalized HST spectra shown in Fig. 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. 1993). Furthermore, we find the spectrum of A bluewards of Lyα emission to be softer than that of B, 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 one and two years 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 that assumptions concerning line widths must be made. The lines were modelled 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 $\text{H} \, \text{I}$ 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 to lines in the Keck spectra using the MIDAS program FITLYMAN (Fontana & Ballester 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 from Verner et al. (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 1$\sigma$-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 non-resolved complexes is less obvious because the $\sigma_{\log N}$’s result from a more complicated Hessian matrix, and are no longer independent. 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$\,\text{II}$ λ1670), 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 (cf. Table 4).
3.2.2. NTT Spectra

In the NTT spectrum, the Mg\textsc{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 $z$ and $b$ fixed at values found for the Si\textsc{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 superimposed to the spectra using XVOIGT (program written by D. Mar), 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 \textit{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\textsc{ii} $\lambda 1608$ ($b = 20 \ \text{km s}^{-1}$) and C\textsc{iv} $\lambda 1548$ ($b = 44 \ \text{km s}^{-1}$) lines in A, respectively. For B, the lines used were Al\textsc{ii} $\lambda 1670$ ($b = 20 \ \text{km s}^{-1}$) and C\textsc{iv} $\lambda 1548$ ($b = 37 \ \text{km s}^{-1}$).

To estimate the uncertainties of our column densities we smoothed and rebinned lines observed in the NTT spectra to HST FOS resolution, and re-computed column densities with the procedure described above. The new column densities showed deviations of the order 0.1 to 0.2 dex from the original, better determined values. Another source of error is our limited ability to de-blend metal lines from Ly\textalpha 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\textsc{ii} $\lambda 1036,1334$; O\textsc{i} $\lambda 988,1302$ (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)

$$
\sigma_W = \frac{\text{FWHM}}{<\text{S/N}>},
$$

where FWHM is the width of the spectral point spread function and $<\text{S/N}>$ is the mean local signal to noise 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. \textbf{H\textsc{i} Column Densities at }z = 1.66

To derive more accurate column densities for H\textsc{i}, we used the normalized \textit{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 \(N(\text{H\textsc{i}})\) 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\textsc{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 \(\log N(\text{H\textsc{i}}) = 20.85 \pm 0.01\); for the LLS (B) we obtained \(\log N(\text{H\textsc{i}}) = 17.57 \pm 0.10\). Notice that these values are independent of the ones estimated for placing the continuum and shown in Table 2.

4. The Damped Ly\textalpha 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\textsc{iv} and Si\textsc{iv} are also present. We now describe the Keck HIRES line profiles, referring to the left hand panels of Figures 3, 4 and 5, throughout this section.

4.1. Low Ion Profiles

The left hand panel of Fig. 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\textsc{ii} in the DLA system. These lines lie redward of the Ly\textalpha forest. In each line complex, we have fitted four Voigt profiles with independent \(z\), \(b\) and \(N\) values. The Ni\textsc{ii} and Fe\textsc{ii} results are based upon simultaneous fits to 3 transitions; the Si\textsc{ii} and Al\textsc{iii} fits on 2 transitions; the Al\textsc{ii} fit on 1 transition; and the Mg\textsc{ii} fit on 2 transitions (cf. Table 3). We fitted 4 components to the Mg\textsc{ii} lines in the \textit{NTT} spectra, with \(z\) and \(b\) tied to the values found for Si\textsc{ii}. Only the three bluemost components show associated Zn\textsc{ii} and Cr\textsc{ii} (see 4.3.1).

From the high-resolution plots, we see that the low ions track each other quite closely, suggesting they occur in the same gas clouds. The whole profile is characterized by one cloud at \(v \approx -30\ \text{km s}^{-1}\) with the strongest absorption, one cloud at \(v \approx +40\ \text{km s}^{-1}\) 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 damped Ly\textalpha systems. It has been variously interpreted as a consequence of absorption by rotating gaseous disks (e.g., Wolfe et al. 1995b) or as the signature of merging protogalactic clumps (PGCs) in hierarchical structure formation (Rauch et al. 1997a). 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 of the independent fits performed to each ion profile, we obtain fit solutions that uniquely characterize each cloud in redshift and broadening parameter (cf. 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\(^{-1}\) (fourth Ni\(\text{II}\) component excluded due to large \(b\)-uncertainties; fit to Zn\(\text{II}\), Cr\(\text{II}\) and Ti\(\text{II}\) lines 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 hand panel of Fig. 5 shows the C\(\text{IV}\) \(\lambda 1548, 1550\), Si\(\text{IV}\) \(\lambda 1393, 1402\) and, for comparison purposes, Al\(\text{II}\) \(\lambda 1670\) velocity profiles associated with the DLA system. For the C\(\text{IV}\) 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\(\text{IV}\) lines and contamination by Ly\(\alpha\) forest lines do not allow a clear comparison with the C\(\text{IV}\) profiles. We decided not to fit these Si\(\text{IV}\) 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 at least part of the C\(\text{IV}\) absorption (velocity component 1) occurs in clouds without low ionization species. On the other hand, C\(\text{IV}\) velocity components 2 to 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\(\text{IV}\), regardless of which line broadening mechanism dominates—thermal or turbulent gas motion—occurs in hotter gas regions than the low ion clouds.

4.3. Abundances

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

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

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\(\text{I}\), assumed to be the dominant ionization stage of oxygen.
4.3.1. Zn, Cr and Ti Abundances and Dust

Fig. 4 shows the Keck velocity profiles of the most outstanding Zn\textsc{ii} and Cr\textsc{ii} transitions. The fit solutions lead to three-component profiles for the Cr\textsc{ii} complex at $v = -29.1$, $-7.3$ and $7.4$ km s$^{-1}$, and two-component profiles for Zn\textsc{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\textsc{ii})$/N$(Cr\textsc{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\textsc{ii} component.

