Metal systems of the Lyman forest

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Abstract. An extremely careful analysis of the forest of weak metal-line systems at \( z \sim 2 \) has allowed the separation into individual 'single-phase ionization' components with accurate parameters. The systems typically span several hundred \( \text{km s}^{-1} \) and within each the components show a strong coherence in their ionization properties. A general feature of the observed systems is the presence of high ionization broad components which co-exist in velocity space with more numerous, narrow, lower ionization components. From a sample of components extending to \( z \sim 3.5 \), taken either individually or as system totals, no rapid evolution is found in the column density ratio \( N(\text{Si IV})/N(\text{C IV}) \), contrary to previous indication of a large change near \( z = 3.1 \). Comparisons of component ion ratios including Si IV, C IV, C II and Si II from the sample at \( z \sim 2 \) with CLOUDY derived values using several model ionizing spectra show the general dominance of the metagalactic ionizing background over local stellar radiation and give Si/C distributed 1–3 times the solar value. Indications of the evolution of structure are highlighted.

1 Introduction

With the spectra of exceptional quality delivered by the high resolution spectrograph of the Keck telescope it has become possible to detect individual metal features, most commonly the C IV \( \lambda \lambda 1548,1550 \) doublet, related to the high redshift Lyman forest clouds for a large fraction of the stronger lines (Cowie et al. 1996; Tytler et al. 1996; Womble, Sargent & Lyons 1996; Songaila & Cowie 1996). In general appearance such metal systems are blended complexes of cloud components. The deduced carbon abundance in the complexes typically is \( < 10^{-2} \) of solar. In their full investigation Songaila & Cowie deduce also that Si/C is about three times solar (for each complex considered as an entity), pointing to chemical abundances in these systems similar to Galactic halo stars. Additionally, they find rapid evolution in the column density ratio \( N(\text{Si IV})/N(\text{C IV}) \), from values of a few \( 10^{-1} \) at higher redshifts to about ten times lower at \( z < 3.1 \) abruptly occurring in a redshift interval \( < 0.1 \), which they suggest arises from a sudden reduction in the opacity to He\(^+\) ionizing photons of the evolving intergalactic medium (see also Cowie in this volume).

Here I give some new results on such metal systems from a full analysis of a high quality spectrum of Q1626+643 \((z = 2.3)\) obtained on the Keck telescope at a resolution \( \sim 6.3 \text{ km s}^{-1} \) FWHM, augmented with an analysis of similar quality Keck spectra of Q1107+487 \((z = 3.0)\) and Q1422+231 \((z = 3.6)\).
Figure 1: Left – Complex at $z = 2.29$ in the normalised spectrum of Q1626+643 and simultaneous profile fits (bold smooth lines) superimposed, demonstrating the overall excellence of the fits. From the bottom: C IV $\lambda 1548$ (overlying C IV $\lambda 1550$ and weak Ni II $\lambda 1741$ from other systems are included), C IV $\lambda 1550$, Si IV $\lambda 1393$, Si IV $\lambda 1402$, C II $\lambda 1334$. The range shown spans 290 km s$^{-1}$. The ticks mark the positions of individual components, each with appropriate $b$-value not indicated here. Upper right – Deconstruction of a portion of the C IV $\lambda 1548$ and Si IV $\lambda 1393$ profile fits, retaining only the high ionization components shown in bold lines. The range here spans 130 km s$^{-1}$. Lower right – Similar, retaining only the lower ionization components.

