

Part 2. Origin

**The Interstellar Medium at
High Redshift**

Metal Abundances and Kinematics of Ly- α Absorbers

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Abstract. Both high resolution spectra of QSOs observed at the 8-10 m telescopes and advanced methods of data analysis are crucial for accurate measurements of the chemical composition and physical parameters of the intervening clouds. An overview of our recent results obtained with the Monte Carlo inversion (MCI) procedure is presented. This includes: (1) variations of the shape of the local background ionizing continuum in the 1–5 Ryd range at redshift $z \sim 2.8 - 3.0$; (2) an inverse correlation between the measured metallicity, $[C/H]$, and the absorber line-of-sight linear size, L ; (3) a functional dependence between the line-of-sight velocity dispersion, σ_v , and L .

1. Introduction

A study of quasar (QSO) absorption-line spectra is generally recognized as the most reliable technique for inferring the physical and dynamical state of gas in the intervening absorption clouds at high redshifts, $z \gtrsim 2$. Of particular interest are the measurements of metallic absorptions in the optically thin diffuse clouds with neutral hydrogen column densities $N(\text{H I}) \lesssim 3 \times 10^{17} \text{ cm}^{-2}$. These systems will be called as ‘Ly- α absorbers’ (LAA) to distinguish from the damped Ly- α absorption systems (DLA) which show much higher column densities, $N(\text{H I}) \gtrsim 2 \times 10^{20} \text{ cm}^{-2}$. The latter are believed to arise in galactic disks (e.g., Wolfe et al. 1995), whereas the former may be physically related to the external (~ 10 -100 kpc-scale) regions of galaxies (e.g., Chen et al. 2001). Thus the measurements of the LAAs can provide fundamental insights into conditions prevailing in the galactic environments (external halos) in the early universe.

Since these regions are mainly photoionized by the local metagalactic UV radiation, the ionization states of the LAAs are sensitive to the spectral shape of the background radiation in the 1-5 Ryd range. The spectral energy distribution in the metagalactic ionizing background is defined in turn by the QSO continua filtered through the quasar environments and the IGM. Two implications of the LAA analysis – the metal content of the external halos and the spectral shape of the local UV background – are, therefore, tightly coupled.

To clarify the mechanism of the metal enrichment, accurate measurements of the metal abundances in the LAAs are required. The main problem here is how to account for the ionization correction. In general, the contribution to the line intensity I_λ within the profile comes from all volume elements distributed along the line of sight and having the same radial velocity. If the gas number

density, n_{H} , varies from point to point, then the intensity I_{λ} is caused by a *superposition* of different ionization states.

Recently, we have developed a method called ‘Monte Carlo inversion’ (MCI) to recover the physical parameters of the LAAs assuming that the absorbing cloud is a continuous region with fluctuating density and velocity fields (Levshakov et al. 2000, hereafter LAK). The MCI was applied to high quality QSO spectra obtained with the VLT/UVES, Keck/HIRES, and HST/STIS (Levshakov et al. 2002; Levshakov et al. 2003a,b,c,d,2004). The results of these studies are briefly reviewed in this contribution.

2. The MCI procedure

The layout of the MCI procedure is the following. We assume that the metal abundances within the absorber are constant, the gas is optically thin for the ionizing UV radiation, and the gas is in thermal and ionization equilibrium. 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 which are represented by their sampled values at equally spaced intervals Δx , i.e. by the vectors $\{v_1, \dots, v_k\}$ and $\{n_1, \dots, n_k\}$ with k large enough ($\sim 150 - 200$) to describe the narrowest components of the complex spectral lines. The radial velocity is assumed to be normal distributed with the dispersion σ_v , whereas the gas density is log-normal distributed with the mean n_0 and the dispersion σ_y ($y = n_{\text{H}}/n_0$). The stochastic fields are approximated by the Markovian processes. The accuracy of the restoring procedure depends on the number of different ions in different ionization stages involved in the analysis of a given LAA.

