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Intergalactic Medium Abundances

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Abstract

Galaxies at high redshifts will enrich the intergalactic medium with heavy elements through winds and supernova ejecta, and QSO absorption lines provide the most useful means of examining the evolution of the element abundances in this medium. Photoionization by background radiation at the densities appropriate for such a medium suggests that ions such as C IV and O VI will provide the strongest absorption lines for comparison with hydrogen. Direct detection of these lines provides heavy element abundance estimates of $\sim 10^{-1.5}$ to 10^{-3} solar in regions where the neutral hydrogen column densities are $\sim 10^{14.5}$ cm^{-2} or more. For lower-density regions, which are generally further from galaxies, average abundances may be inferred by stacking systems or pixel optical depths around the relevant wavelengths. Such methods have some shortcomings, and the results do not always agree very well, but suggest that heavy element abundances are $\leq 10^{-2.5}$ solar.

1.1 Introduction

The cold dark matter simulations describing the growth of structure in the Universe give a very good description of the nature of the intergalactic H I content, as confirmed by high-resolution spectroscopy of QSOs against which the corresponding H I absorption may be seen. What this shows is fairly complex structure with, as one would expect, a smooth transition between condensations, where self-gravity becomes important, and the surrounding medium. Under these circumstances what is truly intergalactic medium becomes a matter of where one wants to put the boundary between what is in galaxies and what is not.

There have been several papers describing the growth of structure in the Universe and the Lyα forest as a tracer of structure in the intergalactic medium (e.g., Miralda-Escudé et al. 1996; Jenkins et al. 1998; Croft et al. 2002). The models show an expected evolution in the gas component in the Universe, and the observational material shows similar behavior (Machacek et al. 2000). Using a range of methods, comparison between models and observations via QSO absorption in neutral hydrogen shows gratifying agreement (Rauch, Haehnelt, & Steinmetz 1997), though of course model selection is based in part on this agreement, and the data themselves for the Lyα forest are particularly uncertain below redshifts $z \approx 1.6$ or so, simply because at low redshifts Lyman forest studies require *HST*.

One of the topics being actively considered now comes under the general heading of "feedback," i.e. how the forming structures generate centers of radiation and heavy element