2 Kinematic Structure

In Q1626+643 there are about 20 metal systems in the range $1.6 < z < 2.3$ as indicated by C IV absorption in the clear spectral region between the Lyman $\alpha$ and C IV emission lines. These metal complexes display a range of ionized species, where detectable in the overall spectrum, from the weakest in which only C IV is detected to the strongest which also contain Si IV, C II, Si II, Al II, Al III, O I, Fe II, Ni II and sometimes N V. An example showing some ions in a relatively rich system is in Figure 1. 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 VP-FIT (e.g. Carswell et al. 1991) I have self-consistently separated these complexes into individual component clouds closely approximating single-phase ionization regions with quite accurate values for column density, Doppler parameter ($b$) and redshift. In the redshift range available to Si IV outside the Lyman forest 68% of the components defined in C IV are also detected in Si IV. Excellent simultaneous fits are achieved (as is obvious in Figure 1) with components each having the same redshift over all species, and the same $b$-value.
for all ions of a given atom, but different column densities. Most of the components are narrow: 60% have $b(C\ IV)$ distributed from 10 km s$^{-1}$ to below 4 km s$^{-1}$ while 12% have $b > 20$ km s$^{-1}$. The distribution here is more peaked to lower $b$-values than that found by Rauch \textit{et al.} (1996) for clouds dominantly at higher redshifts. Particularly for the stronger components 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 $10^4$K, typical of photoionization heating, as found earlier (Rauch \textit{et al.} 1996).

A frequent feature of the systems is the presence of a few broad, high ionization components which co-exist in velocity space with the much more numerous narrow components of lower ionization. A strong example of this, indicated with C IV and Si IV, is shown in Figure 1. In one display the lower ionization components have been suppressed in the fitted profile leaving a very broad component of $b = 32$ km s$^{-1}$ with two narrower components, all of which are present strongly in C IV but weak or absent in Si IV. The converse case shows only the lower ionization components, which now demonstrate a striking similarity between the C IV and Si IV profiles. Such sets of different component structures must therefore be signatures of physically distinct but spatially closely related regions which can be isolated in the fitting procedure. 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. Nonetheless, any spectrum can be described with clustered Voigt profile fits to the accuracy required with the available signal-to-noise ratio. The broad, high ionization components revealed here thus probably represent regions of low volume density dominated by bulk motions. Comparison with the results of simulations (e.g. Rauch, Haehnelt & Steinmetz 1997) is important to derive proper physical meaning from such observed profiles.

3 Ionization Balance

Figure 2 shows values of $N(Si\ IV)/N(C\ IV)$ vs redshift for all system components found in the spectrum of Q1626+643 having $N(C\ IV) \geq 6 \times 10^{11}$ cm$^{-2}$ and Si IV lying redward of the Lyman forest. Immediately noticeable is a remarkable coherence in these values among components in each system, typically extending over a factor only $\sim 10$, while there are bulk differences between systems. Such an ionization pattern is not predicted in recent hydrodynamical simulations of collapsing gas structures in the Universe photoionized by a metagalactic ionizing background (Rauch, Haehnelt & Steinmetz 1997), although in many other aspects this modelling shows considerable success in reproducing observed characteristics of absorbers.

This data set is extended with equivalent high quality samples analysed
Figure 2: Upper – N(Si IV)/N(C IV) vs redshift for all cloud components in the spectrum of Q1626+643 with Si IV outside the Lyman forest and N(C IV) $\geq 6 \times 10^{11}$ cm$^{-2}$. Inverted open triangles are values with upper limits for N(Si IV). To unify the whole data set, where N(Si IV) $\leq 1.6 \times 10^{11}$ cm$^{-2}$ this value is taken as an additional upper limit. Lower left – As upper panel but with an extended sample including components from Q1107+487 and Q1422+231. Here all components within 5000 km s$^{-1}$ of the QSO redshifts and systems assessed as not optically thin in the Lyman continuum are excluded. Lower right – As left but with ratios of total system values.

from the spectra of Q1107+487 and Q1422+231, giving coverage over the range 1.9 < z < 3.5; all are plotted in Figure 2, here excluding systems within 5000 km s$^{-1}$ of the emission redshifts and those not optically thin in the Lyman continuum as assessed from the corresponding Lyman region spectra. Contrary to the finding by Songaila & Cowie (1996) of rapid evolution near z = 3.1 there is no significant overall change in the balance of the ratio values anywhere over the whole range in redshift. The use here of single-phase ionization cloud components to probe the radiation field must be more
Figure 3: Comparison of component ion column density ratios at $z \sim 2$ from the spectrum of Q1623+643 with model predictions of the CLOUDY code in the optically thin regime and for low metallicity. Open symbols show data within 5000 km s$^{-1}$ of the QSO. The models are computed for: (a) Haardt & Madau (1996) latest available versions for the UV background (Haardt 1997) using $q_0 = 0.5$ and $z = 2.160$, and showing two source cases: QSOs – solid line; QSOs + galaxies – long-dash line; (b) power law of $\nu^{-1.8}$ – short-dash line; a 5000K, log $g = 4.5$ stellar spectrum (Kurucz 1979) available within the CLOUDY code – dotted line. The cosmic microwave background, a significant cause of Compton cooling for low density clouds, is included in all cases.