The variation of the abundance ratios of refractory elements among different clouds associated with the DLA gas provide insights into the presence of dust in the disk of damped Ly$\alpha$ 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, also expected to be depleted into dust. The column density ratios Zn\textsc{ii} to Fe\textsc{ii} and Zn\textsc{ii} to Ni\textsc{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, 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 pointed out in section 4.1.1, the bluemost component is characterized by narrower lines than component 2 in all the ions considered (including Zn\textsc{ii} and Cr\textsc{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, however), 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 Ly$\alpha$ damped 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 HIRES data; and the underabundance of Al relative to Si and Mn relative to Fe (the “odd-even effect”; see Lu et al. 1996 for details), which we do not find in this DLA system. Instead, we derive [Al/Si] = +0.25 ± 0.15, and [Mn/Fe] = −0.02 ± 0.14 (cf. Table 4), although we recall that the Al abundance is only based on the Al\textsc{ii} $\lambda 1670$ line. Given the high Mn/Fe ratio and the argument given in the 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 [$Zn/H] = −1.02 ± 0.01$ relative to the solar value, we derive a metallicity $Z_{DLA} \simeq 1/10 Z_\odot$ 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 ($Zn/H)_\odot = −7.35$, and more accurate since it is based on a simultaneous fit to two Zn\textsc{ii}
Additionally, we deduce from \([\text{Cr}/\text{H}] = -1.46 \pm 0.02\) a dust-to-gas ratio of \(\sim 0.11\), using the definition given by Vladilo (1998), eq. [19], and considering that most of chromium should be incorporated into dust grains in the ISM of galaxies showing damped \(\text{H}\)\(_i\) absorption (e.g. Pettini et al. 1990). Furthermore, titanium, another refractory element, is found to have \([\text{Ti}/\text{H}] = -1.50 \pm 0.07\), based upon the unsaturated \(\text{Ti}\)\(_{\text{II}}\) \(\lambda\lambda 1910.6, 1910.9\) lines. This is in full agreement with the incorporation of Ti and Cr into a dust phase in the neutral ISM of this damped Ly\(\alpha\) 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 \([\text{Zn}/\text{H}]\) (cf. Fig. 3 in Pettini et al. 1997); (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 \([\text{O}/\text{N}]\) and \([\text{C}/\text{Mg}]\).

Based on the \(\text{O}\)\(_{\text{I}}\) \(\lambda\lambda 988,1302\) lines, we find \([\text{O}/\text{H}] = -0.98 \pm 0.20\), in very good agreement with the abundance ratio of Zn. This supports O\(_{\text{I}}\) 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 damped Ly\(\alpha\) galaxy, in agreement with observations in the local ISM (Cardelli et al. 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 \([\text{Si}/\text{O}] \simeq 0\) 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 \([\text{Si}/\text{H}]\) is based on reliable column-density measurements of two \(\text{Si}\)\(_{\text{II}}\) lines (observed in the Keck HIRES spectrum), making our oxygen abundance estimation yet more confident.

Concerning the abundance ratio of nitrogen, the bulk of \([\text{N}/\text{H}]\) is provided by the column density of \(\text{N}\)\(_{\text{II}}\) \(\lambda 1083\). 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—like 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 \([\text{O}/\text{N}] = 0.88\) 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 et al. 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 \(\text{km s}^{-1}\) resolution \(\text{NTT}\) 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\textsc{ii} $\lambda\lambda 1036,1334$ lines. C/Mg is found to have the solar value within the errors, but $N$(Mg) might be underestimated through saturation of the Mg\textsc{ii} lines in A.

5. Geometry of the Absorbers at $z = 1.66$

Fig. 6 shows the velocity profiles of the C\textsc{iv} $\lambda \lambda 1548,1550$ and Mg\textsc{ii} $\lambda 2796,2803$ doublets (at 7 and 40 km s$^{-1}$ resolution, respectively) toward HE1104–1805 A (left) and B. In both panels, $v = 0$ km s$^{-1}$ corresponds to $z = 1.66164$, which is the redshift of Mg\textsc{ii} in the DLA system. We have arbitrarily numbered the C\textsc{iv} complexes at $z = 1.66143$ (1), $z = 1.66280$ (2) and $z = 1.66465$ (3) in the A spectra, and at $z = 1.66184$ (4), $z = 1.66284$ (5) and $z = 1.66493$ (6) in the B spectra, so they will be referred to as systems 1 to 6 throughout the following sections. Also shown in Fig. 6, although at a more expanded velocity scale, are the profiles of the Ly$\alpha$, Ly$\beta$ and Ly$\gamma$ H\textsc{i} lines. Note that H\textsc{i} presents (at least) two components both in A and B.

C\textsc{iv} systems 1 to 4 show associated Mg\textsc{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\textsc{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\textsc{ii} in absorption systems 2 and 6 is less evident at this S/N, so only upper limits can be derived. C\textsc{iv} system 5 will not be considered here.

Do C\textsc{iv} and Mg\textsc{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 Lyman-limit systems (Prochaska & Wolfe 1996). As discussed in § 6.2 it is also possible that part of the C\textsc{iv} arises in the same highly ionized gas that gives rise to O\textsc{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\textsc{iv} arises in clouds where no Mg\textsc{ii} is present (see also the right hand panel of Fig. 5).

From inspection of Fig. 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\textsc{ii} lines in A and B, in contrast to the more similar C\textsc{iv} equivalent widths, suggest gas inhomogeneities on spatial scales lower than the linear separation between LOSs $S_L = 8.3 \ h_{50}^{-1}$ kpc, for $q_0 = 0.5$ and a lens at $z = 1$, thus suggesting that C\textsc{iv} arises in a more extended region than Mg\textsc{ii}. However, we find that the velocity difference between the C\textsc{iv} clouds in A and B is $\langle \Delta v \rangle = -11 \pm 2$ km s$^{-1}$.
while \( \langle \Delta v \rangle = -1 \pm 1 \text{ km s}^{-1} \) for the corresponding \( \text{Mg}\,\text{II} \) clouds. If these velocity differences are a consequence of peculiar cloud motions, then a physical association of \( \text{C}\,\text{IV} \) and \( \text{Mg}\,\text{II} \) 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 \( \text{C}\,\text{IV} \) absorbers along both LOSs, we have analyzed each system separately.