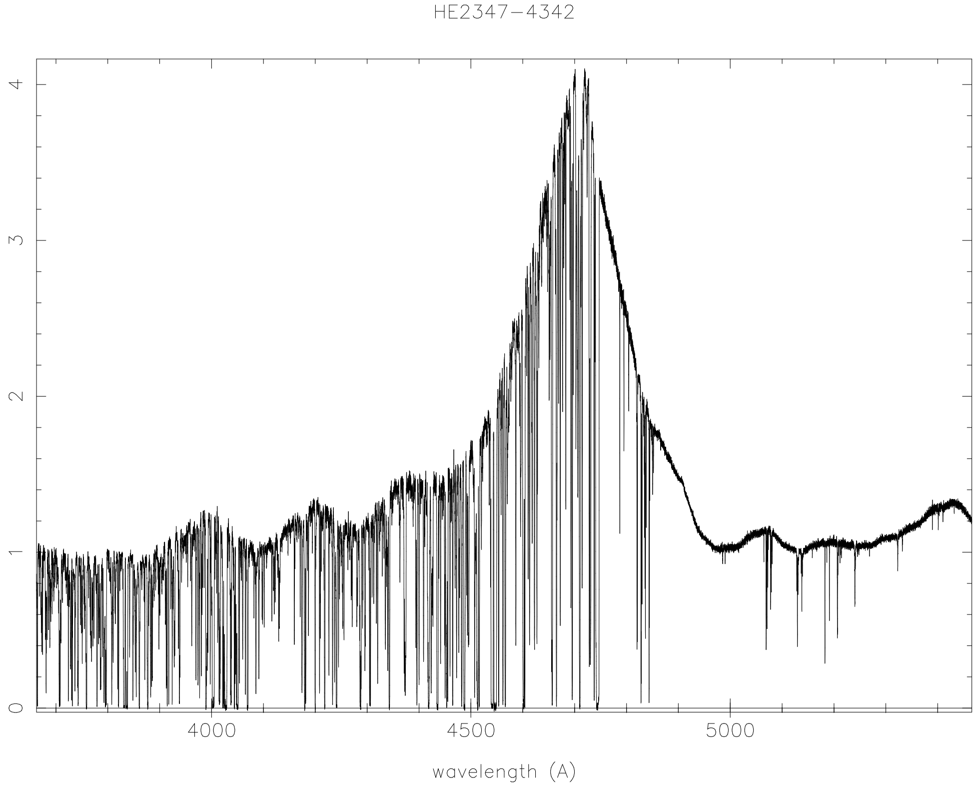

Fig. 1.1. The ESO VLT spectrum of the redshift $z = 2.88$ QSO HE2347−4342 showing the spectral region around the Lyα emission line. (Data from the ESO QSO absorption large program; PI = J. Bergeron.)

production that then affect the surrounding intergalactic medium (Cen & Ostriker 1999). There have been a number of studies of the ionization of an inhomogeneous intergalactic medium by star-forming galaxies and quasars (Ciardi et al. 2000), the heating and ionization, particularly of helium (Theuns et al. 2002; Sokasian, Abel, & Hernquist 2003), the transport of heavy elements by galactic winds (e.g., Croft et al. 2002), and supernova-driven pregalactic outflows (Madau, Ferrara, & Rees 2001; Masao, Ferrara, & Madau 2002).

Here we concentrate on the observational constraints on the chemical enrichment of the intergalactic medium, particularly at redshifts $2 < z < 4$ where there is a wealth of material available from QSO absorption-line studies, especially from Keck HIRES and, more recently, UVES at the VLT. A sample spectrum showing the rich Lyα absorption at wavelengths shortward of the Lyα emission line, and the relative paucity of heavy element lines at longer wavelengths, is shown in Figure 1.1. It is the comparison of the H I line strengths and those from various ionization stages of heavier elements in such spectra that form the basis for intergalactic medium abundance studies.

Since the gas in the intergalactic medium is highly ionized, we consider briefly in the next section the background photoionizing flux. Following that we turn to the detection of heavy elements through the direct measurement of the ion transitions in high signal-to-noise ratio

