METAL ABUNDANCES AND KINEMATICS OF QUASAR ABSORBERS. II.
ABSORPTION SYSTEMS TOWARD Q0347–3819 AND APM BR J0307–4945

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ABSTRACT

Detailed Monte Carlo inversion analysis of the spectral lines from three Lyman limit systems (LLSs) [N(H i)] ≳ 1.0 × 1017 cm−2 and nine lower N(H i) systems [2 × 1014 cm−2 ≳ N(H i) ≳ 2 × 1016 cm−2] observed in the Very Large Telescope/UV-Visual Echelle Spectrograph spectra of Q0347–3819 (in the range 2.21 ≤ z ≤ 3.14) and of APM BR J0307–4945 (at z = 4.21 and 4.81) is presented. Combined with the results from a previous work, the analyzed LLSs show that they are a heterogeneous population originating in different environments. A functional dependence of the line-of-sight velocity dispersion σvir on the absorber size L is confirmed: the majority of the analyzed systems follow the scaling relation σvir ∝ (NH/L)0.3 (with NH being the total gas column density). This means that most absorbers may be related to virialized systems such as galaxies or their halos. Previously noted enhancement of the metal content in small-size systems is also confirmed: metallicities of Z ∝ (L−0.5) Z⊙ are found in systems with L ≲ 0.4 kpc, whereas we observe much lower metal abundances in systems with larger linear sizes. For the first time in LLSs, a pronounced α-element/iron peak enrichment is revealed: the absorber at zabs = 2.21 shows [O/Fe] = 0.65 ± 0.11, [Si/Fe] = 0.51 ± 0.11, and [Mg/Fe] = 0.38 ± 0.11. Several absorption systems exhibit characteristics that are very similar to those observed in high-velocity clouds (HVCs) in the Milky Way and may be considered as high-redshift counterparts of Galactic HVCs.

Subject headings: cosmology: observations — line: identification — quasars: absorption lines — quasars: individual (Q0347–3819, APM BR J0307–4945)

1. INTRODUCTION

With the present paper we continue to study the chemical composition and the kinematic characteristics of quasar absorption systems using a new computational procedure, the Monte Carlo inversion algorithm (MCI), developed earlier in a series of papers (see Levshakov, Agafonova, & Kegel 2000, hereafter LAK00). The MCI technique allows us to recover self-consistently the physical parameters of the intervening gas cloud (such as the average gas number density n0, the column densities for different species Nα, the kinetic temperature Tkabs, the metal abundances Zα, and the linear size L), the statistical characteristics of the underlying hydrodynamical fields (such as the line-of-sight velocity dispersion σv, and the density dispersion σρ, and the line-of-sight density nH(x) and velocity v(x) distributions (here x is the dimensionless coordinate in units of L)). Having this comprehensive information, we are able to classify the absorbers more reliably and hence to obtain important clues concerning the physical conditions in intervening galaxies, galactic halos, and large-scale structure objects at high redshifts. It will also be possible to constrain the existing theories of the origin of galaxy formation, since the observed statistics of the damped Lyα systems (DLAs) and Lyman limit systems (LLSs) is believed to be a strong test of different cosmological models (e.g., Gardner et al. 2001; Prochaska & Wolfe 2001).

In the first part of our study (Levshakov et al. 2002a, hereafter Paper I) we reported results on the absorption systems at zabs = 1.87, 1.92, and 1.94 toward the Hubble Deep Field–South quasar J2233–606. These systems exhibit many metal lines with quite complex structures. It was found that all profiles can be well described with an assumption of a homogeneous metallicity and a unique photoionizing background. According to the estimated sizes, velocity dispersions, and metal contents, the absorbers at zabs = 1.92 and 1.87 were related to the galactic halos, whereas the system at zabs = 1.94 was formed, more likely, in an irregular star-forming galaxy. It was also found that the linear size and the line-of-sight velocity dispersion for all three absorbers obey a scaling relation of the same kind that can be expected for virialized systems.

The present paper deals with absorbers observed in the spectra of Q0347–3819 (zem = 3.23) and APM BR J0307–4945 (zem = 4.75; see § 2.1). Both spectra include several dozens of systems containing metals, but most of them are weak and severely blended and hence do not allow us to estimate the underlying physical parameters with a reasonable accuracy. After preliminary analysis only 12 systems were chosen for the inversion with the MCI, and their properties are described below.

The structure of the paper is as follows. Section 2 describes the data sets. In § 3 our model assumptions and basic equations are specified. The estimated parameters for individual systems are given in § 4. The implication of the
obtained results for the theories of LLS origin are discussed in § 5, and our conclusions are reported in § 6. The Appendix contains a table with typical parameters of different absorbers that are referred to in the present study.

2. OBSERVATIONS

The spectroscopic observations of Q0347−3819 and APM BR J0307−4945 obtained with the UV-Visual Echelle Spectrograph (UVES; D’Odorico et al. 2000) on the Very Large Telescope (VLT)/Kueyen 8.2 m telescope are described in detail by D’Odorico, Dessauges-Zavadsky, & Molaro (2001) and by Dessauges-Zavadsky et al. (2001), respectively. Both spectra were observed with the spectral resolution FWHM ≈ 7 km s⁻¹. For the analysis of metal systems from the Q0347−3819 spectrum with lines in the range 4880–6730 Å, which was not covered by the VLT observations, we used a portion of the Q0347−3819 spectrum obtained with the High-Resolution Echelle Spectrograph (HIRES; Vogt et al. 1994) on the 10 m W. M. Keck I telescope (Prochaska & Wolfe 1999). The spectral resolution in this case was about 8 km s⁻¹. The VLT/UVES data are now available for public use in the VLT data archive.

The majority of the metal systems in the spectrum of Q0347−3819 were identified in Levshakov et al. (2002b), whereas the zabs = 4.21 system toward APM BR J0307−4945 was distinguished by Dessauges-Zavadsky et al. (2001)⁷ as consisting of two subsystems: one at zabs = 4.211 and the other at zabs = 4.218. A new system at zabs = 4.81 is analyzed here for the first time.

2.1. Emission Redshift of APM BR J0307−4945

The emission redshift of this distant quasar (z_em = 4.728 ± 0.015) was previously measured by Péroux et al. (2001) from the Si iv + O iv] λ1400.0 and C iv λ1549.1 lines observed in the ~5 A resolution spectrum obtained with the 4 m Cerro Tololo Inter-American Observatory telescope.

In our VLT/UVES spectrum of this quasar a few additional lines can be identified that are useful for the redshift measurements. One of the most important is the weak O i λ1304 line. From earlier studies (see, e.g., Tytler & Fan 1992 and references therein) it is known that “low-ionization lines” such as O i λ1304 are systematically redshifted and narrower than “high-ionization” lines such as C iv, Si iv, and Lyα.

In Figure 1 we compare the O i profile with those of C iv and of a wide blend of the Lyα + N v + Si ii lines. All these lines are shown in the same velocity scale, which is defined by the O i λ1304 center corresponding to z_em = 4.7525. This O i line is redshifted with respect to the z_em value deduced by Péroux et al. from the measurements of the Si iv + O iv] and C iv lines. Because the Lyα emission line is blended with other emission lines and its blue wing is distorted by numerous narrow absorption lines, profile comparison cannot be very accurate in this case. Nevertheless, we found a smooth fit to the C iv λ1549 profile (which is unblended and shows significant asymmetry) and used this synthetic profile for comparison with other lines (altering the amplitude of the synthetic profile to match the line profile while keeping its center unchanged).

Figure 1 shows that this simplified procedure indeed allows us to achieve a fairly good concordance between the C iv line and the Lyα + N v + Si ii blend. This could indicate that the redshift of the quasar is higher than that measured by Péroux et al., being actually z_em ≈ 4.753.

3. MODEL ASSUMPTIONS AND THE MCI PROCEDURE

The complete description of the MCI code is given in LAK00 and its most updated version—in Paper I. Since this technique is relatively new, we briefly outline it here and stress its difference from the Voigt profile-fitting (VPF) procedure commonly used for QSO absorption line analysis.

The VPF deconvolution is based on the assumption that the observed complex line profiles are caused by several separate clouds randomly distributed along the line of sight. In every cloud, gas is characterized by the constant density and normally distributed velocities (the h-parameter usually estimated in the VPF procedure just stands for the dispersion of the velocity distribution). Because of the constant gas density, the ionizing structure inside the cloud is described by a single ionization parameter U, which can be estimated from the measured column densities of lines of different ions with the help of some photoionization code if the spectrum of the background ionizing radiation is given.

However, numerous cosmological hydrodynamical calculations performed in the previous decade have shown that the QSO absorption line profiles arise more likely in the smoothly fluctuating intergalactic medium (IGM) in a network of sheets, filaments, and halos (e.g., Cen et al. 1994; Miralda-Escude et al. 1996; Theuns et al. 1998). This model finds its support also in modern high-resolution spectroscopic observations: the increasing spectral resolution reveals progressively more and more complex profiles. A very important characteristic of the continuous absorbing medium is that the contribution to any point within the line profile comes not only from a single separate area (a “cloud”) but from all volume elements (“clouds”) distributed along the sight line within the absorbing region and having the same radial velocity (see, for details, § 2.2 in LAK00).