There are two alternative interpretations for the \( \text{H}\,\text{I} \) column densities in A and B: (1) the DLA system arises in a disk-type galaxy (Wolfe 1995a) 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 PGC and LOS B crosses the surrounding less dense gas at an impact parameter of a few kpc (Rauch et al. 1997a). Our data do not allow us to discern between these two models. Consequently, in the following we will simply consider \( \text{C}\,\text{IV} \) absorption systems 2 to 6 to 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 \( \text{C}\,\text{IV}-\text{Mg}\,\text{II} \) systems observed in A (systems 2, 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 Lyman-limit systems and Ly\( \alpha \) forest clouds. This radiation field also has a diffuse component due to recombination continuum radiation. Our model assumes \( J(912) = 0.37 \times 10^{-21} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1} \) 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 and Stasinska 1986). In particular, cloud sizes along the LOSs resulting from this model need to be considered upper limits, because considering slabs illuminated on one side underestimates the true ionizing radiation field.

As we argue below, the wide variety of low- and high-ionization stages 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, but also triply ionized atoms occurs; (2) a “high-ionization phase”, where \( \text{O}\,\text{VI} \) 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

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5The term “low” has just the purpose to distinguish both gas phases.
observed ionic column density ratios \(N(\text{C\textsc{iv}})\) to \(N(\text{Mg\textsc{ii}})\) in systems 2, 3, 4 and 6, and the ratio \(N(\text{O\textsc{vi}})\) to \(N(\text{N\textsc{v}})\) 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 into dust grains. If the dust-to-gas ratio in the halo of this damped Ly\(\alpha\) galaxy were considerably lower than in its DLA region (or even zero), photoionization models should arrive to ionic column densities of refractory elements that are underestimated, compared with the observed value. We observe this effect for Fe\textsc{ii} (see next section).

### 6.1. Low-ionization Phase

#### 6.1.1. The Lyman-limit System at \(z = 1.66184\) toward HE 1104–1805 B

Table 5 displays the observed column densities of ions associated with the LLS at \(z = 1.66184\). The low and high ion velocity profiles are shown in Figures 3 and 5, respectively (right hand panels). Besides the DLA system, this is the second most metal-rich system. Prominent ions observed are: Mg\textsc{ii}, Al\textsc{ii}, Al\textsc{iii}, Si\textsc{ii}, Si\textsc{iii}, C\textsc{ii}, N\textsc{iii} and Fe\textsc{ii}. The detection of Fe\textsc{ii} is marginal but significant. Due to the low S/N and extraction artifacts at the position of Fe\textsc{ii} \(\lambda 1608\) (Fig. 3, top right spectrum), we decided to fit one-component Voigt profiles to the three strongest Fe\textsc{ii} lines in the NTT spectra. The detection of Al\textsc{ii} and Al\textsc{iii} is qualitatively consistent with the assumption of DLA relative metal abundances in the LLS.

Taking the arguments given in § 5 into account, and in order to perform photoionization simulations for the LLS we have to first determine the range of possible values within which \(N(\text{C\textsc{iv}})/N(\text{Mg\textsc{ii}})\) is likely to vary. Since the line profiles of Mg\textsc{ii} do not trace the whole velocity range of C\textsc{iv}, a very conservative upper limit of \(\sim 20\) for the ratios is given by the total column densities of the fitted Voigt profiles. However, from the right hand panel of Fig. 5 we see that the low ion profiles (here represented by Al\textsc{ii} \(\lambda 1670\)) coincide quite well in velocity space with C\textsc{iv} fit components 2 and 3. Considering that these Mg\textsc{ii} line profiles at Keck HIRES resolution would not differ too much from the Al\textsc{ii} \(\lambda 1670\) ones, and taking the column densities integrated over these components leads to \(N(\text{C\textsc{iv}})/N(\text{Mg\textsc{ii}}) = 5.3\), a much more realistic column density ratio.

Table 6 displays the column densities predicted by CLOUDY for the LLS using the Haardt&Madau ionizing radiation field (column labelled MODEL 1). Assuming for this system DLA gas-phase abundances, a column density ratio \(N(\text{C\textsc{iv}})/N(\text{Mg\textsc{ii}}) = 5.3\) implies \(\log n_\text{H} = -1.8\) cm\(^{-3}\) (or \(\log \Gamma = -2.95\) for this radiation field); in other words, the gas is relatively highly ionized.
with \( N(\text{H} \text{II})/N(\text{H} \text{I}) \approx 200 \), but \( \text{Mg} \text{II} \) is still present. The observed \( \log N(\text{H} \text{I}) = 17.57 \) leads to a typical (model dependent) cloud size along the LOSs of \( S_\parallel \lesssim 1.6 \text{ kpc} \). For comparison purposes, a power law of the form \( f \propto \nu^{-2} \) was also used as ionizing background (column labeled MODEL 2 in Table 6). A harder radiation field is not able to reproduce \( N(\text{C} \text{IV})/N(\text{Mg} \text{II}) = 5.3 \) with the assumed element abundances. However, even the selected power law model fails to simultaneously reproduce \( \text{C} \text{II} \) and \( \text{C} \text{IV} \), while the Haardt&Madau model does, due to the continuum break at the \( \text{He} \text{II} \) edge.

Our model assumes that the LLS gas is in photoionization equilibrium. Deviations from this equilibrium can lead to dramatical underestimations of the cloud lengths parallel to the LOSs by photoionization simulations, because the neutral hydrogen fraction is overestimated (Haehnelt et al. 1996a). However, at the density derived for this LLS, \( n_\text{H} \sim 0.01 \text{ cm}^{-3} \), significant departures from the equilibrium temperature (\( T = 1.5 \times 10^4 \text{ K} \)) are rare, as is shown by SPH simulations (Rauch et al. 1997a, Haehnelt et al. 1996b). Thus, the hydrogen recombination timescale in this regime, \( \sim 6 \text{ Myr} \), is short enough to allow line cooling to balance photoheating processes. Consequently, we believe the CLOUDY sizes derived for this LLS to be reliable.