More information on the shape of the ionizing spectrum can be obtained from displays of the ratios N(Si IV)/N(C IV) vs N(C II)/N(C IV) than from N(Si IV)/N(C IV) alone (Songaila & Cowie 1996; Giroux & Shull 1997). In Figure 3 is such a plot from the Q1626+643 data set compared with model predictions of the CLOUDY code (Ferland 1996) for several assumed ionizing backgrounds and for solar relative abundance of Si/C. For the broadly distributed material (filled symbols), evident is the relative insensitivity to the spectral shape assumed for the metagalactic background in the span of most of the data. This allows component values for Si/C distributed up to
about three times solar, the level previously indicated at higher redshifts for system totals (Songaila & Cowie 1996; Rauch, Haehnelt & Steinmetz 1997) although for clouds with log $N$(C II)/$N$(C IV) $\lesssim$ −0.3 (i.e., at lower densities) values seem closer to solar. The same conclusion comes for clouds close to the QSO (open symbols), here using the more appropriate pure power law spectrum. On the other hand, if the ionizing spectrum is dominated by local effects from massive stars, higher values of $N$(Si IV)/$N$(C IV) will result (Giroux & Shull 1997; Savaglio et al. 1997) and Si/C may be closer to the solar value throughout, as illustrated here with use of a 50000K star model spectrum. An alternative display using the same model ionizing spectra to construct the ratios $N$(Si II)/$N$(C II) vs $N$(C II)/$N$(C IV), also shown in Figure 3, gives less overall dependency on spectral shape so is a better indicator of relative abundance, again in the span of most of the data. A similar distribution for Si/C again results. Taken together, the two representations indicate that local stellar sources do not dominate the radiation environment for these absorbers, although the not complete consistency between them suggests some, not unexpected, departure from strict photoionization equilibrium (e.g., Rauch, Haehnelt & Steinmetz). This is developed in a more complete investigation including several other ions in a later paper (in preparation).

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References

[1] Carswell, R.F., Lanzetta, K.M., Parnell, H.C. & Webb, J.K., 1991, ApJ 371, 36
[2] Cowie, L.L., Songaila, A., Kim, T.-S., & Hu, E.M., 1995, AJ 109, 1522
[3] Ferland, C.J., 1996, *Hazy I, Brief introduction to Cloudy 90*, University of Kentucky, Department of Physics and Astronomy Internal Report
[4] Giroux, M.L. & Shull, J.M., 1997, AJ 113, 1505
[5] Haardt, F. & Madau, P., 1996, ApJ 461, 20
[6] Haardt, F., 1997, [http://nemesis.stsci.edu/~haardt/](http://nemesis.stsci.edu/~haardt/)
[7] Kurucz, R.L., 1979, ApJ Sup. 40, 1
[8] Rauch, M., Sargent, W.L.W., Womble, D.S. & Barlow, T.A., 1996, ApJ 467, L5
[9] Rauch, M., Haehnelt, M.G. & Steinmetz, M., 1997, ApJ 481, 601
[10] Savaglio, S., Cristiani, S., D’Odorico, S., Fontana, A., Giallongo, E. & Molaro, P., 1997, A&A 318, 347
[11] Songaila, A. & Cowie, L.L., 1996, AJ 112, 335
[12] Tytler, D., Fan, X.-M., Burles, S., Cottrell, L., Davis, C., Kirkman, D. & Zuo, L., 1995, ed. G. Meylan, in *QSO Absorption Lines*, Berlin: Springer-Verlag, p. 280
[13] Womble, D.S., Sargent, W.L.W. & Lyons, R.S., 1996, eds. M. Bremer, H. Rottgering, C. Carilli & P. van de Werf, in *Cold Gas at High Redshift*, Dordrecht: Kluwer, p. 249