On metal abundances in QSO absorbers

Sergei A. Levshakov

Department of Theoretical Astrophysics, Ioffe Physico-Technical Institute, Politechnicheskaya Str. 26, 194021 St. Petersburg, Russia

Abstract. I review our recent results concerning the metal abundances in quasar absorption-line spectra obtained with the UVES/VLT, HIRES/KECK, and STIS/HST spectrographs. The analysis is based on the Monte Carlo inversion procedure aimed at the restoring the physical parameters and the 1D distributions of the velocity and density fields in quasar absorbers. A functional dependence of the line-of-sight velocity dispersion, $\sigma_v$, on the absorber linear size, $L$, was found: the majority of the analyzed systems follow the scaling relation $\sigma_v \sim (N_H L)^{0.3}$ (with $N_H$ being the total gas column density). This may indicate that the metal absorbers are associated with virialized systems like galaxies or their halos. A metal content enhancement (up to $Z \sim 4Z_\odot$) was observed in small-size absorbers ($L \lesssim 0.4$ kpc), whereas decreasing metal abundances were found in systems with increasing $L$. The lowest metallicity ([C/H] $\equiv -3.0$) was detected in the $z_{\text{abs}} = 2.917$ Lyman-limit system (LLS) with $N(\text{H}\text{I}) = 3.2 \times 10^{17}$ cm$^{-2}$ and $L \approx 140$ kpc. The relative abundance ratio of [Si/C] $\equiv 0.35$, measured in this LLS, seems to indicate that the initial mass function for the stellar population, produced the observed metallicity pattern, was constrained to intermediate masses, $M_{\text{up}} \lesssim 25M_\odot$.

1. Introduction

Metal absorption-line systems in quasar spectra are traditionally used to study different physical processes in the intergalactic matter (IGM) over a wide range of redshifts, back to the time when the Universe was less than 7% of its present age. It is supposed that at $z \gtrsim 10$ the IGM was pre-enriched by the first Population III (Pop III) stars formed from gas with zero metallicity (e.g., Bromm et al. 2001; Nakamura & Umemura 2001) and enriched later due to disruption of low-mass protogalaxies (e.g., Madau et al. 2001) at $6 \lesssim z \lesssim 10$, and due to ejection of metals from massive galaxies at $z \lesssim 6$ (e.g., Aguirre et al. 2001; Scannapieco et al. 2002).

The simulations of collapse and fragmentation of primordial gas clouds suggest that the first generation stars may have been very massive, $M_* \gtrsim 100M_\odot$ (Abel et al. 2000; Bromm et al. 2001). However, the calculations by Nakamura & Umemura (2001) produced a bimodal initial mass function (IMF) for Pop III stars with a second peak at $1 - 2M_\odot$. According to these calculations the first generation supernova ($10M_\odot < M_* < 35M_\odot$) and pair-instability supernova ($140M_\odot < M_* < 260M_\odot$) can produce metallicity in the range $10^{-4}$
to $10^{-3}Z_\odot$. Since the element yields and production rate differ significantly for the massive ($10 - 35M_\odot$) and very massive ($140 - 260M_\odot$) stars (Woosley & Weaver 1995; Umeda & Nomoto 2001; Heger & Woosley 2002), the Pop III IMF can be constrained by measuring the abundance ratios in low metallicity cosmic objects.

Unfortunately, the computational methods usually applied to high resolution spectra of QSOs lie quite often behind the quality of observational data and fail to extract from them all encoded information. The common processing method consists of the deconvolution of complex absorption profiles into an arbitrary number of separate components (assuming a constant gas density within each of them), which are then fitted to Voigt profiles. However, in many cases this procedure may not correspond to real physical conditions: observed complexity and non-similarity of the profile shapes of different ions indicate that these systems are in general absorbers with highly fluctuating density and velocity fields tightly correlated with each other. The need for more sophisticated procedures of data analysis is therefore obvious.