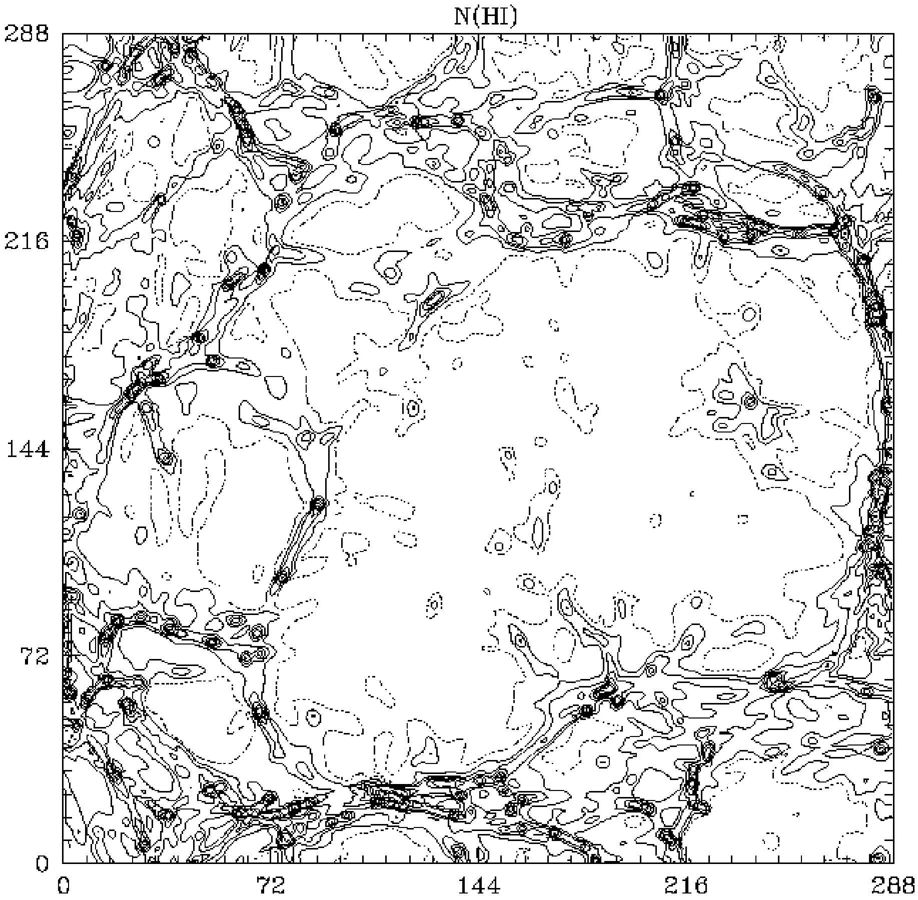

Fig. 1.2. A slice of the simulation by Miralda-Escudé et al. (1996) showing the neutral hydrogen column density at $z = 3$, with contours at $10^{12.5}$ cm^{-2} (dotted) and higher levels at intervals of 0.5 dex. (Reproduced from Miralda-Escudé et al. 1996.)

(S/N) spectra, and note that these generally correspond to the regions with higher densities and higher H I column densities, which place them quite close to condensations that are associated with galaxies (see Fig. 1.2). We then describe some stacking techniques used to explore the abundances in lower-density regions, which represent the intergalacic medium far from galaxies, where the heavy element lines are too weak to be detected in individual cases.

1.2 Abundances and Ionization

The study of element abundances in the intergalactic medium became a matter of observation rather than speculation when Chaffee et al. (1985) drew attention to a $z = 3.32$ absorption system toward the redshift $z_{em} = 3.42$ QSO 0014+81, which has two components with H I column densities $\log N(\text{H I}) = 16.7$ and 16.3 cm^{-2}. The marginal presence of Si III at this redshift in their spectra leads to a metal-to-hydrogen ratio approximately $10^{-2.7}$ solar if the identification is correct. Other possible lines, notably C IV, C II, and O VI, were not detected, so the heavy element abundances in this system were clearly low. A subsequent investigation by Chaffee et al. (1986) concluded from a search for C III λ977 that the heavy element abundances in this system are likely to be $< 10^{-3.5}$ solar. Later work by Cowie et al. (1995) on the same object was based on higher-S/N Keck spectra, and they found both C II and Si IV at levels that turn out to be broadly consistent with a heavy element abundance $\sim 10^{-3}$ solar, but with relative ratios of the various heavy elements somewhat different from the solar values.

The range of values for the abundances in this case is not surprising. There are several assumptions that go into this general modelling and line strength prediction. The most important of these are:

- The clouds are predominantly photoionized and in ionization equilibrium, with a specified ionizing flux.
- the heavy elements are in fixed (usually solar) ratios.

The assumed ionizing flux changes not only with epoch, but, not suprisingly as our knowledge improves, with time of publication. Chaffee et al. (1986) assumed a Weymann-Malkan input spectrum (Bechtold et al. 1987) based on a QSO background with attenuation from the intervening galaxies. Later models by Haardt & Madau (1996) are also based on QSOs as the source, and the most recent models add a contribution from young galaxies (Haardt & Madau 2001). The neutral hydrogen fraction can be as little as 10^{-5} for typical cases, and this fraction depends on the ionizing flux in the region of the spectrum below the Lyman limit where it is not well known. Another major uncertainty in any such model is the nature of the UV photon flux from QSOs and the He II content of the intergalactic medium. Figure 1.3 shows the expected column densities for various ions as a function of total hydrogen number density per cm^3 assuming photoionization equlibrium in a uniform-density medium irradiated by the Haardt-Madau (1996, 2001) background flux estimates at redshift $z = 2$. It is evident from these curves that differences up to about 0.5 dex may be expected, even given best estimates for the photoionizing background fluxes.