If the absorption systems are indeed formed in the fluctuating IGM, then the above-described VPF procedure that interprets each absorption feature in the line profile as caused by one distinguished cloud is not, in general, physically justified. In some systems, this approach can produce rather erratic results, such as extremely varying metallicities between subcomponents, negative kinetic temperatures, exotic UV background spectra, etc. (see examples in Levshakov, Takahara, & Agafonova 1999; LAK00; Paper I).

The MCI procedure is based on the assumption that all lines observed in a metal system arise in a continuous absorbing gas slab of thickness L with a fluctuating gas density and a random velocity field. We also assume that within the absorber the metal abundances are constant, the gas is optically thin for the ionizing UV radiation, and the gas is in thermal and ionization equilibrium. The last assumption means that the fractional ionizations of different ions are determined exclusively by the gas density and vary from point to point along the sight line. These fractional ionization variations are just the cause of the observed diversity of

⁷ Data are listed in Table 5, which is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5).
profile shapes between ions of low and high ionization stages.

Whereas most of the above-mentioned assumptions are quite natural, that of constant metallicity over the entire absorbing region needs additional discussion. On the one hand, it is required from a mathematical point of view. Namely, the splitting of the velocity and density fields is effective if all observed ions share the same velocity distribution but respond differently to the gas density. If in addition to varying the density and velocity one allows for varying the metallicity, the inverse problem becomes fully degenerate; i.e., it would have an infinitely large number of solutions. On the other hand, the constant metallicity has some observational support: results obtained in numerous studies of the Galactic halo chemical composition reveal no systematic differences in the gas-phase abundances within Galactocentric distances of 7–10 kpc in various directions (e.g., Savage & Sembach 1996). However, of course, we cannot exclude the case when the line of sight passes through many types of environments with different enrichment histories within a given absorber. If the metallicities within such an absorber differ only slightly (\( \lesssim 0.5 \) dex), the observed lines of different ions can be well fitted to the synthetic profiles calculated with some average value of the metal content. If, however, the differences in the metallicities are really large (\( \gtrsim 1 \) dex), the self-consistent fitting of all observed lines becomes impossible. In this case we have to split the absorber into separate regions having different metal abundances (see \( \S \S \) 4.2.2 and 4.3.1 for examples).

It is well known that the measured metallicities depend in a crucial way on the adopted background ionizing spectrum. We started in all cases with the Haardt-Madau (HM) background ionizing spectra (Haardt & Madau 1996), computing the fractional ionizations and the kinetic temperatures with the photoionization code CLOUDY (Ferland 1997). If the fitting with the HM spectrum was impossible,
we used another spectrum, e.g., the Mathews & Ferland (MF) spectrum (Mathews & Ferland 1987).

The MCI procedure itself is implemented in the following way. Within the absorbing region the radial velocity \(v(x)\) and the total hydrogen density \(N_{\text{H}}(x)\) along the line of sight are considered as two random fields that are represented by their sampled values at equally spaced intervals \(\Delta x\), i.e., by the vectors \(\{v_1, \ldots, v_k\}\) and \(\{n_1, \ldots, n_k\}\) with \(k\) large enough \((\sim 150–200)\) to describe the narrowest components of the complex spectral lines. The radial velocity is assumed to be normally distributed with the dispersion \(\sigma_v\), whereas the gas density is distributed lognormally with the mean \(n_0\) and the second central dimensionless moment \(\sigma_n (\nu = \langle n_{\text{H}} \rangle / n_0)\). Both stochastic fields are calculated using the Markovian processes (see LAK00 for mathematical basics). The model parameters estimated in the least-squares minimization of the objective function (see eqs. [29] and [30] in LAK00) include \(\sigma_v\) and \(\sigma_n\) along with the total hydrogen column density \(N_{\text{H}}\), the mean ionization parameter \(U_0\), and the metal abundances \(Z_a\) for a elements observed in a given absorption-line system.

The computations are carried out in two steps: first a point in the parameter space \((N_{\text{H}}, U_0, \sigma_v, \sigma_n, Z_a)\) is chosen at random, and then an optimal configuration of \(\{v_i\}\) and \(\{n_i\}\) for this parameter set is searched for. These steps are repeated until a minimum of the objective function \((\chi^2 \sim 1\) per degree of freedom) is achieved. To optimize the configurations of \(\{v_i\}\) and \(\{n_i\}\), the simulated annealing algorithm with Tsallis acceptance rule (Xiang et al. 1997) and an adaptive annealing temperature choice are used (details are given in Paper I).

The following important fact should be taken into account when one interprets the results obtained with the MCI technique. The mean ionization parameter \(U_0\) is related to the parameters of the gas cloud as (see eq. [28] in LAK00)

\[
U_0 = \frac{n_{\text{ph}}}{n_0}(1 + \sigma_n^2).
\]

Here \(n_{\text{ph}}\) is the number density of photons with energies above 1 ryd, which is determined by the intensity of the adopted background ionizing spectrum.

This equation shows that if the density field is fluctuating \((\sigma_n > 0)\), then with the same mean density \(n_0\) and the same background ionizing spectrum we obtain a higher value of \(U_0\) without any additional sources of ionization. Intermittent regions of low and high ionization caused by the density fluctuations will occur in this case along the sight line. On the other hand, for a given \(U_0\) the mean gas density \(n_0\) is also higher in the fluctuating media as compared to the completely homogeneous gas clouds \((\sigma_n = 0)\). Since the linear size of the absorber is \(L = N_{\text{H}}/n_0\), the sizes estimated with the assumption of a constant density \((\text{as, e.g., in the } \text{VPF})\) may be too large.

Another important question is whether the MCI solution is unique and accurate. In general, the inverse problems are highly nonlinear and ill posed, which implies multiple solutions and/or very broad uncertainty ranges for the recovered parameters. To produce a physically reasonable solution, one has to account for all available information related to the case under study. For instance, the more lines of different ionic transitions are included in the analysis, the more accurate result can be obtained since both low- and high-density regions are probed simultaneously. One may also compare the relative metal abundances predicted by nucleosynthetic theories with those provided by the MCI. An odd pattern may indicate a misleading solution. The recovered linear sizes must also be in agreement with the characteristic sizes of the absorbers stemming from observations of gravitationally lensed quasars and quasar pairs that show \(L \lesssim 100\) kpc.

One of the main problems in the analysis of the QSO high-redshift spectra is the line blending, which hampers significantly the inversion of the observed spectra. As compared to the VPF method, the MCI is much more robust dealing with blended lines because of the assumption that all ions trace the same underlying gas density and velocity distributions. This means that we are able to reconstruct both distributions using unblended parts of different lines. It is obvious that the accuracy of the recovered parameters improves with increasing number of lines and the variety of ions involved in the analysis. A priori we do not know which parts of the lines are blended and which are not. To clarify this, several test runs with different arrangements of lines are carried out until a self-consistent fit for the majority of lines observed in the spectrum is found.

4. RESULTS ON INDIVIDUAL METAL SYSTEMS

All results given below in Tables 1, 2, and 3 were obtained using the MCI procedure as described in Paper I. Given the shape and the intensity at 1 ryd of the background ionizing radiation, the errors of the fitting parameters \(U_0, N_{\text{H}}, \sigma_v, \sigma_n,\) and \(Z_a\) are about 15%–20% and the errors of the estimated column densities are less than 10%, whereas the derived parameters \(n_0\) and \(L\) are estimated with about 50% accuracy. These errors, however, should be considered as internal in the sense that they reflect merely the configuration of the parameter space in the vicinity of a minimum of the objective function. To what extent the recovered parameters may correspond to their real values is discussed separately for each individual absorbing system. We note in passing that the density \(n_0\) and by this the linear size \(L\) scales with the intensity of the radiation field (see eq. [1]).

The analyzed metal systems are described within three categories: (1) LLSs with \(N(\text{H} \ i) > 5 \times 10^{16} \) cm\(^{-2}\), (2) \(\text{Ly}_\alpha\) absorbers with \(N(\text{H} \ i) < 5 \times 10^{16} \) cm\(^{-2}\), and (3) \(\text{Ly}_\alpha\) systems with a probable metallicity gradient. Their physical properties are compared with different types of absorbers listed in the Appendix.