In recent years, it has been shown that accounting for the correlations in the velocity field (mesoturbulence) may change the interpretation of the absorption spectra substantially (e.g., Levshakov et al. 2000a; Levshakov et al. 2002, hereafter LACM). Our first inversion codes, — the Reverse Monte Carlo (Levshakov et al. 1999a), and the Entropy-Regularized Minimization (Levshakov et al. 1999b), — have been developed for a model of a stochastic velocity field neglecting any density fluctuations. They have been applied to the analysis of the H I and D I lines and/or to the metal absorption lines with similar profiles when different species trace the same volume elements independently of the density fluctuations. Later on, we extended this study to the inverse problem for a model of compressible turbulence when one observes non-similar profiles of different atoms and/or ions from the same absorption-line system. The developed procedure, called the Monte Carlo inversion (MCI), is described in Levshakov et al. (2000b, hereafter LAK), and its advanced version in LACM.

The MCI code has been applied to the analysis of metal absorbers with $4 \times 10^{13}$ cm$^{-2} < N$(H I) $< 5 \times 10^{17}$ cm$^{-2}$ from the following QSO spectra: J2233–606 (LACM), Q0347–3819 and APM BR J0307–4945 (Levshakov et al. 2003a), HE 0940–1050 (Levshakov et al. 2003b), HE 0515–4414 (Agafonova et al. 2003a), and PKS 0528–250 (Agafonova et al. 2003b). A brief description of the obtained results is given below.

2. Model assumptions and the MCI procedure

Numerous hydrodynamical calculations performed in the previous decade have shown that the QSO absorption lines arise more likely in the smoothly fluctuating intergalactic medium in a network of sheets, filaments, and halos (e.g., Cen et al. 1994; Miralda-Escudé et al. 1996; Theuns et al. 1998). 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 sightline within the absorbing region and having the same radial velocity (see, for details, § 2.2 in LAK).
The MCI procedure is based on the assumption that all lines observed in a metal system arise in a continuous absorbing gas slab of a 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 the 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 sightline. These fractional ionization variations are just the cause of the observed diversity of profile shapes between ions of low- and high-ionization stages.

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 spectra.

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 which 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 log-normally with the mean $n_0$ and the second central dimensionless moment $\sigma_y (y = n_\text{H}/n_0)$. Both stochastic fields are calculated using the Markovian processes (see LAK for mathematical basics). The set of parameters estimated in the least-squares minimization of the objective function (see eqs.[29] and [30] in LAK) includes $\sigma_v$ and $\sigma_y$ 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: firstly a point in the parameter space \( \{N_\text{H}, U_0, \sigma_v, \sigma_y, Z_a\} \) 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 till 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 is used (details are given in LACM).

3. Main results

From the above mentioned QSO spectra, we have selected 22 absorption systems suitable for the inversion analysis. Our results show that the QSO intervening systems are a heterogeneous population which 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 interpretation of a single system is sometimes subject to
Figure 1. (left panel) Carbon abundances plotted against the logarithmic linear size of the corresponding systems as measured by the MCI procedure. Small size QSO absorbers seem to have systematically higher metal content than systems with larger sizes.

(right panel) Plot of the line of sight velocity dispersion \( \log(\sigma_v) \) vs. \( \log(N_H L) \) for the same sample of the metal systems. The dashed line is the linear regression \( \log(\sigma_v) \propto \kappa \log(N_H L) \) calculated for the points shown as filled circles having both horizontal error bars. The slope \( \kappa \) is equal to \( 0.30 \pm 0.03 \) (1 \( \sigma \) c.l.). Open squares represent HVC-like systems.

large uncertainties, the existence of a wide spread of properties in the different systems is certainly proved.

Figure 1 (left panel) shows an example of the measured carbon abundances \([\text{C}/\text{H}] \) versus logarithmic sizes of the studied systems. Systematically higher metal abundances are seen in compact systems with linear sizes \( L \lesssim 0.4 \) kpc. The highest metallicity of \([\text{C}/\text{H}] = 0.59 \pm 0.08 \) was measured in the associated system at \( z_{\text{abs}} = 1.697 \) toward HE 0515–4144, the linear size of this system is only about 1 pc (Agafonova et al. 2003a). The lowest carbon content (\([\text{C}/\text{H}] = -2.93 \pm 0.13 \)) was found in the LLS at \( z_{\text{abs}} = 2.917 \) toward HE 0940–1050, which shows \( L \simeq 140 \) kpc (Levshakov et al. 2003b). In this LLS we also measured \([\text{Si}/\text{C}] = 0.35 \pm 0.15 \) and \([\text{Al}/\text{Si}] = -0.18 \pm 0.13 \). These values certainly rule out the enrichment by very massive stars explosions and constrain the stellar masses by \( \sim 25M_{\odot} \). If, nevertheless, the Pop III stars were massive (\( M > 140M_{\odot} \)), then the average metagalactic metallicity produced by their explosions should be much lower than \( 10^{-3}Z_{\odot} \).