The He II opacity is expected to be critically important for species such as O VI, since the ionization potential of He II is considerably less than that required to reach O VI. The O VI doublet at $\lambda\lambda$1032, 1037 Å is likely to be the strongest observable heavy element feature if the Universe is optically thin in the He II absorption continuum, but not otherwise. Thus, O VI searches are important for two reasons—metallicity studies and ionizing background considerations. However, there is a major complication in that the O VI doublet lies deep in the Lyα forest and so it is difficult to measure. The C IV $\lambda\lambda$ 1548, 1550 Å doublet is at longer wavelengths and does not suffer from such confusion, so, while the lines are expected to be weaker, it may be the most sensitive for heavy element abundance searches, especially at higher redshifts where the Lyα forest confusion is most severe.

1.3 C IV Searches

An early in-depth study of heavy elements associated with the lower H I column density systems, which are more typical of the Lyα forest, was that of Cowie et al. (1995). They found that roughly half of the Lyman forest lines with $\log N(\text{H I}) > 14.5$ cm^{-2} at redshifts $z \approx 3$ have measurable C IV with $\log N(\text{C IV}) > 12.0$; so inferred metallicities are

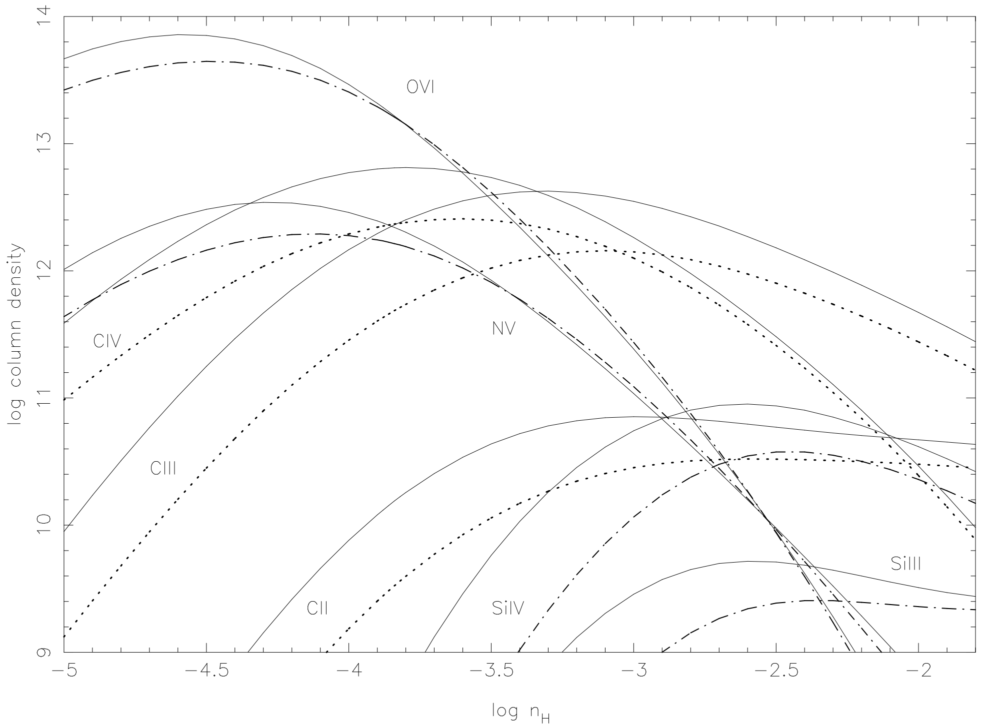

Fig. 1.3. The predicted column densities for ions in a system at redshift $z = 2.0$ for $\log N$(H I) = 15.14, heavy element abundances $10^{-2.65}$ solar, and a range of hydrogen densities $n_{\rm H}$ in the absorbing region. The solid lines are for the Haardt-Madau (2001) background, and the others are for the Haardt-Madau (1996) background flux. Carbon ions are shown as dotted lines to distinguish them from other species.