4.1. Lyman Limit Systems

4.1.1. \(Q0347–3819\), \(z_{\text{abs}} = 2.21\)

This system consists of a broad saturated \(\text{Ly}_\alpha\) hydrogen line spread over 500 km s\(^{-1}\) and of metal lines of low- and high-ionized species: \(\text{O} \ i \ \lambda 1302, \ C \ ii \ \lambda 1334, \ Mg \ ii \ \lambda 2796, 2803, \ Al \ ii \ \lambda 1670, \ Si \ ii \ \lambda 1275, 1193, \ Fe \ ii \ \lambda 1608, 2344, 2382, 2586, 2600, \ Al \ ii \ \lambda 1854, \ Si \ ii \ \lambda 1206,\) and \(\text{C} \ iv \) and \(\text{Si} \ iv\) doublets as well. The physical parameters obtained with the MCI are presented in Table 1, whereas the corresponding observed and synthetic spectra are shown in Figure 2. The recovered density and velocity distributions along the line of sight are plotted in Figure 3. The intermittent high- and low-density regions giving rise to, respectively, low- and high-ionization species (a multiphase medium) are clearly seen. This means that the lines of different ionization stages arise in different areas despite having
the same radial velocities [see, e.g., the regions with \(v\) \(\approx 140\) km s\(^{-1}\)] of the Ly\(\alpha\) profile and the C iv line from the system at \(z_{\text{abs}} = 2.8102\), which falls in the range \(-40\) km s\(^{-1}\) < \(\Delta v\) < \(140\) km s\(^{-1}\), has a little influence on the Ly\(\alpha\) column density.

The inferred H\(i\) column density of \(4.6 \times 10^{17}\) cm\(^{-2}\) classifies this system as a typical LLS [since \(N(\text{H}\,\text{i}) > 17\) cm\(^{-2}\)]. In principle, this value lies beyond the applicability limit of the MCI, which is formally valid for \(N(\text{H}\,\text{i}) < 1\) [if \(N(\text{H}\,\text{i}) = 4.6 \times 10^{17}\) cm\(^{-2}\), then \(T_{\text{kin}} < 1\)]. Besides, having only one saturated Ly\(\alpha\) line, we cannot in any case say for sure that the estimated value is the real hydrogen column density. However, there are also reasons that make the obtained solution quite plausible.

First, we consider an absorber as a clumpy region, which implies that the ionizing radiation may penetrate the cloud from different directions without being significantly altered (i.e., we assume that the density of the background ionizing radiation is not reduced much and its spectral distribution is not changed considerably in a gas cloud that is not a slab of a uniform density). Second, the observed mixture of the O i and Fe ii lines and the C iv and Si iv lines makes it possible to fix the mean ionization parameter \(U_0\) quite strictly because the fractional ionization curves for, e.g., O i and C iv are very different. Thus, the H\(i\) column density can hardly be less than the value estimated by the MCI since in that case the metallicity would be higher than solar. Besides, the same velocity interval covered by both the Ly\(\alpha\) and Si iii \(\lambda\lambda 1206\) lines suggests that we observe probably the real profile of the H\(i\) Ly\(\alpha\) (a blend with the Ly\(\beta\) line from the system at \(z_{\text{abs}} = 2.8102\), which falls in the range \(-40\) km s\(^{-1}\) < \(\Delta v\) < \(140\) km s\(^{-1}\), has a little influence on the Ly\(\alpha\) red wing; see Fig. 2). Higher values of \(N(\text{H}\,\text{i})\) cannot be excluded, but additional calculations have shown that the maximum of the H\(i\) column density is limited: both avail-

**TABLE 1**

| Parameter | Q0347—3819 | APM BR J0307—4945 |
|-----------|------------|-------------------|
| \(U_0\) (cm\(^{-2}\)) | 2.1E-3 | 7.5E-3 |
| \(N_\text{H}\) (cm\(^{-2}\)) | 2.2E19 | 4.2E19 |
| \(\sigma_v\) (km s\(^{-1}\)) | 80.8 | 80.0 |
| \(Z_C\) | 2.0E-4 | 1.3E-4 |
| \(Z_O\) | 4.4E-4 | <2.5E-5 |
| \(Z_{\text{Al}}\) | 1.5E-5 | <2.5E-6 |
| \(Z_{\text{Mg}}\) | 2.0E-5 | 1.1E-5 |
| \(Z_{\text{Si}}\) | 5.0E-6 | 1.5E-5 |
| \(N(\text{H}\,\text{i})\) (cm\(^{-2}\)) | 4.6E17 | 1.4E17 |
| \(N(\text{C}\,\text{i})\) (cm\(^{-2}\)) | 1.5E14 | 1.2E15 |
| \(N(\text{Si}\,\text{ii})\) (cm\(^{-2}\)) | 1.1E14 | 1.0E14 |
| \(N(\text{Fe}\,\text{ii})\) (cm\(^{-2}\)) | 2.3E14 | 4.8E13 |
| \(N(\text{C}\,\text{iii})\) (cm\(^{-2}\)) | 1.3E13 | 4.3E15 |
| \(N(\text{N}\,\text{ii})\) (cm\(^{-2}\)) | ... | <2.0E14 |
| \(N(\text{Al}\,\text{iii})\) (cm\(^{-2}\)) | ... | <2.0E14 |
| \(N(\text{Si}\,\text{iii})\) (cm\(^{-2}\)) | 2.0E14 | 2.6E14 |
| \(N(\text{Fe}\,\text{iii})\) (cm\(^{-2}\)) | 7.7E13 | 2.6E14 |
| \(n_\text{ii}\) (cm\(^{-3}\)) | 3.0E13 | 2.9E14 |
| \(T(\text{K})\) | 9.1E3 | 1.2E4 |
| \(T_{\text{max}}(\text{K})\) | 8.6E3 | 1.1E4 |
| \(L(\text{Kpc})\) | 0.38 | 30 |

**Note:** The internal errors of \(U_0\), \(N_\text{H}\), \(\sigma_v\), \(Z_C\), and \(Z_O\) are \(\approx 15\%\); the column density errors are \(\approx 10\%\), whereas \(n_\text{ii}\) and \(L\) are known with \(\approx 50\%\) accuracy; \(Z_X = N/\text{H}; Z_X = \log(Z_X) - \log(Z_X)\) (solar abundances are taken from Holweger 2001 except Al for which solar abundance from Grevesse & Sauval 1998 is used).
able wings of the Ly$\alpha$ line do not allow an increase in $N($H I$)$ by more than a factor of 3.

This uncertainty does not change, fortunately, the main characteristic of this system—we do observe at $z_{\text{abs}} = 2.21398$ a compact ($L < 1 \text{ kpc}$) metal-rich ($Z > 0.1 Z_{\odot}$) cloud. As seen from Figure 2, the synthetic profiles represent well all unblended spectral features (broad absorption features at the position of the C IV doublet are not consistent with each other, and hence they cannot be attributed to the real C IV profiles; the same is valid for the Si IV doublet). The measured relative abundances are discussed later in § 5.3. Here we note that a set of the identified species and their pattern as well as the estimated mass ($\sim 10^{4} \, M_{\odot}$) resemble parameters measured in so-called high- and intermediate-velocity clouds (HVCs, IVCs) in the Local Group (Wakker 2001). Although the nature of the HVCs and IVCs is still poorly understood, they are unlikely to be phenomena restricted to the Milky Way. The system at $z_{\text{abs}} = 2.21$ may be one of similar HVCs likely to be encountered in a high-redshift galactic halo. A more precise determination of its properties would require the higher Lyman series lines to be included in the analysis (these lines, however, can be observed with space telescopes only).

4.1.2. Q0347−3819, $z_{\text{abs}} = 2.81$

Here we identified three neutral hydrogen lines and several metal absorption lines of both low and high ionic transitions (see Fig. 4; the C IV doublet falls, unfortunately, in a wavelength coverage gap of the Keck spectrum). The estimated physical parameters are listed in Table 1, whereas the corresponding synthetic spectra are shown in Figure 4 by
the smooth curves. It should be noted, however, that the solution with the \( N(\text{HI}) = 5 \times 10^{16} \) cm\(^{-2}\) is not unique because all available hydrogen lines are saturated and partly blended in the red wings. We found also another solution with \( N(\text{HI}) = 10^{17} \) cm\(^{-2}\). The solution presented in Table 1 was chosen because it delivered a more or less consistent set of all parameters: the velocity dispersion \( \sigma_v \simeq 60 \) km s\(^{-1}\), the mean gas density \( n_0 \simeq 10^{-3} \) cm\(^{-3}\), the linear size \( L \simeq 30 \) kpc, and the metallicity \( Z \simeq 1/10 Z_\odot \). For comparison, the second solution with \( N(\text{HI}) = 10^{17} \) cm\(^{-2}\) gives the metallicity \( Z \simeq 1/20 Z_\odot \), the size \( L \simeq 70 \) kpc, and the same other parameters. According to both sets of the estimated parameters and the fact that rather strong low-ionization lines of C\( \text{ii} \) and Si\( \text{ii} \) are observed, the \( z_{\text{abs}} = 2.81 \) system could be related to an inner galactic halo.

4.1.3. APM BR J0307–4945, \( z_{\text{abs}} = 4.21 \)

In the available spectral range we identified hydrogen lines Ly\( \alpha \), Ly\( \beta \), and Ly\( \gamma \) as well as metal lines C\( \text{ii} \) \( \lambda 1334 \), Si\( \text{ii} \) \( \lambda 1526 \), C\( \text{iii} \) \( \lambda 977 \), N\( \text{iii} \) \( \lambda 989 \), Al\( \text{iii} \) \( \lambda 1854 \), Si\( \text{iii} \) \( \lambda 1206 \), and the C\( \text{iv} \) and Si\( \text{iv} \) doublets. From the metal line profiles, two main subsystems can be clearly distinguished: the first at \( v' \simeq 200 \) km s\(^{-1}\) and the second at \( v' \simeq 200 \) km s\(^{-1}\) (see Fig. 5). The analysis of the \( z_{\text{abs}} = 4.21 \) absorber was carried out in two steps: (1) the subsystem at \( v \simeq 200 \) km s\(^{-1}\) was treated separately (the results are listed in col. [4] in Table 1, and the corresponding synthetic spectra are shown by the solid lines in Fig. 5); (2) both systems were fitted together (col. [5] in Table 1; dotted lines in Fig. 5).