**Gas Metallicity in the Lyman-limit System.** 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 (\( \text{Al} \text{II}, \text{Al} \text{III}, \text{and Fe} \text{II} \) are not considered). In particular, \( N(\text{C} \text{II}), N(\text{C} \text{IV}), N(\text{Mg} \text{II}), \) and \( N(\text{Si} \text{III}) \) are *simultaneously* very well reproduced if \( Z_{\text{LLS}} = 0.63 Z_{\text{DLA}} \). This is an upper limit for \( Z_{\text{LLS}} \) because due to saturation of the \( \text{Mg} \text{II} \) lines in A, we obtain only a lower limit for [Mg/H]; hence, to reproduce \( N(\text{Mg} \text{II}) \) 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 to 10 kpc in various directions, suggesting uniform physical properties over these radii. In addition, warm disk clouds show gas abundances that are 0.2 to 0.6 dex lower than those in warm Halo clouds (Sembach & Savage 1996, and references therein; Savage & Sembach 1996, but see Cardelli et al. 1995). If we assume that the LLS observed at \( z = 1.66184 \) in HE 1104–1805 B arises in the halo of the \( z = 1.66162 \) damped Ly\( \alpha \) 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 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.
Fe and Al Abundances in the Lyman-limit System. Singly ionized iron is the most outstanding outlier in our model, yielding an Fe\textsuperscript{II} abundance one order of magnitude lower than observed (cf. Table 6). We conclude that this difference can only be due to different iron gas abundances between A and B, qualitatively consistent with the absence of dust in the halo of this damped Ly\alpha 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\textsuperscript{II}) = 12.47 can be reproduced if [Fe/H]$_{LLS}$ = −0.8 (Haardt&Madau) or −1.0 ($j_\nu \propto \nu^{-2}$). An opposite effect is found for aluminum, where our model reproduces Al\textsuperscript{III} only if [Al/H] = −1.0, that is, if the Al overabundance is limited to the DLA gas (but such overabundance might be consequence of a saturated Al\textsuperscript{II} $\lambda$1670 line in A [see also section 3.2.1]).

A third ionization phase? $N$(C\textsuperscript{IV})/$N$(Mg\textsuperscript{II}) = 5.3 also requires $N$(C\textsuperscript{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\textsuperscript{IV}, C\textsuperscript{III}, N\textsuperscript{III} and Si\textsuperscript{IV} but no singly ionized species occur (neither does Si\textsuperscript{III}, whose ionizing potential of 33.5 eV is considerably lower than that of C\textsuperscript{III}). We would be thus 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\textsuperscript{III} and Al\textsuperscript{III} in the low-ionization phase (provided the Al relative abundance is lower than in the DLA gas), and with the C\textsuperscript{IV} line profiles, showing a much wider velocity span than the low ions (Fig 5). Unfortunately, the HST spectral resolution does not allow an appropriate analysis of the C\textsuperscript{III} and N\textsuperscript{III} line profiles.

6.1.2. The C\textsuperscript{IV} Systems at $z = 1.66280$ and $z = 1.66465$ toward HE 1104−1805 A

The $N$(C\textsuperscript{IV})/$N$(Mg\textsuperscript{II}) ratios in the C\textsuperscript{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 $\Gamma$ and $Z$. Since only the total neutral hydrogen column density is known, $N$(H\textsuperscript{I}) was distributed according to the $N$(Mg\textsuperscript{II}) ratios.

Table 8 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 $N$(C\textsuperscript{IV})/$N$(Mg\textsuperscript{II}) = 70.8 can be well reproduced if log $n_\text{H} = −2.21$ cm$^{-3}$ (or log $\Gamma = −2.54$ for this radiation field), implying a longitudinal cloud size of $S_\parallel = 0.9$ kpc, where the inequality stands for [Mg/H] > −0.97. This size estimate assumes both C\textsuperscript{IV} and Mg\textsuperscript{II} to arise from the same density region in photoionization equilibrium.

In System 2, the detection of Mg\textsuperscript{II} is uncertain, and we can only derive $N$(C\textsuperscript{IV})/$N$(Mg\textsuperscript{II}) > 117.5, which requires that log $n_\text{H} < −2.30$ (log $\Gamma > −2.45$), or $S_\parallel \gtrsim 0.5$ kpc for $N$(H\textsuperscript{I}) = 16.05. Predicted column densities for system 2 are shown in Table 7. The
disagreement for $N(C\text{\textsc{iii}})$ arises as a consequence of a bad fit to the $C\text{\textsc{iii}}\lambda 977$ line. None of these photoionization models necessarily requires that $Z < Z_{\text{DLA}}$.

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

Observed and predicted column densities for the $C\text{\textsc{iv}}$ system at $z = 1.66493$ in B (system 6) are shown in Table 9. Because the detection of Mg II is very uncertain, our model was required to reproduce $C\text{\textsc{iv}}$ assuming $Z = 0.63 \, Z_{\text{DLA}}$. We arrived at $\log n_H = -2.40$ (or $\log \Gamma = -2.35$), implying $S_{\parallel} \sim 0.6$ 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. Fig. 7 shows the corresponding section of the HST spectra of the A and B images with tickmarks above the spectrum indicating the O\textsc{vi} $\lambda\lambda 1031, 1037$ doublet at $z = 1.66253$ and the C\textsc{ii} $\lambda 1036$ lines associated with the damped Ly$\alpha$ and Lyman-limit systems; tickmarks below the flux level indicate lines identified with other systems. The O\textsc{vi} $\lambda 1031$ lines at $\lambda = 2747$ Å have similar rest equivalent widths of $W_r = 0.93 \pm 0.07$ (Å) and $0.86 \pm 0.10$ Å. 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. Voigt profiles convolved with a $b_{\text{INST}} \simeq 130$ km s$^{-1}$ Gaussian have been overplotted in the spectra of A and B. They have Doppler parameters $b = 180$ (Å) and $110$ km s$^{-1}$ (obtained from Gaussian profiles fits to the O\textsc{vi} $\lambda 1031$ lines) and common column density $\log N = 14.95$. $N$ shows little variation with $b$ within $110$–$180$ km 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 line in spectrum A (B) shows the resulting profiles of 3 (2) O\textsc{vi} lines with common $b = 50$ km s$^{-1}$ and total column density $\log N = 15.1$ (15.0) at redshifts corresponding to systems 1, 2 and 3 (4 and 5) of 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