$\sim 10^{-2}$ solar. Thus, most of these systems do not have primordial element abundances, as had been assumed at the time. The C IV lines are more usually in blended complexes, and if these are not transient (with a time scale $\sim 10^7$ yr), they must be parts of some gravitationally bound systems. Such velocity structure may be present in the corresponding H I lines, but in Lyα, particularly, saturation effects, and the fact that any thermal broadening of the lines is greater for hydrogen than for other species, usually make it extremely difficult to determine.

Studies by Songaila & Cowie (1996) and Songaila (1998) refined this further. They found C IV in about 75% of absorbers with $\log N$(HI) > 14.5 and more than 90% of those with $\log N$(HI) > 15.2. The latter group were found to have a narrow range of ionizations, covering less than a factor of 10 in number ratios of C IV/H I, C II/C IV, Si IV/C IV, and N V/C IV. The line widths imply photoionization rather than collisional ionization is dominant. The typical carbon abundance is $\sim 10^{-2}$ solar, and the Si/C ratio about 3 times solar. A typical example of such a system, with a total $\log N$(H I) > 15.2, is shown in Figure 1.4.

One very interesting finding was that Si IV/C IV decreases rapidly with redshift from high values (> 0.1) at $z > 3.1$. This could be the result of a change in the ionizing spectrum as the intergalactic medium becomes optically thin to He II ionizing photons. There have been indications of a change in Lyα forest line width at a similar redshift (Kim, Cristiani, &