The recovered metallicities are high (about \( 1/3 Z_\odot \) at \( v \simeq 200 \) km s\(^{-1}\) and slightly higher at \( v \simeq -200 \) km s\(^{-1}\)), and their pattern is nearly solar. At low redshifts similar charac-

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**Fig. 3.**—Computed velocity (top) and gas density (bottom) distributions along the line of sight within the \( z_{\text{abs}} = 2.21 \) LLS toward Q0347–3819. Shown are patterns rearranged according to the principle of minimum entropy production rate (see Paper I).

**Fig. 4.**—Same as Fig. 2 but for the \( z_{\text{abs}} = 2.81 \) LLS. The zero radial velocity is fixed at \( v = 2.8102 \). The corresponding physical parameters are listed in Table 1. Here \( \chi^2_{\text{min}} = 1.38; \nu = 763 \).
teristics are measured, e.g., in high-metallicity blue compact
galaxies. At high redshifts, some radio galaxies are known
that show two spatially resolved emitting regions, slightly
subsolar metallicities, and sizes of about tens of kiloparsecs,
e.g., MRC 2104/C0242 at z = 2.49 (Overzier et al. 2001) or
TN J1338/C01942 at z = 4.11 (De Breuck et al. 1999). It is
also known that galaxies showing morphological evidence
of a merger have excessive velocity widths of their spectral
lines (e.g., Maller et al. 1999).

Thus, we conclude that the LLS under study probably
arises when the line of sight intersects two clumps that may
be merging. The observed range of the metal lines (from
\(N(C)\) to \(N(O)\)) and their very complex structures are
also in line with this picture.

Although the recovered values are self-consistent, we can-
not guarantee their uniqueness because of the following rea-
sons. The hydrogen lines are blended and saturated, and
hence the real \(N(H)\) value may be higher, leading to lower
metal abundances. Besides, in our calculations the HM
background ionizing spectrum was adopted. However, it is
probable that in a close pair of galaxies where significant
star-forming activity is triggered by the merging, the HM
spectrum can be affected by the local sources. In particular,
the discrepancies between the observed and theoretical
intensities seen in the C IV and Si IV components at \(v = 100\)
km s\(^{-1}\) as well as the estimated overabundant ratio of
\([C/O] = 0.1\) (usually \([Si/O]\) lies between 0 and 0.4; see
Appendix) may be caused by inadequate choice of the back-
ground ionizing spectrum. Nevertheless, the observed metal
profiles are quite consistent with the HM spectrum, and
therefore we expect that the influence of the local sources
may not be very strong and, hence, the interpretation of this
absorption system will not be significantly altered.

4.2. Absorbers with \(N(H) < 5 \times 10^{16} \text{ cm}^{-2}\)

4.2.1. Q0347–3819, \(z_{\text{abs}} = 2.53\) and 2.65

These two metal systems with \(z_{\text{abs}} = 2.5370\) and 2.65044
show broad and saturated hydrogen Ly\(\alpha\) lines and lines of
silicon and carbon in different ionization stages. Computa-
tional results are presented in Table 2; the observed and
synthetic profiles are shown in Figures 6 and 7.

The solutions listed in Table 2 are nonunique because of
the low hydrogen line and blended low-ionization lines of
\(\text{Si II\lambda}2160\) and \(\text{C II\lambda}1334\). If in reality the Si II\lambda2160
absorption is absent at \(z_{\text{abs}} = 2.5370\), then the solution with
a higher \(U_0\) and, hence, with a large linear size can also be
obtained. Therefore, we consider the estimated linear size of
13 kpc as a lower limit. The system at \(z_{\text{abs}} = 2.65\) may have
low-ionization C II\lambda1334 absorption, resulting in a lower
mean ionization parameter and a smaller linear size as
TABLE 2

| Parameter | Q0347–3819 | APM BR J0307–4945 |
|-----------|------------|-------------------|
| \( \zeta_{\text{abs}} \) \ (1) | 2.3530 | \( \zeta_{\text{abs}} \) \ (2) |
| \( \zeta_{\text{abs}} \) \ (3) | 2.69044 | \( \zeta_{\text{abs}} \) \ (4) |
| \( \zeta_{\text{abs}} \) \ (5) | 2.96171 | \( \zeta_{\text{abs}} \) \ (6) |
| \( \zeta_{\text{abs}} \) \ (7) | 3.13985 | \( \zeta_{\text{abs}} \) \ (8) |

**Note.**—The internal errors of \( U_0, N_{\text{H}0}, \sigma_z, \sigma_r, \text{and } Z_r \) are \( \pm 15\% \)–\( 20\% \); the column density errors are \( \pm 10\% \), whereas \( n_0 \) and \( L \) are known with \( \pm 50\% \) accuracy; \( Z_X = X/H; |Z_X| = \log(Z_X) - \log(Z_X) \), (solar abundances are taken from Holweger 2001).

... compared with those listed in Table 2. A rather high overabundance ratio \( \frac{\text{Si} \text{C}}{\text{C}} \approx 0.5 \) estimated for this system also allows us to speculate that the real ionization parameter may be lower. However, these considerations do not change the classification of both absorbers: most probably they are hosted by halos of some distant galaxies.

4.2.2. Q0347–3819, \( \zeta_{\text{abs}} = 2.962 \) and 2.966

These two systems are separated by only 300 km s\(^{-1}\) but demonstrate very different physical characteristics (see Table 2 and Figs. 8 and 9). Multiple hydrogen lines available in their spectra make it possible to estimate quite accurately the hydrogen column densities and all other physical parameters.

The \( \zeta_{\text{abs}} = 2.96171 \) system shows a broad \( \text{Ly} \alpha \) line extending over 400 km s\(^{-1}\) and weak absorption lines of highly ionized silicon and carbon (the \( \text{C} \text{m} \lambda 977 \) line is contaminated by the \( \text{Ly} \gamma \) line from the \( \zeta_{\text{abs}} = 2.97915 \) system [see Fig. 11]; the \( \text{C} \text{m} \lambda 1334 \) line is in a wavelength coverage gap of the Keck spectrum; the \( \text{Si} \text{m} \lambda 1260, 1193 \) lines are strongly blended). The derived physical parameters are typical for a galactic halo absorber: a low-density \( (n_0 \approx 3 \times 10^{-4} \text{ cm}^{-3}) \), low-metallicity \( (Z \approx 0.01 Z_\odot) \), hot \( (T_{\text{kin}} \approx 40,000 \text{ K}) \) cloud of \( L \approx 20 \text{ kpc} \) size. The large overabundance of silicon as compared with carbon \( (\text{SiC}) \leq 0.8 \) can be explained by the uncertainty in the estimated carbon abundance: only one weak \( \text{C iv} \lambda 1548 \) line is available for the analysis.

The adjacent system at \( \zeta_{\text{abs}} = 2.96591 \) is on the contrary a very compact \( (L \approx 120 \text{ pc}) \), warm \( (T_{\text{kin}} \approx 10,000 \text{ K}) \) cloud, 5 times denser and 30 times more metal abundant. This absorber reveals also a weak \( \text{N m} \lambda 989 \) line [contaminated in the right wing by the \( \text{H}_2 \lambda 110-0 \) line from the \( \zeta_{\text{abs}} = 3.025 \) DLAS; see Fig. 5 in Levshakov et al. 2002b].

We do not detect high-amplitude fluctuations in the density and velocity fields in this compact system (see Fig. 10), and as a result the observed metal line profiles are almost symmetric. The low-density region with the space coordinate \( 0 \leq x \leq 0.2 \) does not contribute much to the line profiles, although a weak absorption arising in this gas can be seen in Figure 9 in the \( \text{C m} \lambda 977 \) and \( \text{C iv} \lambda 1548 \) lines at \( t \approx -30 \text{ km s}^{-1} \).

Since it is hardly possible that a cloud with a 120 pc size could exist in space on its own, the two systems are probably physically related. For instance, this small and metal-rich cloud may be a condensation of supernova-heated gas in a galactic halo seen in the \( \zeta_{\text{abs}} = 2.96171 \) absorption lines. This process, known as a galactic fountain (Bregman 1980), is believed to be the origin of the high-metallicity HVCs observed in the halo of the Milky Way. The velocity excess of the HVCs is usually greater than 90 km s\(^{-1}\), which is consistent with the shift of \( \approx 120 \text{ km s}^{-1} \) between the redward absorption in the \( \text{Ly} \alpha \) profile at \( \zeta_{\text{abs}} = 2.96171 \) and the center of the \( \text{Ly} \alpha \) line at \( \zeta_{\text{abs}} = 2.96591 \).