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6It seems very unlikely that the absorption feature at $\lambda \sim 2747$ Å is entirely due to a Ly$\alpha$ forest interloper. In such a case, two Ly$\alpha$ lines with $N(\text{H}I) \sim 10^{16}$ cm$^{-2}$ ($b = 30$ km s$^{-1}$) would be required to reproduce the absorption profiles; however, no associated $C\text{\textsc{iv}}$ is found, as it would be expected in this class of Ly$\alpha$ clouds.
confirms the prediction by Rauch et al. (1997a) based on simulations of PGCs. In this model, PGCs with a few times $10^9 \, M_\odot$ (in baryons) are embedded in a filamentary, low density and largely featureless O\textsc{vi} phase with spatial extent of up to several hundred kpc at the $N$(O\textsc{vi}) = $10^{13}$ cm$^{-2}$ column density contour (cf. 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 $n_H \sim 0.01$ cm$^{-3}$ derived for the C\textsc{iv}+Mg\textsc{ii} clouds, the fraction of ionizing photons with the $E > 114$ 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 data, we made the following, simplifying assumptions: (1) both LOSs pass through a common phase giving rise to the O\textsc{vi} $\lambda\lambda 1032, 1036$ doublet absorption lines, 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, suggested by the line profile symmetry (this assumption may not be valid, but it is equivalent to integrating $N$(O\textsc{vi}) over several line components). A 3$\sigma$ upper limit of $W_{\text{rest}} = 0.034$ Å for the N\textsc{v} $\lambda 1238.8210$ line (the stronger line of the N\textsc{v} doublet) measured in the AAT spectrum of A leads to a 3$\sigma$ upper limit of $\log N$(N\textsc{v}) < 13.2. The non-detection of N\textsc{v} places the stringent (but otherwise very conservative) lower limit of $N$(O\textsc{vi})/$N$(N\textsc{v}) > 60. This ratio requires densities lower than $\log n_H = -3.55$, or a large ionization parameter $\log \Gamma \geq -1.2$, 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\textsc{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 nontrivial 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 $N$(O\textsc{vi}) and $N$(N\textsc{v}) uniquely, but both $N$(H) and the gas metallicity Z will determine them. This is shown in Fig. 9, where we have plotted all the pairs (Z,$N$(H)) that reproduce $\log N$(O\textsc{vi}) = 15.0 and $\log N$(N\textsc{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 $Z < 0.63Z_{\text{DLA}}$, 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 one to two orders of magnitude larger than the systems giving rise to Mg\textsc{ii} absorption. These cloud sizes ($S_\parallel \sim 100$ kpc), if representative of transverse dimensions, are widely consistent with the
detection of OVI of similar strength in both LOSs. Typical masses derived from these models are \( \sim 10^9 \) M\(_{\odot}\).

To see if CIV 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 \( \log N(\text{OVI}) = 15.0 \), i.e., curves departing from points on the \( Z \) vs. \( N(\text{H}) \) curve in Fig. 9. The predicted \( N(\text{CIV}) \) column densities in such models are shown in Fig. 10 for the Haardt&Madau (solid line) and power-law radiation field (dashed line). At the minimum value of \( \Gamma \) allowed by the observations \( \log \Gamma = -1.2 \), and for a wide range of gas metallicities, CLOUDY predicts \( \log N(\text{CIV}) \approx 14.4 \), in agreement with the observed value; however, at higher ionization parameters like \( N(\text{OVI})/N(\text{NV}) \approx 90 \) or \( \log \Gamma = -1.0 \) (corresponding to a 2\( \sigma \) significant non-detection of \( \text{NVI} \)), \( N(\text{CIV}) \) becomes \( \sim 40\% \) lower, independently of \( Z \). This result in turn indicates that at least part of the observed CIV 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 CIV is likely to occur in both phases.

Collisional ionization of gas in thermal equilibrium can also reproduce the observed \( N(\text{OVI})/N(\text{NV}) \) ratio at \( T = 10^{5.45} \) K if one assumes solar relative abundances (Sutherland & Dopita 1993); so we cannot rule out this process as responsible for ionizing OVI into OVI. In such a case, the line broadening would be mostly due to macro-turbulence. Collisionally ionized OVI gas in a Lyman-limit system at \( z \simeq 3.4 \) has been recently proposed by Kirkman & Tytler (1997), who detect both CIV and OVI at the same redshift in high resolution data. These authors favor collisional ionization due to the high kinetic temperatures implied by the line widths of both ions. In the case of HE 1104–1805 AB, additional, higher resolution \((R \sim 23000)\) UV spectra are needed, in order to finally discern between collisional and photoionization as the dominant ionization mechanism in the OVI-phase.

7. Conclusions and Final Remarks

We outline our conclusions as follows:

1. The damped Ly\( \alpha \) system observed at \( z = 1.66162 \) in the ultraviolet and optical spectra of HE 1104–1805 A has a neutral hydrogen column density of \( \log N(\text{HI}) = 20.85 \pm 0.01 \). The 6.6 km s\(^{-1}\) resolution line profiles show that this high-density gas is distributed in four clouds spanning \( \sim 80 \) km s\(^{-1}\). Since the low ionization and AlIII 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 CIV line profiles show that at least some of CIV absorption occurs in clouds with no singly ionized species. We find a metallicity of \( Z_{\text{DLA}} \simeq 1/10 \) \( Z_{\odot} \) and a dust-to-gas ratio of \( \sim 0.11 \), based on \( [\text{Zn/H}] = -1.02 \) and \( [\text{Cr/H}] = -1.46 \). Other element abundances
are: \([C/H]=-0.91, [N/H]=-1.86, [O/H]=-0.98, [Mg/H]=-0.97, [Al/H]=-0.77, [Si/H]=-1.02, [Ti/H]=-1.50, [Mn/H]=-1.61, [Fe/H]=-1.59\) and \([Ni/H]=-1.68\). These abundance pattern has a nucleosynthetic origin given the large \(O/N\) ratio, but we find evidence for the presence of dust given (a) the underabundance of \(Cr\) and \(Ti\) relative to \(Zn\); and (b) the variation of the abundance ratios of these and other refractory elements among different clouds associated with the damped \(Ly\alpha\) system.