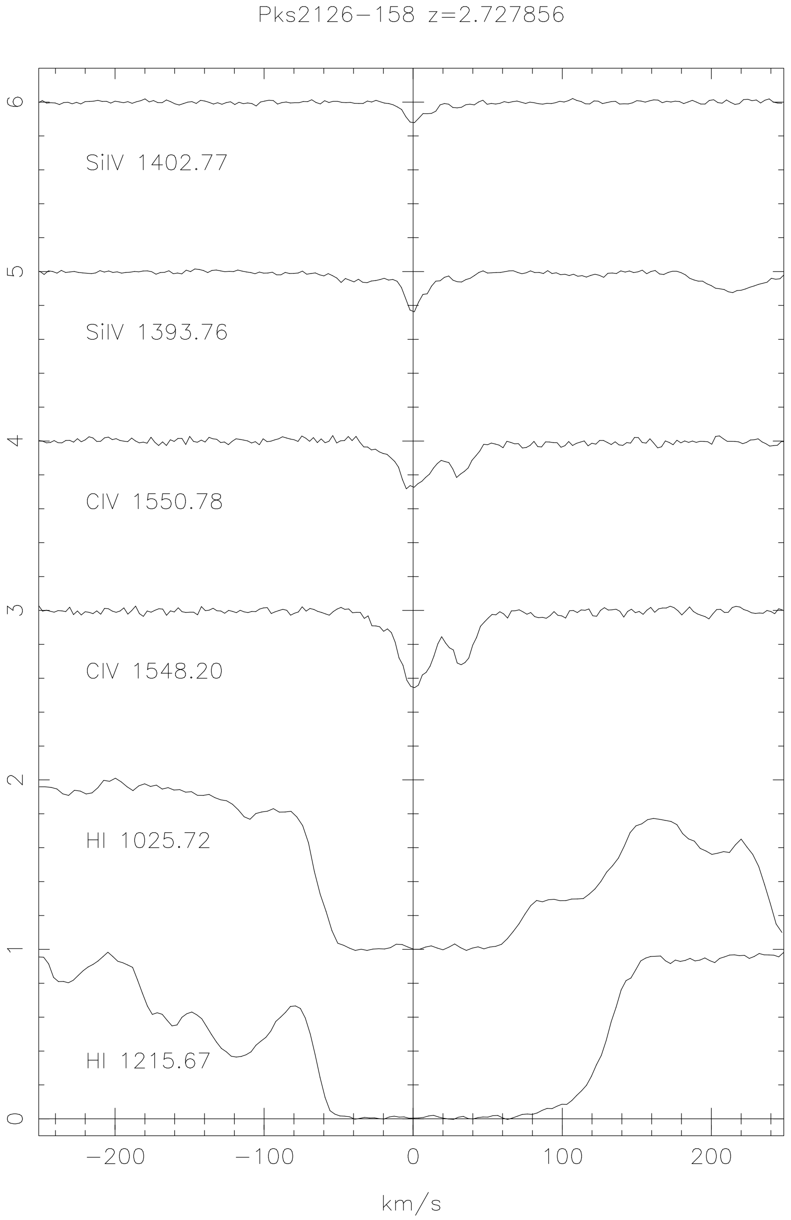

Fig. 1.4. The Lyα, Lyβ, C IV, and Si IV lines, on a common velocity scale, in the redshift system at $z = 2.727856$ in the spectrum of PKS 2126–158. Note the common velocity structure in the C IV and Si IV lines spreading over ~ 50 km s^{-1}, which cannot be seen in the saturated Lyman lines.

D'Odorico 2002; Theuns et al. 2002), which may arise for the same reason. However, later work shows that the trend in the Si IV/C IV ratio is less clear (Boksenberg 1997), so such an association may be spurious.

A feature of the systems in which C IV is generally found is that the H I column densities generally correspond to overdensities relative to the Universe mean of 5 or more, and these are likely to be close to galaxies, i.e. close to likely sources of chemical enrichment. However, the association is not as straightforward as the current simulations suggest, since the outflows from the galaxies themselves, necessary for the heavy element enrichment, disturb the local intergalactic medium. In detail there is a tendency for Lyα absorption to be weaker at the galaxy redshift, and stronger than the norm for a range of velocities a few hundred km s^{-1} from that redshift (see Adelberger et al. 2003). Despite this, the general trend for higher densities (and usually H I column densities) near to galaxies remains.

1.4 O VI Searches

As is evident from Figure 1.3 for the lower-density systems, which are the ones likely to be in the true intergalactic medium, O VI is the species that is most likely to be detected. The major difficulty in attempts to do this is the confusing lines from the Lyα forest, and higher-order Lyman lines. However, at redshifts $\sim$ 2–3 the Lyman forest is not so dense as to preclude searches for individual O VI systems, and recently there have been some successes in this.

Simcoe, Sargent, & Rauch (2002) found several cases where the O VI doublet is present at redshifts $2.2 < z < 2.8$ from a search of Keck HIRES spectra. One of the search requirements was that the O VI lines be clearly present, and they found that these are generally associated with $\log N(\text{H I}) > 15.2$, along with C IV and lower-ionization species. The velocity structure is often complex, and for these systems there is frequently different velocity structure in different ions. They inferred oxygen abundances $> 10^{-1.5}$ solar on average for their sample. Figure 1.5 shows an example that illustrates this based on a UVES/VLT spectrum.

From a study of two QSOs, Carswell, Schaye, & Kim (2002) found that for $2.0 < z < 2.35$ O VI and C IV are generally present if $\log N(\text{H I}) > 14.5$, but usually without Si IV and the other lines. Their systems have lower H I column densities and often apparently simpler velocity structure. The heavy element lines are usually weak, and even at the lower redshifts they were dealing with the blending from Lyα and higher-order Lyman lines from the forest was sometimes considerable. In many cases, though these contaminants could be removed by using the profiles of other lines in the Lyman series, so the procedure is not as uncertain and arbitrary as it might appear. An example is shown in Figure 1.5, showing the fitted heavy element lines and the O VI contamination. Photoionization rather than collisional ionization must be the dominant mechanism in some cases, since the observed C IV lines are much narrower than they would have to be at the temperatures needed for collisional ionization. The heavy element abundances inferred are in the range [C/H]≈ -3 to -2, and the inferred hydrogen densities $\sim 10^{-4}$ cm^{-3} are very similar to the densities expected in the Universe models from the relation between N(H) and total hydrogen density given by Schaye (2002).