A set of the fitting parameters in the least-squares minimization of the objective function (Eqs. [29] and [30] in LAK) includes σ_v and σ_y along with the total hydrogen column density N_{H} , the mean ionization parameter U_0 , and the metal abundances Z_a for a elements observed in the LAA. With these parameters we can further calculate the mean gas number density n_0 , the column densities for different species N_a , the mean kinetic temperature T_{kin} , and the line-of-sight size $L = N_{\text{H}}/n_0$ of the absorber (note that n_0 and, correspondingly, L scales with the intensity of the local background radiation field).

We start calculations assuming some standard ionizing spectrum [e.g., power law, Mathews & Ferland (1987), or Haardt & Madau (1996, hereafter HM)] and compute the fractional ionizations and the kinetic temperatures at each point x along the sightline with the photoionization code CLOUDY (Ferland 1997). To optimize the patterns of $\{v_i\}$ and $\{n_i\}$ and to estimate simultaneously the fitting parameters, the simulated annealing algorithm with Tsallis acceptance rule and an adaptive annealing temperature choice are used. If the fitting with the standard spectrum is impossible, its shape is adjusted using the procedure based on the experimental design technique (Levshakov et al. 2003d).

3. The spectral shape of the ionizing continuum

In practice, the shape of the ionizing spectrum can be estimated in cases when the value of $N(\text{H I})$ is measured accurately and the absorption system contains

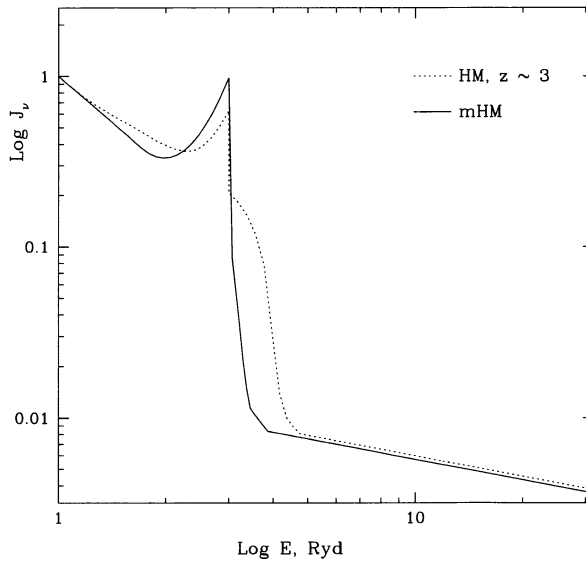


Figure 1. A typical metagalactic ionizing spectrum at redshift $z \sim 3$ (the dotted curve) modeled by Haardt & Madau (1996), and its modification (the solid curve) required to match the absorption lines observed in a LAA at $z = 2.82$ toward HE 0940–1050 (Levshakov et al. 2003d). The spectrum is normalized so that $J_\nu(h\nu = 1 \text{ Ryd}) = 1$. The emission bump at 3 Ryd is caused by reemission of He II Ly α and two-photon continuum emission from intergalactic clouds.

unsaturated lines of at least C II–C IV and Si II–Si IV, otherwise the system is not sensitive to the fine tuning of the continuum shape.

We estimated the spectral shape for the LAAs at $z = 2.82$ (H I, C II, C III, Si III, C IV, Si IV) toward HE 0940–1050; $z = 2.7711$ (H I, C II, Si II, C III, N III, Si III, C IV, Si IV, O VI), and $z = 2.94$ (H I, C II, Si II, C III, Si III, C IV, Si IV) toward Q 1157+3143 (Levshakov et al. 2003d).

All three recovered spectra of ionizing radiation show common features: a bump at $E = 3$ Ryd, which is more pronounced comparing to the model mean intergalactic UV spectra at $z = 3$ like that of Haardt & Madau (1996), and a sharp break just after the bump – also at variance with the model predicting a smeared out break at $E = 4$ Ryd due to ionization of He II. An example of ionizing background estimated for the $z = 2.82$ absorption system toward HE 0940–1050 is shown in Fig. 1. This spectral shape rules out a considerable galactic contribution to the QSO dominated UV ionizing background at $z \sim 3$. The recovered UV spectrum can be well explained in the scenario of the delayed re-ionization of He II (Reimers et al. 1997). In this case the sharp break at $E = 3$ Ryd occurs due to strong resonant scattering of QSO radiation in metal and He II Lyman series lines whereas a part of the absorbed photons re-emitted by the intergalactic gas in the He II Ly α and two-photon continuum emission increases the amplitude of the bump at 3 Ryd. Our results also indicate that

