METALLIC ABSORBERS AND THE EVOLUTION OF GALAXY HALOES AND THE METAGALACTIC IONIZING BACKGROUND

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Abstract

An extremely careful separation of the weak metal-line systems relating to the Lyman forest absorbers into individual “single-phase ionization” components with accurate parameters has yielded a large sample in the wide redshift range $1.9 < z < 4.4$. The systems typically span several hundred km s$^{-1}$ and within each the components show a strong coherence in their ionization properties. No sudden evolution is found in the column density ratio $N$(Si IV)/$N$(C IV), contrary to previous indication of a large change near $z = 3$, although there is an apparent rise below $z \sim 2.2$ and above $z \sim 3.8$. A smooth not sudden spectral evolution is reflected in the $z$ distribution of $N$(N V)/$N$(C IV). Comparisons of $N$(Si IV)/$N$(C IV) vs $N$(C II)/$N$(C IV) from the observations with CLOUDY derived values using several model ionizing spectra show the general dominance of a QSO ionizing background at the lower redshifts while an additional strong and eventually dominating stellar contribution is required progressively to higher redshifts.

1 Introduction

Until quite recently most astronomers believed the Lyman forest clouds to be pristine. It was a surprise, therefore, when the spectra of exceptional quality delivered by the high resolution spectrograph of the Keck Telescopes revealed individual metal features related to the high redshift Lyman forest for a large fraction of the stronger lines $[4, 14, 15]$. These metal systems provide a powerful probe of the earliest stages in the growth of structure and the formation of galaxies and give an observational approach to determining the character of the cosmological ionizing sources and the stellar birthrate at those times. Here we give some new results on such metal systems from an analysis of the high quality Keck spectra of the 9 QSOs (emission redshift in brackets) $1626 + 6433$ (2.32), $1442 + 2931$ (2.67), $1107 + 4847$ (2.97), $0636 + 6801$ (3.18), $1425 + 6039$ (3.20), $1422 + 2309$ (3.62), $1645 + 5520$ (4.06), $1055 + 4611$ (4.13) and $2237 - 0607$ (4.56), obtained at a resolution $\sim 6.3$ km s$^{-1}$ FWHM. This work will be more fully described and discussed in a forthcoming publication (in preparation).
2 Component Structure

In general appearance the metal systems associated with the Lyman forest lines are blended complexes of absorber components. They display a range of ionized species, where detectable in the overall spectrum, from the weakest in which only C IV is seen to the strongest which also contain Si IV, C II, Si II, Al II, Al III, O I, Fe II, Ni II and frequently N V. Typically a complex spans a few hundred km s$^{-1}$ and often is associated with one or more others in a close group with wide expanses of clear spectrum between such groups. In an extremely careful analysis using the Voigt profile fitting package VPFIT [10], such complexes, involving all detected ionic species, here have been self-consistently separated into individual component “clouds” closely approximating single-phase ionization regions with quite accurate values for column density (N), Doppler parameter (b) and redshift (z). Excellent simultaneous fits over all species are achieved with the same pattern of redshifts in each and the same pattern of b-values for all ions of a given atom. Most of the components are narrow with b(C IV) largely contained within the range 4-10 km s$^{-1}$. Particularly for the stronger components (which are more precisely determined) the resultant ratios of b-values for ions of different atoms, e.g., b(Si IV)/b(C IV), are physically realistic and yield a temperature structure within the complexes containing values distributed up to a few $\times 10^4$K, typical of photoionization heating.

A frequent feature of the systems is the presence of some broad (a few $\times 10$ km s$^{-1}$), high ionization components which co-exist in velocity space with the much more numerous narrow components of lower ionization [1]. Such sets of different component structures must therefore be signatures of physically distinct but spatially closely related regions. While the implicit model in such profile constructions has only temperature and Gaussian turbulence broadening included in the specific b-parameter characterising each assumed cloud in a complex, large velocity gradients from bulk motions must also contribute to the true overall absorption profile. The broad, high ionization components revealed thus probably represent regions of low volume density dominated by bulk motions.