2. Photoionization by the metagalactic radiation field proposed by Haardt & Madau (1996) implies that the Lyman-limit System 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 to 1.6 kpc) and relatively dense \((n_H=0.01 \text{ cm}^{-3})\) clouds where both \(C\ IV\) and \(Mg\ II\) absorption occurs.

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 to the high-density gas (within a transverse separation of \(\sim 8\ h_{50}^{-1}\) kpc), suggesting regions of different star-formation rates, or a metal enrichment through gas outflows yet 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 non-detection of \(N\ V\) implies large (\(\sim 100–200\) kpc), low-density (\(\sim 10^{-4}\ \text{ cm}^{-3}\)) 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 damped \(Ly\alpha\) and Lyman-limit systems. Such an extended low-density \(O\ VI\) phase confirms the predictions of simulations of protogalactic clumps (Rauch et al. 1997a).

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 disk-like 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 et al. 1998); hydrodynamic simulations of merging protogalactic clumps are capable of explaining the large velocity spans seen in these class of absorption systems (Haehnelt et al. 1998). Here we have demonstrated the powerful tool with which 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\textsc{iv} clouds surrounded by extended O\textsc{vi} gas suggested by our observations can indeed be theoretically understood and is in good agreement with the predictions of a cold-dark-matter based model (Rauch et al.1997a). Furthermore, in a hierarchical structure formation scenario damped Ly\textalpha and Lyman limit systems 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\textsc{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\textsc{ii}, implying gas inhomogeneities on spatial scales similar to the separation between LOSs, and in concordance with Mg\textsc{ii} arising in smaller regions than C\textsc{iv} and O\textsc{vi}.

S. L. thanks the BMBF (DARA) for support under grant No. 50OR96016; M. R. thanks NASA for support through grant HF-0107501-94A from the Space Telescope Science Institute; W. L. W. S. was supported by grant AST 9529073 from the National Science Foundation. A. S. thanks the financial support under grant no. 781-73-058 from the Netherlands Foundation for Research in Astronomy (ASTRON), which receives its funds from the Netherlands Organisation for Scientific Research (NWO).
Table 1. Journal of Observations.

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$^b$ Maximum signal-to-noise ratio per pixel.

$^c$ Reference: Paper I
Table 2. Lyman-edges in HE 1104-1805 A and B.

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$^a$Optical depth $\tau = \ln(f_+/f_-)$, where $f_+$ is the extrapolated continuum redward of $912 \times (1 + z_{\text{LLS}})$, and $f_-$ the absorbed continuum.

$^b$Column density constrained by the damped Ly$\alpha$ wings.
Table 3. Line Parameters for $z_{\text{abs}} = 1.66$ Absorption Systems toward HE 1104–1805 A.

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$^a$Rest frame equivalent widths. For blends, the total equivalent width is given. Upper limits (3σ) represent non-detections.

$^b$σ$_b$ = 0 indicates fixed $b$ parameter

$^c$(1) Keck; (2) NTT; (3) AAT; (4) HST
Table 4. Ionic Column Densities (cm$^{-2}$) and Gas-Phase Abundances in the $z_{\text{abs}} = 1.66162$ DLA toward HE 1104–1805 A.

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*a*Relative to solar element abundances compiled by Verner et al. 1994.
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$^a$Rest frame equivalent widths. For blends, the total equivalent width is given. Upper limits (3σ) represent non-detections.

$^b\sigma_b = 0$ indicates fixed $b$ parameter

$^c$ (1) Keck; (2) NTT; (3) AAT; (4) HST
Table 6. Ionic Column Densities (cm$^{-2}$) in the LLS at $z_{\text{abs}} = 1.66184$ toward HE 1104–1805 B in Comparison to Results from Photoionization Models.

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<th>$\sigma_{\log N}$</th>
<th>MODEL 1\textsuperscript{a}</th>
<th>MODEL 2\textsuperscript{b}</th>
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<td>H$^+$</td>
<td>17.57</td>
<td>0.10</td>
<td>17.57</td>
<td>0.10</td>
<td>17.57</td>
<td>17.57</td>
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<td></td>
</tr>
<tr>
<td>H$^+$</td>
<td></td>
<td>19.89</td>
<td>19.82</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>C$^+$</td>
<td>14.50</td>
<td>0.20</td>
<td>14.50</td>
<td>0.20</td>
<td>15.50</td>
<td>0.20</td>
<td>14.47</td>
<td>14.75</td>
</tr>
<tr>
<td>C$^{++}$</td>
<td>14.41</td>
<td>0.05</td>
<td>14.40</td>
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<td>13.89</td>
<td>0.06</td>
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<td>13.99</td>
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<tr>
<td>N$^+$</td>
<td>&lt;14.00</td>
<td></td>
<td>&lt;14.00</td>
<td></td>
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<td></td>
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<td>10.97</td>
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<tr>
<td>N$^{++}$</td>
<td>&lt;13.70</td>
<td></td>
<td>&lt;13.70</td>
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<tr>
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<td>13.79</td>
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<td>N$^{+++}$</td>
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<tr>
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<td>&lt;14.10</td>
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<td>&lt;14.10</td>
<td></td>
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<td>&lt;11.90</td>
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<td>11.68</td>
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<td>Mg$^{++}$</td>
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<td>13.28</td>
<td>0.09</td>
<td>13.23</td>
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<td>Al$^+$</td>
<td>&lt;12.60</td>
<td></td>
<td>&lt;12.60</td>
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<tr>
<td>Al$^{++}$</td>
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<td>12.44</td>
<td>0.03</td>
<td>12.98</td>
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</tr>
<tr>
<td>Si$^{++}$</td>
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<td>0.05</td>
<td>12.39</td>
<td>0.03</td>
<td>12.60</td>
<td></td>
<td>12.86</td>
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<tr>
<td>Si$^{+++}$</td>
<td>&lt;13.20</td>
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<td>&lt;13.20</td>
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<td>10.29</td>
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<tr>
<td>Si$^{+++}$</td>
<td>13.52</td>
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<td>0.05</td>
<td>13.50</td>
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<td>13.47</td>
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<td>Fe$^{++}$</td>
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<td>0.12</td>
<td>12.47</td>
<td>0.08</td>
<td>11.45</td>
<td>11.08</td>
</tr>
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</table>

\textsuperscript{a}MODEL 1: Haardt&Madau, $\log \Gamma = -2.95$, $\log n_{\text{H}} = -1.8$, $Z = 0.63 Z_{\text{DLA}}$, $S = 1.6 \text{kpc}$.