4.2.3. Q0347–3819, \( \zeta_{\text{abs}} = 2.98 \)

Although this system belongs to the most commonly observed type in the \( \text{Ly} \alpha \) forest (apart from hydrogen lines only weak \( \text{C iv} \) and \( \text{Si iv} \) doublets and no apparent absorption in other ionic species are registered), its hydrogen lines are unusually broad—extended over 600 km s\(^{-1}\). Available \( \text{Ly} \alpha, \text{Ly} \beta \), and \( \text{Ly} \gamma \) lines (see Fig. 11) allow us to estimate the hydrogen column density with a sufficiently high accuracy. According to the recovered physical parame-
ters (see Table 2), in this case we are dealing with a large \((L \approx 50 \text{ kpc})\) cloud of a rarefied \((n_0 \approx 10^{-9} \text{ cm}^{-3})\), metal-poor \((Z < 0.01 Z_\odot)\), and hot \((T_{\text{kin}} \approx 40,000 \text{ K})\) gas. Blending of the C\(\text{iii}\) λ977 and Si\(\text{iii}\) λ1206 lines and the weakness of the Si\(\text{iv}\) λ1393 line do not allow us to estimate accurately the mean ionization parameter. The \(U_0\) value presented in Table 2 should be considered as a lower limit. If in reality \(U_0\) is higher, then the absorber may have a lower mean gas density and a larger linear size.

The most probable host for this system might be an external region of a giant galactic halo or a large-scale structure object.

4.2.4. \(Q0347-3819\), \(z_{\text{abs}} = 3.14\)

The unsaturated Ly\(\gamma\) line gives accurate estimations of the total neutral hydrogen column density (Fig. 12; Table

\[\frac{\text{Relative Velocity (km s}^{-1}\text{)}}{-300, -200, -100, 0, 100, 200, 300}\]

\[\text{Ly}-\alpha, \text{VLT}\]

\[\text{CII} \ 1334, \text{VLT}\]

\[\text{SII} \ 1260, \text{VLT}\]

\[\text{SIII} \ 1266, \text{VLT}\]

\[\text{CIV} \ 1548, \text{Keck}\]

\[\text{CIV} \ 1550, \text{Keck}\]

\[\text{SIV} \ 1393, \text{Keck}\]

Fig. 6.—Same as Fig. 2 but for the \(z_{\text{abs}} = 2.53\) system. The zero radial velocity is fixed at \(z = 2.5370\). The corresponding physical parameters are listed in Table 2. Here \(\chi^2_{\text{min}} = 1.07; \nu = 602\).

4.2.5. \(APM BR J0307-4945\), \(z_{\text{abs}} = 4.81\)

This is the most distant absorber in our set where a low metal abundance can be directly measured. Its

\[\frac{\text{Relative Velocity (km s}^{-1}\text{)}}{-200, -100, 0, 100, 200}\]

\[\text{Ly}-\alpha, \text{VLT}\]

\[\text{CII} \ 1334, \text{VLT}\]

\[\text{SII} \ 1260, \text{VLT}\]

\[\text{SIII} \ 1266, \text{VLT}\]

\[\text{CIV} \ 1548, \text{Keck}\]

\[\text{CIV} \ 1550, \text{Keck}\]

\[\text{SIV} \ 1393, \text{Keck}\]

Fig. 7.—Same as Fig. 2 but for the \(z_{\text{abs}} = 2.65\) system. The zero radial velocity is fixed at \(z = 2.65044\). The corresponding physical parameters are listed in Table 2. Here \(\chi^2_{\text{min}} = 1.15; \nu = 962\).

2). Clean continuum windows seen at the expected positions of metal lines make it possible to estimate the upper limits on metal abundances and to calculate the total hydrogen column density \(N_H\). The result obtained shows a rather low metallicity cloud with \([C/\text{H}] < -2.2\) and linear size \(L > 13\) kpc. One may expect to observe similar systems in the outer parts of galactic halos.
hydrogen Lyα line is clearly seen at Δv = 3000 km s⁻¹ in the wide emission blend Lyα + N v + Si ii shown in Figure 1c. Absorption lines in Figure 13 give the redshift z₁₄ = 4.8101, and, thus, this system has z₁₄ > z_em. The same order-of-magnitude velocity difference (Δv ≈ 3000 km s⁻¹) between the H₂-bearing cloud at z₁₄ = 2.811 (Levshakov & Varshalovich 1985) and the quasar redshift z_em = 2.770 (Foltz, Chaffee, & Black 1988) has been observed toward PKS 0528−250. This H₂ cloud seems to be at a distance larger than 10 kpc from the quasar as shown by Srianand & Petitjean (1998). However, in our case we are not able to estimate the proximity of the quasar. We can only assume that the photoionization of the z₁₄ system could be affected by the quasar radiation.

This assumption is supported by the following facts. It turned out to be impossible to fit all available lines with the HM ionizing spectrum: the relative intensities of C iii λ977 and C iv λλ1548, 1550 required very high U₀ values (U₀ > 0.1) that contradicted the shallow extended wings of the Lyα line. On the other hand, the MF ionizing spectrum, corresponding to the active galactic nucleus, allowed us to fit all lines and delivered a self-consistent set of physical parameters (Table 2; Figs. 13 and 14). The intensity at 1 ryd was set to J₀₁₂ = 10⁻²² ergs cm⁻² s⁻¹ Hz⁻¹ sr⁻¹, which corresponds to the intensity of the HM spectrum at z = 4.9.

According to the recovered values, the absorber at z₁₄ = 4.81 is a metal-poor cloud with a linear size of about 25 kpc and mean density n₀ ≈ 2 × 10⁻⁴ cm⁻³. Figure 14 shows that the shallow wings of the Lyα line are produced by the streaming out low-density gas, whereas the central region of the cloud remains very quiet.

Since we clearly see only the C iv doublet⁸ and have upper limits for the intensity of the C iii λ977 and Si iv λ1393 lines, the mean ionization parameter U₀ listed in Table 2 should be considered as a lower limit, implying that lower metal abundances and lower gas densities may also be possible. Taking into account that the density n₀ and by this the linear size L scales with the intensity of the radiation field (see eq. [1]), the value of L becomes quite uncertain. It could be larger or smaller than the estimated size of 25 kpc (this uncertainty is marked by a question mark in Table 2).

An absorption system with similar spectral characteristics (wide and shallow wings of the Lyα line, a weak C iv doublet) was previously observed by Reimers et al. (2001) at z₁₄ = 1.674 toward HE 0515−4414 (z_em = 1.73). The system at z₁₄ = 1.674 shows in addition a strong O vi doublet, which, unfortunately, cannot be identified in the z₁₄ cloud because of blending in the dense Lyα forest.

Thus, we may conclude that such systems are probably formed in the gas clouds affected by the QSO radiation.

4.3. Lyα Systems with Metallicity Gradient

4.3.1. Q0347−3819, z₁₄ = 2.848 and 2.899

These systems present several seemingly unblended hydrogen lines and pronounced lines of highly ionized silicon and carbon (Figs. 15 and 16; Table 3). In addition, the N v λ1238 and O vi λλ1031 lines were identified at z₁₄ = 2.848.

⁸ The 1549 Å component is slightly blended with the night sky lines, whereas the 1548 Å line is clear as found from the comparison of the two spectra of APM BR J0307−4945 taken in a 2 month interval.
In spite of the multiple H\textsc{i} lines, it turned out that the MCI failed to fit adequately all available ionic profiles in the apparent velocity ranges when homogeneous metallicities over the entire absorbing regions were assumed. The most sensitive restrictions in these calculations are set by the continuum windows seen in the profiles of the strong C\textsc{iii} λ977 and Si\textsc{iii} λ1206 lines. We consider the observed lines from these systems as arising in clouds with metallicity gradients for the following reasons.

The hydrogen Ly\textsc{α} and Ly\textsc{β} lines seen at $z_{\text{abs}} = 2.848$ in the $\Delta v$ range between 100 and 400 km s$^{-1}$ do not show any metal absorption in this velocity interval. Absorption features seen in the range 140 km s$^{-1} \leq \Delta v \leq 400$ km s$^{-1}$ in Figure 15 (panel C\textsc{iii}) and in the range 180 km s$^{-1} \leq \Delta v \leq 400$ km s$^{-1}$ in panel Si\textsc{iii} cannot be attributed to the corresponding hydrogen subsystem; otherwise we should observe pronounced C\textsc{iv} lines in the same velocity range. If the redward hydrogen absorption is physically connected with the blueward one, then we may conclude that the $z_{\text{abs}} = 2.848$ absorber has a metallicity gradient.

A very similar picture is seen in the $z_{\text{abs}} = 2.899$ system for the blueward portions of the hydrogen lines in the range $-220$ km s$^{-1} \leq \Delta v \leq -80$ km s$^{-1}$ (Fig. 16). The C\textsc{iii} λ977 line (which is the most sensitive absorption line in a wide range of the ionization parameter from $\log U_0 \gtrsim -4$ to $\log U_0 \approx 0$) shows no absorption in this velocity range. If the redward hydrogen absorption is physically connected with the blueward one, then we may conclude that the $z_{\text{abs}} = 2.848$ absorber has a metallicity gradient.