3 Ionization Balance and the Ionizing Radiation Environment

Values of the column density ratio N(Si IV)/N(C IV) among the components in each system show remarkable coherence, typically extending over a factor only $\sim 10$. There are similar bulk differences between systems. It is interesting that such an ionization pattern is not predicted in recent hydrodynamical simulations of metal-bearing collapsing gas structures in the Universe photoionized by a metagalactic ionizing background [11], although in many other aspects this modeling shows considerable success in reproducing the observed characteristics of absorbers.

As shown in Figure 1 the distribution in redshift of N(Si IV)/N(C IV) for the components of all systems detected over the range $z = 1.9 - 4.4$ (but sufficiently removed from the target QSOs to avoid proximity effects and excluding those assessed as not optically thin in the Lyman continuum to avoid complications from self-shielding) is smooth in the observed range, with a progressive rise in the median value up to a factor $\sim 3$ above $z \sim 3.8$ and $\sim 2$ below $z \sim 2.2$, and is quite constant between these redshifts. Sub-sets of the data, including those containing only simple systems (5 or fewer components) and only complex systems (6 or more components), all show similar trends. Median values for the simple systems also are shown in Figure 1; that these are somewhat lower than those of the full data set (and of the complex systems) is consistent with the positions of these generally more highly ionized systems on the diagrams to be described in Section 3. This observed trend with redshift is quite contrary to previous presentations of a sudden large change near $z = 3$, interpreted as due to a change
Figure 1: Upper left – N(Si IV)/N(C IV) vs redshift (z) for all cloud components in the spectra of 9 QSOs with Si IV outside the Lyman forest and N(C IV) ≥ 10^{12} cm^{-2}. Inverted open triangles are values with 1-σ upper limits for N(Si IV). All systems within 3000 km s^{-1} of the lowest QSO redshifts and progressively up to 10000 km s^{-1} of the highest redshifts, and systems assessed as not optically thin in the Lyman continuum, are excluded. The components of each absorption complex, separated as described in the text, show here as vertically distributed associations (several complexes, from different QSOs, happen to overlap near z = 3.5). Upper right – Median values for the data at left describing the full data set (full line) and only the simple systems (5 or fewer components – dotted line). Errors are ±1-σ values. Lower left – N(N V)/N(C IV) as for N(Si IV)/N(C IV) with the exception that many N(V) values are obtained from components within the Lyman forest where it happens to be relatively clear; apart from strong, unambiguous cases these values are taken as upper limits. Lower right – N(C II)/N(C IV) as for N(Si IV)/N(C IV).

in the metagalactic ionizing spectrum at that epoch from a sudden reduction in the opacity of the evolving intergalactic medium to He^+ ionizing photons as He^+ ionizes completely to He^{++} [13, 12]. Although the basis of the difference is not clear, it is important to stress that the Voigt profile component-fitting technique used here has much more physical relevance than using aggregated system quantities [13], which mix the ionization conditions, or optical
depth determinations [12], which do not discriminate against blends, overlapping structures or temperature effects. While the relevant ionization potentials of the Si and C species related to the appearance of Si IV and C IV straddle the He\(^+\) edge, the presence of N(V) requires higher energies so is a more sensitive indicator of He\(^+\) continuum photons. The redshift distribution of N(N V)/N(C IV) (Figure 1) shows smooth not sudden spectral evolution rising by a factor \(\sim 10\) continuously from \(z \sim 3.5\) to \(z \sim 2.0\). This is consistent with a continuously diminishing break at the He\(^+\) edge, not only from progressive evolution in the opacity of the intergalactic medium but, importantly, also from a greater effective presence of stellar systems, with their intrinsically soft emission spectra, over QSOs at higher redshifts. Also shown in Figure 1 is the distribution of N(C II)/N(C IV), closely representing the ionization parameter. This also has a general rising trend with decreasing redshift, here by a factor \(\sim 4\) from \(z \sim 4\), with an apparent rise also to higher redshift beyond \(z \sim 4\).