\textsuperscript{b}MODEL 2: Power Law $\alpha = -2.0$, $\log \Gamma = -3.02$, $\log n_{\text{H}} = -1.91$, $Z = 0.79 Z_{\text{DLA}}$, $S = 1.8 \text{kpc}$.

\textsuperscript{c}Sum of fit components 2 and 3.
Table 7. Ionic Column Densities (cm$^{-2}$) in the C iv Systems at $z_{abs} = 1.66280$ toward HE 1104-1805 A and Photoionization Models.

<table>
<thead>
<tr>
<th>Species</th>
<th>$\log N_{\text{fit}}(X_i)$</th>
<th>$\sigma_{\log N}$</th>
<th>$\log N_{\text{app}}(X_i)$</th>
<th>$\sigma_{\log N}$</th>
<th>$\log N_{\text{ad}}(X_i)$</th>
<th>$\sigma_{\log N}$</th>
<th>MODEL</th>
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</thead>
<tbody>
<tr>
<td>H i</td>
<td>16.59</td>
<td>0.07</td>
<td>⋯</td>
<td>⋯</td>
<td>16.05</td>
<td>0.07</td>
<td>16.05</td>
</tr>
<tr>
<td>H ii</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>18.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C iii</td>
<td>13.15</td>
<td>0.20</td>
<td>⋯</td>
<td>⋯</td>
<td>13.15</td>
<td>0.20</td>
<td>14.42</td>
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<tr>
<td>C iv</td>
<td>13.87</td>
<td>0.10</td>
<td>13.85</td>
<td>0.01</td>
<td>13.87</td>
<td>0.10</td>
<td>13.84</td>
</tr>
<tr>
<td>N iii</td>
<td>&lt;13.00</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>&lt;13.00</td>
<td></td>
<td>12.97</td>
</tr>
<tr>
<td>Mg ii</td>
<td>&lt;11.80</td>
<td>⋯</td>
<td>⋯</td>
<td>⋯</td>
<td>&lt;11.80</td>
<td></td>
<td>11.76</td>
</tr>
<tr>
<td>Si iv</td>
<td>⋯</td>
<td>&lt;12.58</td>
<td>⋯</td>
<td>⋯</td>
<td>&lt;12.58</td>
<td></td>
<td>12.88</td>
</tr>
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</table>

aMODEL: Haardt&Madau, $\log \Gamma = -2.45$, $\log n_H = -2.30$, $Z = Z_{DLA}$, $S = 0.5$ kpc.

b$N$(H i) distributed according to the $N$(Mg ii) ratios
Table 8. Ionic Column Densities (cm$^{-2}$) in the C$^\text{iv}$ Systems at $z_{\text{abs}} = 1.66465$ toward HE 1104–1805 A and Photoionization Models.

<table>
<thead>
<tr>
<th>Species</th>
<th>log $N_{\text{fit}} (X_i)$</th>
<th>$\sigma_{\log N}$</th>
<th>log $N_{\text{app}} (X_i)$</th>
<th>$\sigma_{\log N}$</th>
<th>log $N_{\text{ad}} (X_i)$</th>
<th>$\sigma_{\log N}$</th>
<th>MODEL $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$^\text{i}$</td>
<td>16.59</td>
<td>0.07</td>
<td>...</td>
<td>...</td>
<td>16.44$^b$</td>
<td>0.07</td>
<td>16.44</td>
</tr>
<tr>
<td>H$^\text{ii}$</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>19.22</td>
</tr>
<tr>
<td>C$^\text{iii}$</td>
<td>15.42</td>
<td>0.20</td>
<td>...</td>
<td>...</td>
<td>15.42</td>
<td>0.20</td>
<td>14.74</td>
</tr>
<tr>
<td>C$^\text{iv}$</td>
<td>14.04</td>
<td>0.03</td>
<td>14.03</td>
<td>0.01</td>
<td>14.04</td>
<td>0.03</td>
<td>14.06</td>
</tr>
<tr>
<td>N$^\text{iii}$</td>
<td>&lt;13.20</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>&lt;13.20</td>
<td>...</td>
<td>13.29</td>
</tr>
<tr>
<td>Mg$^\text{ii}$</td>
<td>12.19</td>
<td>0.03</td>
<td>...</td>
<td>...</td>
<td>12.19</td>
<td>0.03</td>
<td>12.20</td>
</tr>
<tr>
<td>Si$^\text{iii}$</td>
<td>13.70</td>
<td>0.20</td>
<td>...</td>
<td>...</td>
<td>13.70</td>
<td>0.20</td>
<td>13.42</td>
</tr>
<tr>
<td>Si$^\text{iv}$</td>
<td>...</td>
<td>...</td>
<td>13.11</td>
<td>0.07</td>
<td>&lt;13.11</td>
<td>0.07</td>
<td>13.19</td>
</tr>
</tbody>
</table>

$^a$MODEL: Haardt&Madau, log $\Gamma = -2.54$, log $n_H = -2.21$, $Z = Z_{\text{DLA}}$, $S = 0.9$ kpc.

$^b$N(H$^\text{i}$) distributed according to the $N$(Mg$^\text{ii}$ ratios)
Table 9. Ionic Column Densities (cm$^{-2}$) in the C$\text{iv}$ Systems at $z_{\text{abs}} = 1.66493$ toward HE 1104–1805 B and Photoionization Models.