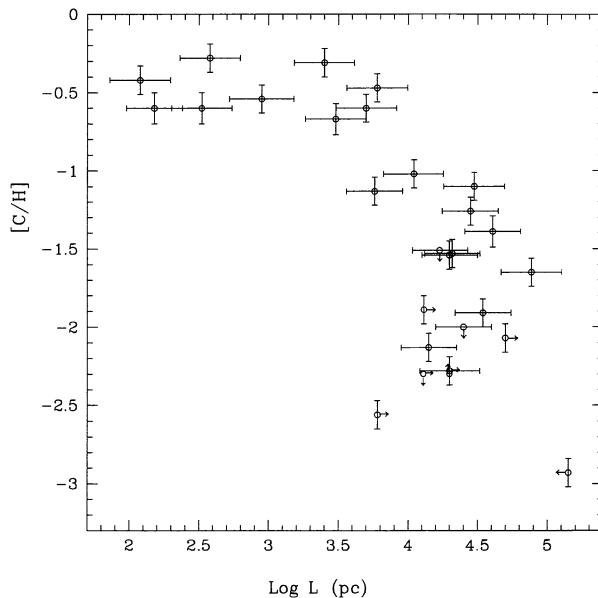


Figure 2. Carbon abundances $[C/H]$ plotted against the logarithmic linear size L of the absorber estimated by the MCI procedure (Levshakov et al. 2002; 2003a,b,c,d). $[C/H]$ decreases with increasing L reflecting, probably, the dilution of metals within galactic halos caused by the mass transport processes.

the re-ionization of He II has not been yet completed by $z = 2.77$. This result is in line with recent observations of the He II Ly- α forest by Shull et al. (2004) who claim that ‘the ionizing background is highly variable throughout the IGM’ at $z \sim 2.8$.

4. ‘ $[C/H]-L$ ’ and ‘ $\sigma_v - N_H L$ ’ relations

The analyzed LAAs show that they are a *heterogeneous* population that is formed by at least three groups of absorbers: (1) extended metal-poor ($Z < 0.1 Z_\odot$) gas halos of distant galaxies; (2) gas in dwarf galaxies ($0.1 Z_\odot < Z \lesssim 0.3 Z_\odot$); and (3) metal-enriched gas ($Z \gtrsim 0.5 Z_\odot$) arising from the inner galactic regions and condensing into the clouds within the hot galactic halo (high redshift analogs to the Galactic high velocity clouds, HVC).

Figure 2 shows a plot of the measured carbon abundances $[C/H]^1$ versus logarithmic sizes of the studied systems. Systematically higher abundances are seen in compact systems. This tendency reflects, probably, the dilution of metals within galactic halos caused by the mass transport processes (like diffusion, turbulent mixing, galactic rotation, shear, and etc.). Metals are, probably,

¹Using the customary definition $[X/H] = \log(X/H) - \log(X/H)_\odot$. Photospheric solar abundances are taken from Holweger (2001).

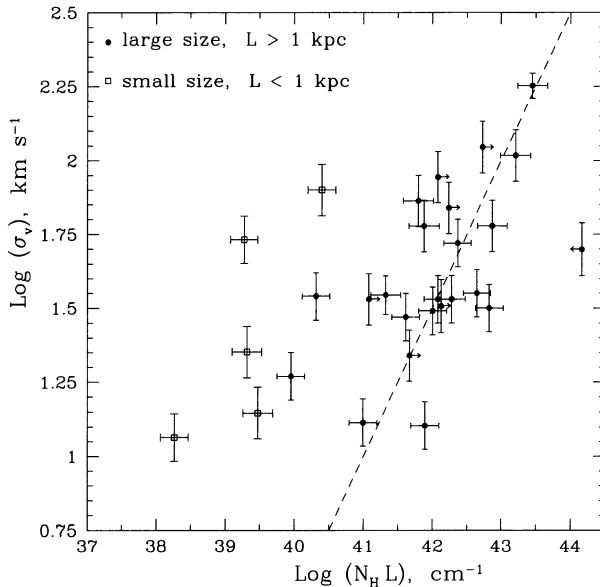


Figure 3. Plot of the line of sight velocity dispersion $\log(\sigma_v)$ vs. $\log(N_H L)$ for the same sample of the LAAs shown in Fig. 2. The dashed line corresponds to the relation $\log(\sigma_v) \propto 0.5 \log(N_H L)$ expected for the virialized systems. Open squares represent HVC-like clouds with $L \lesssim 1$ kpc.