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profiles—the configuration noticed previously at $z_{\text{abs}} = 1.385$ toward HE 0515–4414 by Reimers et al. (2001); i.e., this unusual pattern is not unique and seems to indicate some special kind of absorption systems. Preliminarily, we may conclude that the system at $z_{\text{abs}} = 2.848$ as well as probably that at $z_{\text{abs}} = 2.899$ arise when the line of sight intersects a distant halo with very low (if any) metal content and encounters a metal-rich HVC. Unfortunately, the accurate quantitative analysis of both systems cannot be carried out because the velocity excesses of the assumed HVCs are not large enough to separate the inputs to the hydrogen lines from the halos and from the clouds as was

Fig. 11.—Same as Fig. 2 but for the $z_{\text{abs}} = 2.98$ system. The zero radial velocity is fixed at $z = 2.97915$. The corresponding physical parameters are listed in Table 2. Here $\chi^2_{\text{min}} = 1.20; \nu = 858$.

Fig. 12.—Same as Fig. 2 but for the $z_{\text{abs}} = 3.14$ system. The zero radial velocity is fixed at $z = 3.13985$. The corresponding physical parameters are listed in Table 2. Here $\chi^2_{\text{min}} = 1.00; \nu = 407$. 
possible in the case of the $z_{\text{abs}} = 2.962$ and $z_{\text{abs}} = 2.965$ systems. Therefore, the results presented in Table 3 are tentative, but they are physically reasonable and self-consistent. The corresponding synthetic spectra are shown in Figures 15 and 16 by the solid lines. It should be noted that for both systems, only one wing of the available H i lines (marked with the horizontal bold lines) was included in the analysis, whereas the synthetic profiles for the entire H i lines of the encountered HVCs were computed using the velocity and density distributions estimated from the metal profiles.

According to the data from Table 3, the suggested HVCs belong to different types. The system at $z_{\text{abs}} = 2.899$ has the metal abundance pattern, the set of the ions observed (notice the pronounced Si iv doublet), and the size similar to those estimated for the supposed HVC at $z_{\text{abs}} = 2.965$ and consistent with the parameters of the HVCs observed in the Milky Way (see Appendix). The system at $z_{\text{abs}} = 2.848$ is more highly ionized (O vi and N v and no Si iv), and it has a size of several kiloparsecs. Highly ionized HVCs with similar parameters were observed by Sembach et al. (1999) near the Milky Way. Their origin is still uncertain. Probably the $z_{\text{abs}} = 2.848$ absorber may belong to the intercluster gas clouds in a distant group of galaxies as was suggested by Sembach et al. for the local highly ionized HVCs.

5. DISCUSSION

5.1. The Origin of Metal Systems

Metal systems with $N(\text{H} \text{i}) < 5 \times 10^{16}$ cm$^{-2}$ are usually believed to originate in galactic halos at different galactocentric distances. At low redshifts ($z < 1$) the galaxies associated with certain metallic absorptions (e.g., C iv) can be in most cases identified directly (e.g., Chen, Lanzetta, & Webb 2001a). Our results on absorption systems with $z \gtrsim 2$ also support this assumption: absorbers with $z_{\text{abs}} = 1.87$ (Paper I), 2.54, 2.65, 2.962, and 2.98 (present paper) are produced by metal-enriched ($Z < 0.1 Z_{\odot}$), hot ($T_{\text{kin}} \approx 20,000$ K), rarefied ($n_0 \approx 10^{-4}$ to $10^{-3}$ cm$^{-3}$) gas clouds that have typical linear sizes of $L > 10$ kpc. These parameters are consistent with contemporary models of galactic halos (e.g., Viegas, Friaca, & Gruenwald 1999).
The nature of Lyman limit absorbers is less understood. Mo & Miralda-Escudé (1996) associate them with cold photoionized clouds randomly moving in hot spherical halos. The clouds are supposed to form from the initial density inhomogeneities in the accreting intergalactic gas during its cooling. Both the cloud and the halo obviously reveal equal inhomogeneities in the accreting intergalactic gas during its cooling. It was shown by hydrodynamic simulations (e.g., Katz et al. 1996; Gardner et al. 2001) that LLSs can also arise on lines of sight that pass through small protogalaxies. We found two systems with $z_{\text{abs}} = 1.94$ (Paper I) and 4.21 (present paper) that can be explained within this framework. These metal-rich ($Z \geq Z_{\odot}$) absorbers with sizes of several kiloparsecs are probably hosted by objects that may be akin to the local compact blue galaxies.

However, this scenario obviously fails to explain metal-abundant ($Z > 0.1 Z_{\odot}$) systems since it is hard to understand how the whole halo can be metal-enriched to such a high level. It was shown by hydrodynamic simulations (e.g., Katz et al. 1996; Gardner et al. 2001) that LLSs can also arise on lines of sight that pass through small protogalaxies. We found two systems with $z_{\text{abs}} = 1.94$ (Paper I) and 4.21 (present paper) that can be explained within this framework. These metal-rich ($Z \geq Z_{\odot}$) absorbers with sizes of several kiloparsecs are probably hosted by objects that may be akin to the local compact blue galaxies.

Some absorbers in our present study ($z_{\text{abs}} = 2.21, 2.965$, and, possibly, 2.89) reveal small linear sizes ($L < 1$ kpc) together with very high metal content ($Z \approx Z_{\odot}$). These three systems may be explained in the framework of the process known as a galactic fountain: metal-enriched (supernova-heated) gas arises from the inner region of a galaxy and condenses into the clouds within the hot galactic halo. After formation, clouds fall back toward the galaxy center because of their higher density. It is suggested that high-metallicity HVCs observed in the Milky Way halo are formed by this mechanism (Bregman 1980). The HVCs are common objects in our Galaxy and are detected in every longitude and latitude region. If the galactic fountain process also functions in distant galaxies, it would be quite probable to encounter such a cloud on the line of sight that

### Table 3

| Parameter | $z_{\text{abs}} = 2.84829$ | $z_{\text{abs}} = 2.89922$ |
|-----------|--------------------------|--------------------------|
| $U_\text{H}$ | 0.1                      | 2.2E-2                   |
| $N_{\text{H}}$ (cm$^{-3}$) | 2.3E18                  | 1.9E18                   |
| $\sigma_t$ (km s$^{-1}$) | 34.9                     | 54.3                     |
| $T_{\text{min}}$ (K) | 9.1E-5                   | 9.6E-5                   |
| $Z_{\text{O}}$ | $\leq 2.5E-5$             | $\leq 2.5E-4$             |
| $Z_{\text{N}}$ | $\geq 2.5E-5$             | 2.4E-5                   |
| $Z_{\text{C}}$ | $\geq -0.5$               | $\leq -0.21$             |
| $Z_{\text{O}}$ | $\geq -0.14$             | $\leq -0.15$             |
| $N(\text{H})$ (cm$^{-3}$) | 1.8E14                   | 4.1E15                   |
| $N(\text{C})$ (cm$^{-3}$) | $\geq 1.1E13$            | $\leq 1.3E14$            |
| $N(\text{Si})$ (cm$^{-3}$) | 3.6E12                   | 2.7E13                   |
| $N(\text{C})$ (cm$^{-3}$) | 3.6E12                   | 2.7E13                   |
| $N(\text{O})$ (cm$^{-3}$) | 3.6E12                   | 5.8E13                   |
| $n_0$ (cm$^{-3}$) | 2.5E-4                   | 2.0E-3                   |
| $T_{\text{min}}$ (K) | 2.3E4                     | 1.2E4                    |
| $T_{\text{max}}$ (K) | 1.9E4                     | 9.9E3                    |
| $L$ (kpc) | 3.0                      | 0.33                     |

Note.—The internal errors of $U_\text{H}$, $N_{\text{H}}$, $\sigma_t$, $\sigma_z$, and $Z_\text{O}$ are $\pm 15\% - 20\%$; the column density errors are $\pm 10\%$, whereas $n_0$ and $L$ are known with $\pm 50\%$ accuracy. $Z_{\odot} = X/\text{H}; [Z_\odot] = \log(Z_{\odot}) - \log(Z_{\odot})$ (solar abundances are taken from Holweger 2001).
intersects the galactic halo, as also discussed by Charlton, Churchill, & Rigby (2001). Another type of HVCs—hot, highly ionized clouds with sizes of several kiloparsecs—is represented by the absorption system at $z_{\text{abs}} = 2.848$. The origin of this type of HVC is uncertain, but they may be produced by the intergalactic metal-enriched gas falling onto metal-poor galactic halos.

Measured abundances of C and Si are depicted versus logarithmic sizes of the studied systems in Figure 17. Systematically higher metal abundances are seen in compact systems with linear sizes $L < 4 \text{ kpc}$. This result seems to indicate that the more effective metal enrichment occurs within relatively compact regions.

Our results show that LLSs are a heterogeneous population that is formed in at least three different environments. This should be taken into account when statistics of LLSs are used to verify different models in hydrodynamic cosmological simulations.