<table>
<thead>
<tr>
<th>Species</th>
<th>log $N_{\text{H}}(X_i)$</th>
<th>$\sigma_{\log N}$</th>
<th>log $N_{\text{app}}(X_i)$</th>
<th>$\sigma_{\log N}$</th>
<th>log $N_{\text{tot}}(X_i)$</th>
<th>$\sigma_{\log N}$</th>
<th>MODEL $^a$</th>
</tr>
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<tbody>
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<td>H I</td>
<td>15.90</td>
<td>···</td>
<td>···</td>
<td>···</td>
<td>15.90</td>
<td>···</td>
<td>15.90</td>
</tr>
<tr>
<td>H II</td>
<td>···</td>
<td>···</td>
<td>···</td>
<td>···</td>
<td>···</td>
<td>···</td>
<td>18.90</td>
</tr>
<tr>
<td>C III</td>
<td>&lt;12.90</td>
<td>···</td>
<td>···</td>
<td>···</td>
<td>&lt;12.90</td>
<td>···</td>
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<td>C IV</td>
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<td>0.02</td>
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<td>0.03</td>
<td>13.67</td>
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<td>···</td>
<td>···</td>
<td>···</td>
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<td>···</td>
<td>12.71</td>
</tr>
<tr>
<td>Mg II</td>
<td>&lt;12.40</td>
<td>···</td>
<td>···</td>
<td>···</td>
<td>&lt;12.40</td>
<td>···</td>
<td>11.33</td>
</tr>
<tr>
<td>Si IV</td>
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<td>···</td>
<td>&lt;12.86</td>
<td>···</td>
<td>&lt;12.86</td>
<td>12.58</td>
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</table>

$^a$MODEL: Haardt&Madau, log $\Gamma = -2.35$, log $n_\text{H} = -2.40$, $Z = 0.63 Z_{\text{DLA}}$, $S = 0.6$ kpc.
REFERENCES

Ferland, G. J. 1993, University of Kentucky, Physics Department Internal Report
Fontana, A. & Ballester, P. 1995, *ESO Messenger* 80, 37


This preprint was prepared with the AAS \LaTeX\ macros v4.0.
Fig. 1.— *HST* 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 level, smoothed and rebinned to the *HST* FOS resolution, and plotted for λ ≥ 3277 Å. Metal absorption lines lying longward of Lyα 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. Possible emission by S vii, Lyβ and O vi is indicated.

Fig. 2.— Sections of the normalized *HST* FOS (FWHM ∼ 2 Å) and AAT (FWHM ∼ 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 damped Lyα system (A) and Lyman-limit System (B) at z = 1.66. Tickmarks (from upper panel to right-lower panel) indicate the positions of H i λλ918 to 949, C ii λλ1036, 1334, N ii λ1083 and O i λλ988, 1302.

Fig. 3.— Low ions: Velocity profiles at 6.6 and 40 km s$^{-1}$ (Mg ii) resolution of lines associated with the damped Lyα system (left hand panel) toward HE 1104–1805 A, and the Lyman-limit System toward HE 1104–1805 B. The zero velocity scale in both panels corresponds to z = 1.66164. The smoothed lines represent the best-fit Voigt profiles and ticks mark the line positions. Fits to the Fe ii lines in B were made using lines observed in the *NTT* spectra (cf. Table 5).

Fig. 4.— Velocity profiles at 6.6 km s$^{-1}$ resolution of Cr ii, Zn ii and Ti ii lines associated with the damped Lyα system (left hand panel) toward HE 1104–1805 A. The zero velocity scale in both panels corresponds to z = 1.66164. The smoothed lines represent the best-fit Voigt profiles and ticks mark the line positions.

Fig. 5.— High ions: Velocity profiles at 6.6 km s$^{-1}$ resolution of lines associated with the damped Lyα system (left hand panel) toward HE 1104–1805 A, and the Lyman-limit System toward HE 1104–1805 B. The Al ii λ1670 velocity profiles are also shown for comparison purposes (see text). The zero velocity scale in both panels corresponds to z = 1.66164. The smoothed lines represent the best-fit Voigt profiles and ticks mark the line positions. The absorption feature at v ∼ +110 km s$^{-1}$ in the C iv λ1548 B plot is identified with Si ii λ1808 at z = 1.28.

Fig. 6.— Bottom: Velocity profiles of the C iv λλ1548,1550 (at 6.6 km s$^{-1}$ resolution) and Mg ii λλ2796,2803 (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, the redshift of Mg ii in the DLA system. In the Mg ii λ2796 plot, the feature at −100 km s$^{-1}$ is identified with Mn i λ2795. Top: *HST* velocity profiles of the corresponding Lyo, Lyβ and Lyγ H i lines (Note the different velocity scales).

Fig. 7.— Section of the *HST* spectra A and B showing the O vi λλ1031,1037 doublet at z = 1.66253. Solid lines: Voigt profiles – convolved with a bINST ≃ 130 km s$^{-1}$ Gaussian – with b = 180 (A) and 110 km s$^{-1}$, and column density log N = 14.95. Dotted line: Voigt profiles of 3 (2) O vi lines with common b = 50 km s$^{-1}$ and total column density log N = 15.1(15.0) at redshifts 1, 2 and 3 (4 and 5) of Fig. 6.
Fig. 8.— Section of the AAT spectra A and B. Tickmarks show the positions at which the \( \text{N\textsc{v}} \) \( \lambda \lambda 1238, 1242 \) doublet lines would appear if \( \text{N\textsc{v}} \) were present at \( z = 1.66253 \). Part of the red wing of the damped Ly\( \alpha \) line appears in the overplotted synthetic spectrum A. In B, the absorption at \( \lambda = 3308 \) Å is identified with a Ly\( \alpha \) line, supported by the detection of Ly\( \beta \) at the same redshift in the \textit{HST} spectrum.

Fig. 9.— Hydrogen column density vs. metallicity in the O\textsc{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 \( \log N(\text{O\textsc{vi}}) = 15.0 \) and \( \log N(\text{N\textsc{v}}) = 13.2 \).

Fig. 10.— Column densities vs. ionization parameter \( \Gamma \) in the O\textsc{vi}-phase for different CLOUDY models assuming the Haardt\&Madau radiation field with \( Z = Z_{\text{DLA}} \) (solid line) and \( Z = 0.4 Z_{\text{DLA}} \) (dotted line), and a power law as ionizing background. The relative abundances are the same as in the DLA gas. These models yield throughout \( \log N(\text{O\textsc{vi}}) = 15.0 \).
H&M, \( \log \Gamma = -1.2 \)

\( f \propto \mu^{-2}, \ \log \Gamma = -0.9 \)

\( \log N(\text{OVI}) = 15.0 \)

\( \log N(\text{NV}) = 13.2 \)