transported into the halo in form of small dense clouds carried out by wind or jets. In some cases we directly observe such blobs. For instance, the LAAs at $z = 1.385$ ($[C/H] \simeq -0.3$, $L \simeq 1.7 - 2.5$ kpc) and at $z = 1.667$ ($[C/H] \simeq -0.5$, $L \simeq 1$ kpc) toward HE 0515–4414 as well as that at $z = 2.966$ ($[C/H] \simeq -0.4$, $L \simeq 100$ pc) toward Q 0347–3819 are embedded in extremely metal-poor halos with $[C/H] < -2$ (Levshakov et al. 2003b,c).

If LAAs are formed in gas clouds gravitationally bound with intervening galaxies, their internal kinematics should be closely related to the total masses of the host galaxies. We find a correlation between the absorber’s linear size L and its line-of-sight velocity dispersion σ_v . The virial theorem states: $\sigma_v^2 \propto M/L \propto n_0 L^2 = N_H L$. Assuming that the gas systems are in quasi-equilibrium, one can expect $\sigma_v \propto (N_H L)^{1/2}$. In Fig. 3 we plot the measured values of σ_v versus the product of L and the total gas column density N_H . It is seen that most systems with linear sizes $L > 1$ kpc lie along the line with the slope 0.5. 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 the expected relation for the virialized systems. Hence we may conclude that most absorbers with $L > 1$ kpc are gravitationally bound with systems that appear to be in virial equilibrium at the cosmic time when the corresponding LAAs were formed.

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References

- Chen, H.-W., Lanzetta, K. M., & Webb, J. K. 2001, *ApJ*, 556, 158
- Ferland, G. J. 1997, *A Brief Introduction to Cloudy* (Internal Rep., Lexington: Univ. Kentucky)
- Haardt, F., & Madau, P. 1996, *ApJ*, 461, 20 [HM]
- Holweger, H. 2001, in *Solar and Galactic Composition*, ed. R. F. Wimmer-Schweingruber, *AIP Conf. Proceed.* 598, 23
- Levshakov, S. A., Agafonova, I. I., & Kegel, W. H. 2000, *A&A*, 360, 833 [LAK]
- Levshakov, S. A., Agafonova, I. I., Centurión, M., & Mazets, I. E. 2002, *A&A*, 383, 813
- Levshakov, S. A., Agafonova, I. I., Centurión, M., & Molaro, P. 2003a, *A&A*, 397, 851
- Levshakov, S. A., Agafonova, I. I., D'Odorico, S., Wolfe, A. M., & Dessauges-Zavadsky, M. 2003b, *ApJ*, 582, 596
- Levshakov, S. A., Agafonova, I. I., Reimers, D., & Baade, R. 2003c, *A&A*, 404, 449
- Levshakov, S. A., Agafonova, I. I., Molaro, P., Centurión, M., & Tytler, D. 2003d, *A&A*, submitted
- Levshakov, S. A., D'Odorico, S., Agafonova, I. I., & Dessauges-Zavadsky, M. 2004, *A&A*, 413, 827
- Mathews, W. G., & Ferland, G. J. 1987, *ApJ*, 323, 456
- Reimers, D., Köhler, S., Wisotzki, L., Groote, D., Rodriguez-Pascual, P., & Wamsteker, W. 1997, *A&A*, 327, 890
- Shull, J. M., Tumlinson, J., Giroux, M. L., Kriss, G. A., & Reimers, D. 2004, *ApJ*, 600, 570
- Wolfe, A. M., Lanzetta, K. M., Foltz, C. B., & Chaffee, F. H. 1995, *ApJ*, 454, 698