5.2. $\sigma_\pi - N_{\text{HI}}L$ Relation

If QSO metal systems are formed in gas clouds gravitationally bound to intervening galaxies, the internal kinematics of the QSO absorbers should be closely related to the total masses of the host galaxies. In the case of galactic population, different types of galaxies show different scaling relations between the linear size and the velocity width of emission lines (e.g., Mallén-Ornelas et al. 1999). Possible correlation between the absorber linear size $L$ and its line-of-sight velocity dispersion $\sigma_\pi$ was also mentioned in Paper I.

The correlation between $\sigma_\pi$ and $L$ stems from the virial theorem, which states

$$\sigma_\pi^2 \sim \frac{M}{L} \sim n_0L^2 = N_{\text{HI}}L.$$  \(2\)

Assuming that the gas systems are in quasi-equilibrium, one can expect $\sigma_\pi \sim (N_{\text{HI}}L)^{1/2}$.

In Figure 18 we examine our systems by comparing their kinematics ($\sigma_\pi$) with measured sizes ($L$) and total gas column densities ($N_{\text{HI}}$). Shown are the data for all QSO absorbers studied in Paper I and in the present paper except for the systems at $z_{\text{abs}} = 2.848$ and 2.899 (Table 3), which show inhomogeneous metallicities. It is seen that in the log($\sigma_\pi$) versus log($N_{\text{HI}}L$) diagram, most systems with linear sizes $L > 1 \text{ kpc}$ lie along the line with slope $\kappa = 0.30 \pm 0.03$ (1 $\sigma$ c.l.).

Taking into account that we know neither the impact parameters nor the halo density distributions, this result can be considered as a quite good fit to relation (2). Hence, we may conclude that most absorbers with $L > 1 \text{ kpc}$ are gravitationally bound to systems that appear to be in virial equilibrium at the cosmic time when the corresponding Ly$\alpha$ absorbers were formed. The possible consequence of this conclusion is that since the most metal rich absorbers identified in the QSO spectra arise in the galactic systems, the
question whether the intergalactic matter is metal enriched or pristine remains open.

5.3. [\(\alpha\)-Element/Iron Peak] Ratio

The metal abundances measured in the \(z_{\text{abs}} = 2.21\) LLS (Table 1) can be used to estimate the \(\alpha\)-element to iron peak group ratio, which is a good indicator of the chemical evolutionary status of high-redshift gas clouds. During the chemical evolution, heavy elements produced in stars show different nucleosynthetic histories, so their relative abundances vary with cosmic time.

Oxygen and other \(\alpha\)-chain elements are mainly produced by Type II supernovae (SNe), while iron is also a product of Type Ia SNe, which have longer evolution scales. In the early stages of the chemical evolution of galaxies (\(\Delta t \lesssim 2 \times 10^7\) yr) the interstellar gas is likely enriched by Type II SNe products, while at \(\Delta t \gtrsim 10^8\) yr, the [\(\alpha/Fe\)] ratio should decline. Observations reveal both low (e.g., \(\approx 0.1–0.2\) in the \(z_{\text{abs}} = 3.390\) dust-free DLAS [Q0000–2621; Molaro et al. 2001] and in the \(z_{\text{abs}} = 3.386\) DLAS [Q0201+1120; Ellison et al. 2000]) and high (e.g., \(\approx 0.7\) in the DLAS I Zw 18 [Levshakov, Kegel, & Agafonova 2001] and 0.68 \pm 0.08 in the \(z_{\text{abs}} = 3.025\) DLAS [Q0347–3819; Levshakov et al. 2002b]) ratios of [\(\alpha\)-element/iron peak].

Oxygen with its weak affinity with dust grains is a good tracer of the [\(\alpha\)-element] abundances. Nevertheless, the intrinsic [\(\alpha/Fe\)] ratio may be affected by depletion of iron since being a refractory element iron may be partly locked into dust grains. The dust content in the \(z_{\text{abs}} = 2.21\) LLS may not, however, be too high. The relative abundances of the \(\alpha\)-elements O, Mg, and Si are [\(Si/O\)] = \(-0.14 \pm 0.11\) and [\(Mg/O\)] = \(-0.27 \pm 0.11\).

In Galactic stars the \(\alpha\)-elements show the same behavior relative to iron peak elements (oversolar at [\(Fe/H\)] \(\lesssim -1\); see, e.g., Goswami & Prantzos 2000). We thus expect to find solar \(\alpha\)-element ratios in dust-free absorbing regions, as observed, e.g., in the above-mentioned \(z_{\text{abs}} = 3.390\) DLAS toward Q0000–2620. A negative value of [\(Mg/O\)] found in this LLS may indicate the presence of some amount of dust with a depletion factor of about 0.2 dex for the magnesium abundance. If, however, only the gas-phase abundances of O and Fe are taken, the upper bound on the [\(O/Fe\)] ratio is 0.65 \pm 0.11, which is comparable with that found, for instance, in the \(z_{\text{abs}} = 3.025\) DLAS toward Q0347–3819, where the dust-to-gas ratio is \(\approx 1/30\) of the mean Galactic interstellar medium value (Levshakov et al. 2002b). The enrichment of the \(\alpha\)-elements in the \(z_{\text{abs}} = 2.21\) LLS is also supported by the relative abundances of Si, Mg to Fe: [\(Si/Fe\)] = 0.51 \pm 0.11 and [\(Mg/Fe\)] = 0.38 \pm 0.11. Thus, the absorbing cloud at \(z_{\text{abs}} = 2.21\) appears to be a chemically young object.

6. SUMMARY

We have deduced the physical properties of 10 absorption-line systems in the range \(\Delta z = 2.21–2.966\) toward Q0347–3819 and of two systems at \(z_{\text{abs}} = 4.21\) and 4.81 toward APM BR J0307–4945. The main conclusions are as follows:

1. The analyzed LLSs belong to a heterogeneous population that is formed by at least three groups of absorbers: (1)
extended metal-poor gas halos of distant galaxies, (2) gas in
dwarf galaxies, and (3) metal-enriched gas arising from
the inner galactic regions and condensing into the clouds within
the hot galactic halo (galactic fountain). While the interpre-
tation of a single system is sometimes subject to large uncer-
tainties as discussed in chapter 4, the existence of a wide
spread of properties in the different systems is certainly
proved.

2. A correlation between the line-of-sight velocity disper-
sion $\sigma_v$ and the linear size $L$ of the absorbing systems noted
in Paper I is confirmed. New results show that large-size QSO
absorbers ($L > 1$ kpc) obey a scaling law $\sigma_v \sim (N_H L)^{0.1}$
over two decades in velocity dispersion and in the product
$(N_H L)$. This means that the majority of the metal
absorbers are probably bound to the galactic systems, and
hence the question whether the IGM is enriched or pristine
requires further investigations.

3. Systematically higher metal abundances are found in
compact systems: in our sample there are no small-size sys-
tems ($L < 1$ kpc) with metallicity lower than 0.1 $Z_\odot$.

4. The gas-phase metal abundances from the $z_{\text{abs}} = 2.21$
LLS reveal a pronounced [$\alpha$-element/iron peak] enhance-
ment with $[O/Fe] = 0.65 \pm 0.11$ at the 6 $\sigma$ confidence level,
the first time when this abundance pattern is unambiguously
found in an LLS. The measured $[O/Fe]$ ratio implies that
the chemical history of this LLS is $< 10^9$ yr.

5. The absorption systems at $z_{\text{abs}} = 2.21$ and 2.965 and
possibly the systems at $z_{\text{abs}} = 2.848$ and 2.899 toward
Q0347–3819 show characteristics very similar to those
observed for different types of HVCs in the Milky Way and
may be interpreted as being the high-redshift counterparts
of these Galactic objects.

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APPENDIX
POSSIBLE COUNTERPARTS OF QSO ABSORBERS

In our interpretation of the nature of the different metal systems with $N(\text{H}) \sim 10^{14} - 10^{17}$ cm$^{-2}$ we have referred to a set of
absorbers whose physical parameters are summarized in Table 4. Comparison between the reference absorbers and the QSO
systems is based on the following parameters:

1. Linear sizes.—The systems can be divided into small-size ($L < 1$ kpc), intermediate-size (1 kpc $\lesssim L \lesssim 10$ kpc), and large-
size (10 kpc $\lesssim L \lesssim 150$ kpc) absorbing regions connected with galactic gaseous envelopes, as well as into very large size ($L \gtrsim 150$
 kpc) absorbers (filaments) showing correlation with the large-scale distribution of galaxies (e.g., Penton, Stocke, & Shull 2002). Filaments are probably intergalactic material not recycled by
galaxies.

2. Metallicities.—Values of $0.3 \lesssim Z/Z_\odot \lesssim 1$, $0.03 \lesssim Z/Z_\odot \lesssim 0.3$, and $Z/Z_\odot < 0.03$ classify the systems as metal-rich, metal-
enriched, and metal-poor, respectively.