Displays of N(Si IV)/N(C IV) vs N(C II)/N(C IV) give much more complete information on the spectral shape of the ionizing flux. Figure 2 compares values for these ratios, derived for the individual components in the full data set, with model predictions of the CLOUDY code [4] (version 90.04) computed for several trial ionizing fields with the aim of matching the observed characteristic curves traced by the observed ion ratios. For a lower redshift set of the data \((z = 1.9 - 2.6)\) a good match is achieved with (a) an ionizing spectrum contributed by QSOs and reprocessed by the intergalactic medium [7, 9] and (b) low metallicity clouds with a distribution in the relative abundance of silicon to carbon ranging over \(\sim 1 - 2.5\) times the solar value, similar to that exhibited by stars in the Galactic halo. Towards higher redshifts there is an increasing overall rise in the data, by a factor \(\sim 2\) for a set at \(z = 2.7 - 3.2\) and \(\sim 4\) for a set at \(z = 3.4 - 4.4\). As already noted there is a general accompanying trend in the distribution in N(C II)/N(C IV) towards lower values (higher ionization parameter), implying greater intensity of the ionizing flux with increasing redshift, lower absorber density, or both. As shown by the CLOUDY modelling in Figure 2 this observed change with increasing redshift cannot be explained by increasing (albeit not sudden) opacity of the intergalactic medium at the He\(^+\) ionization edge. Also tried was a metagalactic ionizing background computed with increasing source contributions from star-forming galaxies adding to the QSO contribution [3] (with the QSOs following the observed drop-off with redshift [1]). A specific case is shown using a model selected from the 1996 updated version of the Bruzual & Charlot population synthesis code [2, 3] (Salpeter IMF, constant star-formation rate, age \(3 \times 10^8\) years). In both these trials there is a substantial rise in the computed characteristic curves only at higher ionization levels, not a general rise as in the observations. Achieving a general rise is very sensitive to the spectral shape between \(\sim 2.5\) and 4 Rydbergs. Contributions to the metagalactic ionizing background from galaxies having other star-formation histories will be explored. However, such a general rise is easily reproduced when “unfiltered” spectra of stars are used in the CLOUDY modelling. Adding the expected metagalactic QSO background reduces but does not destroy this rise. In the specific illustration of this in Figure 2 a stellar contribution equivalent to about \(\sim 30\) times the general QSO flux at 1 Rydberg is indicated at the highest redshifts. A similar pattern of evolutionary behaviour is seen from a display of N(Si II)/N(Si IV) vs N(C II)/N(C IV), which does not have the complication of relative abundance differences. Adding the same stellar flux level at the low redshifts results in a very poor fit to the data.

4 Conclusions

This all is indicating that at lower redshifts the ionization of the metal systems is dominated by QSO light as modified by its passage through the intergalactic medium, while at higher
Figure 2: Comparison of cloud component ion column density ratios with C II and Si IV outside the Lyman forest and N(CIV) $\geq 10^{12}$ cm$^{-2}$ from the spectra of 9 QSOs, with model predictions of the CLOUDY code in the optically thin regime and for low metallicity (1/300 $\times$ solar), for three redshift ranges. Left-indicating open triangles are values with 1-$\sigma$ upper limits for C II. Upper limits including both C II and Si IV (not shown) all are consistent with the data. 

Upper panels – Model predictions computed for Haardt & Madau [7] latest available versions for the QSO UV background [9] appropriate for the indicated redshifts using $q_0 = 0.5$ and in each showing the two cases of Si/C relative abundance: solar (lower line) and $2.5 \times$ solar (upper line). 

Lower panels – Model predictions computed for the highest redshift range (upper right) for three different contributions to the ionizing flux at the absorbers, again showing the two cases of Si/C relative abundance: short-dash lines – the same QSO background as in the upper panel but with a cut-off beyond 4 Rydbergs; dotted lines – the full QSO background with an additional contribution from a source population of star-forming galaxies (see text) included in the radiative transfer analysis, equal to 30 times the general QSO flux at 1 Rydberg [6]; long-dash line – the full QSO background with an additional local stellar contribution (Kurucz 45000K, log $g = 4.5$ [8], available within the CLOUDY code) equal to 30 times the general QSO flux at 1 Rydberg. The cosmic microwave background, a significant cause of Compton cooling for low density clouds, is included in all cases.

At redshifts the ionization becomes progressively dominated by the intense light of “local” stellar regions close enough to retain their intrinsic spectral shape (indeed increasing emphasis on local sources is expected at higher redshifts due to the increasing cosmic opacity). This has important bearing on the star formation history of the Universe and can give evidence of galaxy evolution for a population of structures not directly observable. It is also suggestive of an origin for the weak metal absorption systems of the Lyman forest which is not related to Population III stars but more directly with protogalactic or other star-forming structures.
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