If metal systems are formed in gas clouds gravitationally bound with intervening galaxies, the internal kinematics of the QSO absorbers should be closely related to the total masses of the host galaxies. In case of galactic population, different types of galaxies show different scaling relations between the linear size

\[^{1}\text{Using the customary definition } [X/H] = \log(X/H) - \log(X/H)_{\odot}. \text{ Photospheric solar abundances are taken from Grevesse & Sauval (1998) and Holweger (2001).}\]
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 $\sigma_v$ was also mentioned in LACM.

The correlation between $\sigma_v$ and $L$ stems from the virial theorem which states: $\sigma_v^2 \sim M/L \sim n_0 L^2 = N_H L$. Assuming that the gas systems are in quasi-equilibrium, one can expect $\sigma_v \sim (N_H L)^{1/2}$.

In Figure 1 (right panel) we examine our systems by comparing their kinematics ($\sigma_v$) with measured sizes ($L$) and total gas column densities ($N_H$). It is seen that in the log($\sigma_v$) versus log($N_H L$) diagram, most systems with linear sizes $L > 1$ kpc lie along the line with the 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 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 Ly$\alpha$ absorbers were formed. If the most metal absorbers identified in the QSO spectra arise in the galactic systems then the question to what degree the intergalactic matter is metal enriched remains open.

The absorption systems shown in Figure 1 (right panel) by open squares exhibit characteristics very similar to that observed for different types of HVCs in the Milky Way and may be interpreted as the high-redshift counterparts of these Galactic objects. The most clear example of such high-$z$ HVC is the mentioned above very metal-rich system at $z_{abs} = 1.697$ with the neutral hydrogen column density $N(\text{H}^\text{i}) = 4.4 \times 10^{13}$ cm$^{-2}$. The system shows absorption from highly ionized transitions of C $\text{III}$, C $\text{IV}$, N $\text{V}$, O $\text{VI}$, Si $\text{IV}$, and probably S $\text{VI}$. We found that only a power law ionizing spectrum ($J_\nu \propto \nu^{-1.5}$) is consistent with the observed sample of the line profiles, i.e., the system was probably blown out from the QSO/host galaxy by a cumulative effect of the supernova in the starburst and the quasar activity. Such metal-enriched outflowing gas is supposed to give rise to some HVCs observed in the Milky Way halo (Bregman 1980; Wakker 2001).

Some of the small-size metal systems show very strong metallicity gradients. A system at $z_{abs} = 1.385$ toward HE 0515–4414 is a good example. Here we measured $N(\text{H}^\text{i}) \simeq 5.3 \times 10^{13}$ cm$^{-2}$, $[\text{C/He}] \simeq -0.5$, and $L \simeq 2$ kpc. This system is probably embedded in an extremely metal-poor halo with $N(\text{H}^\text{i}) \simeq 1.1 \times 10^{15}$ cm$^{-2}$, $[\text{C/He}] < -4$, and $L \simeq 90$ kpc (Agafonova et al. 2003a). The velocity shift between these subsystems is only $\Delta v = 140$ km s$^{-1}$. The velocity excess of the Galactic HVCs is usually greater than 90 km s$^{-1}$, which is consistent with this $\Delta v$ value.

In conclusion, we would like to emphasize that in spite of a utterly inhomogeneity in metal abundances revealed in the Ly$\alpha$ absorbers, all of them are perfectly described within pure photoionization models. Our results show that the fraction of the supposed shock-heated hot gas with temperature $T > 10^5$ K is negligible in the analyzed absorbers, and that it is impossible to relate unambiguously highly ionized absorption systems to the ‘warm-hot’ gas predicted in cosmological models (e.g., Cen & Ostriker 1999; Davé et al. 2001). Each highly ionized system requires a comprehensive study in order to determine its nature and origin.
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