3. Metallicity patterns.—Relative element abundances allow us to distinguish between chemically young and old systems
(low and high relative [$\alpha$-element/iron peak] ratio, respectively).

| Type of Absorber                                      | Scale Size, $L$ (kpc) | Metallicity, $X = Z/Z_\odot$ | Metallicity Pattern$^a$ | References |
|------------------------------------------------------|-----------------------|-----------------------------|-------------------------|------------|
| 1. HVC-type absorbers inside galactic halos............| $L < 1$               | $0.1 \lesssim X \lesssim 1$ | $[\text{C}/\text{Fe}] \approx 0.2, [\text{N}/\text{Fe}] \approx 0.6$ | 1, 2       |
|                                                      |                       |                             | $[\text{O}/\text{Fe}] \approx 0.7, [\text{Mg}/\text{Fe}] \approx 0.2$ | 1, 2       |
|                                                      |                       |                             | $[\text{Al}/\text{Fe}] \approx 0.3, [\text{Si}/\text{Fe}] \approx 0.3$ | 1, 2       |
| 2. Gas in dwarf galaxies of                          |                       |                             | $[\text{C}/\text{Fe}] \approx -0.2, [\text{O}/\text{Fe}] \approx 0.3$ | 3, 4       |
| (i) Low metallicity                                   | $1 \lesssim L \lesssim 10$ | $0.03 \lesssim X \lesssim 0.06$ | $[\text{N}/\text{Fe}] \approx 0.2, [\text{Si}/\text{Fe}] \approx 0.1$ | 3, 4       |
| (ii) High metallicity                                 | $1 \lesssim L \lesssim 10$ | $0.06 \lesssim X \lesssim 0.3$ | $[\text{C}/\text{Fe}] \approx 0.2, [\text{O}/\text{Fe}] \approx 0.4$ | 3, 4       |
|                                                      |                       |                             | $[\text{N}/\text{Fe}] \approx -0.1, [\text{Si}/\text{Fe}] \approx 0.3$ | 3, 4       |
| 3. Gaseous envelopes of galaxies seen$^b$             | $10^{-1} \lesssim L \lesssim 160 \text{ h}^{-1}$ | $X < 1$                     |                          | 5, 6       |
| (i) H I Lyα ........................................... | $15 \text{ h}^{-1} \lesssim L \lesssim 75 \text{ h}^{-1}$ | $X < 1$                     |                          | 7, 8       |
| (ii) Mg ii λ2796, 2803 ................................| $100 \text{ h}^{-1} \lesssim L \lesssim 180 \text{ h}^{-1}$ | $X < 1$                     |                          | 9, 10      |
| (iii) C iv λ1548, 1550 ................................| $L \gtrsim 150 \text{ h}^{-1}$ | $X < 1$                     | $[\text{Si}/\text{C}] \approx 0.4, [\text{N}/\text{C}] \approx -0.7$ | 6          |

$^a$ The patterns for the absorbers of type 1 and 2 are taken from Savage & Sembach 1996 and Izotov & Thuan 1999, respectively, whereas the pattern for case 4 is a characteristic abundance of low-metallicity intergalactic systems; Songaila 1998.

$^b$ Following Chen et al. 1998, by "gaseous envelopes" we mean a gaseous structure of large covering factor but unspecified geometry or filling factor.

References.—(1) Savage & Sembach 1996; (2) Wakker 2001; (3) Izotov & Thuan 1999; (4) Mallén-Ornelas et al. 1999; (5) Chen et al. 1998; (6) Penton et al. 2002; (7) Bergeron & Boissé 1991; (8) Steidel et al. 1997; (9) Chen et al. 2001a; (10) Chen et al. 2001b.
REFERENCES

Bergeron, J., & Boissé, P. 1991, A&A, 243, 344
Bregman, J. N. 1980, ApJ, 236, 577
Cen, R., Miralda-Escudé, J., Ostriker, J. P., & Rauch, M. 1994, ApJ, 437, L9
Charlton, J. C., Churchill, C. W., & Rigby, J. R. 2001, in ASP Conf. Ser. 240, Gas and Galaxy Evolution, ed. J. E. Hibbard, M. P. Rupen, & J. H. van Gorkom (San Francisco: ASP), 487
Chen, H.-W., Lanzetta, K. M., & Webb, J. K. 2001a, ApJ, 556, 158
Chen, H.-W., Lanzetta, K. M., Webb, J. K., & Barcous, X. 1998, ApJ, 498, 77
Chen, H.-W., Lanzetta, K. M., Webb, J. K., & Barcous, X. 2001b, ApJ, 559, 654
De Breuck, C., van Breugel, W., Minniti, D., Miley, G., Röttgering, H., Stanford, S. A., & Carilli, C. 1999, A&A, 352, L51
Dessauges-Zavadsky, M., D’Odorico, S., McMahon, R. G., Molaro, P., Ledoux, C., Péroux, C., & Storrie-Lombardi, L. J. 2001, A&A, 370, 426
D’Odorico, S., Cristiani, S., Dekker, H., Hill, V., Kaufier, A., Kim, T., & Primas, F. 2000, Proc. SPIE, 4005, 121
D’Odorico, S., Dessauges-Zavadsky, M., & Molaro, P. 2001, A&A, 368, L21
Ellison, S., Songaila, A., Schaye, J., & Pettini, M. 2000, AJ, 120, 1175
Ferland, G. J. 1997, HAZY: A Brief Introduction to CLOUDY (Lexington: Univ. Kentucky Phys. Dept. Int. Rep.)
Foltz, C. B., Chaffee, F. H., Jr., & Black, J. H. 1988, ApJ, 324, 267
Gardner, J. P., Katz, N., Hernquist, L., & Weinberg, D. H. 2001, ApJ, 559, 131
Goswami, A., & Prantzos, N. 2000, A&A, 359, 191
Grevesse, N., & Sauval, A. J. 1998, Space Sci. Rev., 85, 161
Haardt, F., & Madau, P. 1996, ApJ, 461, 20
Hollweg, H. 2001, in AIP Conf. Proc. 598, Solar and Galactic Composition, ed. R. F. Wimmer-Schweingruber (Melville: AIP), 598, 23
Katz, N., Weinberg, D. H., Hernquist, L., & Miralda-Escudé, J. 1996, ApJ, 457, L57
Levshakov, S. A., Agafonova, I. I., Centurión, M., & Mazets, I. E. 2002a, A&A, 383, 813 (Paper I)
Levshakov, S. A., Agafonova, I. I., & Kegel, W. H. 2000, A&A, 360, 833 (LAK00)
LEVSHAKOV ET AL.
Levshakov, S. A., Dessauges-Zavadskyy, M., D’Odorico, S., & Molaro, P. 2002b, ApJ, 565, 696
Levshakov, S. A., Kegel, W. H., & Agafonova, I. I. 2001, A&A, 373, 836
Levshakov, S. A., Takahara, F., & Agafonova, I. I. 1999, ApJ, 517, 609
Levshakov, S. A., & Varshalovich, D. A. 1985, MNRAS, 212, 517
Mallén-Ornelas, G., Lilly, S. J., Crampton, D., & Schade, D. 1999, ApJ, 518, L83
Mathews, W. G., & Ferland, G. J. 1987, ApJ, 323, 456
Miralda-Escudé, J., Cen, R., Ostriker, J. P., & Rauch, M. 1996, ApJ, 471, 582
Mo, H. J., & Miralda-Escudé, J. 1996, ApJ, 469, 589
Molaro, P., Levshakov, S. A., Dessauges-Zavadskyy, M., & D’Odorico, S. 2001, ApJ, 549, 90
Overzier, R. A., Röttgering, H. J. A., Kurk, J. D., & De Breuck, C. 2001, A&A, 367, L5
Penton, S. V., Stocke, J. T., & Shull, J. M. 2002, ApJ, 565, 720
Péroux, C., Storrie-Lombardi, L. J., McMahon, R. G., Irwin, M., & Hook, I. M. 2001, AJ, 121, 1799
Prochaska, J. X., & Wolfe, A. 1999, ApJS, 121, 369
Reimers, D., Baade, R., Hagen, H.-J., & Lopez, S. 2001, A&A, 374, 871
Savage, B. D., & Sembach, K. R. 1996, ARAA, 34, 279
Sembach, K. R., Savage, B. D., Lu, L., & Murphy, E. M. 1999, ApJ, 515, 108
Songaila, A. 1998, AJ, 115, 2184
Srianand, R., & Petitjean, P. 1998, A&A, 335, 33
Steidel, C. C., Dickinson, M., Meyer, D. M., Adelberger, K. L., & Sembach, K. R. 1997, ApJ, 480, 568
Theuns, T., Leonard, A., Efstathiou, G., Pearce, F. R., & Thomas, P. A. 1998, MNRAS, 301, 478
Tytler, D., & Fan, X. 1992, ApJS, 79, 1
Viegas, S. M., Friaca, A. C. S., & Gruenwald, R. 1999, MNRAS, 309, 355
Vogt, S. S., et al. 1994, Proc. SPIE, 2198, 362
Wakker, B. P. 2001, ApJS, 136, 463
Xiang, Y., Syn, D. Y., Fan, W., & Gong, X. G. 1997, Phys. Lett. A, 233, 216