Bergeron et al. (2002) also undertook a study of O VI systems toward the $z = 2.45$ QSO Q0329–385, with generally similar results. They also investigated the oxygen-to-carbon ratio, and suggested that size constraints based on the Hubble flow require that this ratio be greater than the solar value. Overall they found that [O/C]$\approx 0 - 1.3$.

While the first reaction is to note the differences between the results described by Simcoe et al. (2002) and Carswell et al. (2002) particularly, they seem to be compatible. The Simcoe at al. sample is at higher H I column densities where complex velocity structure will, in any case, be more evident. It is not clear if the general velocity agreement found by Carswell

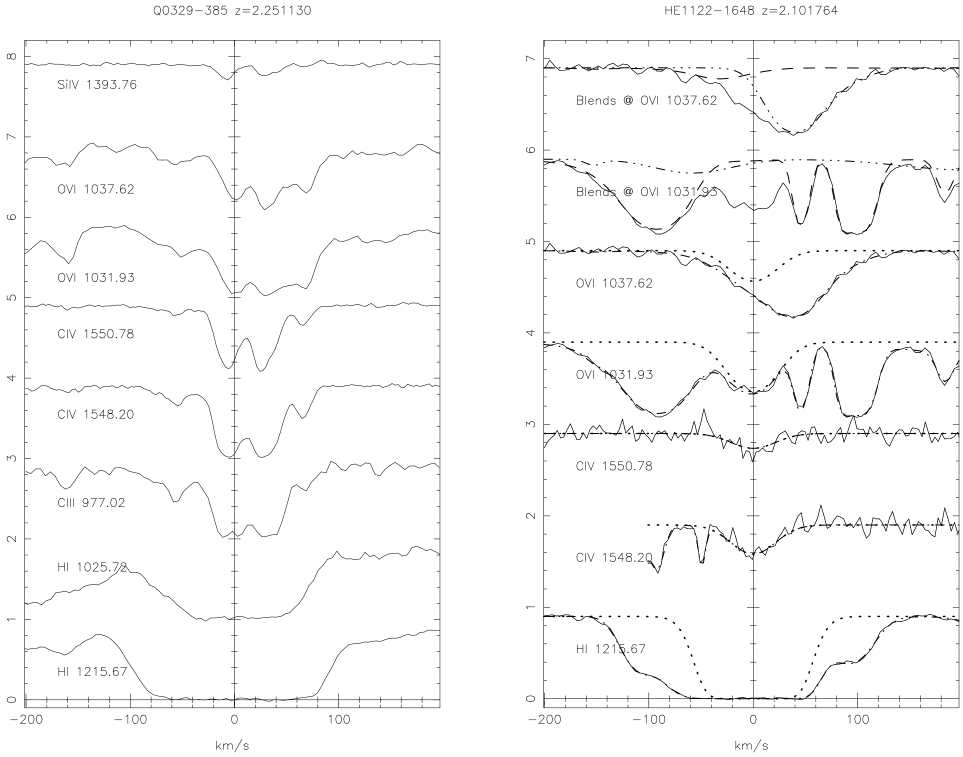

Fig. 1.5. *Left:* A complex absorption system with H I column density $N(\mathrm{H\ I}) \approx 10^{15.2}$ cm^{-2}. Note the differences in the velocity structure between the C III, C IV, O VI, and Si IV lines, and particularly that O VI shows significant offsets in this case. *Right:* An absorption system with $N(\mathrm{H\ I}) \approx 10^{14.9}$ cm^{-2} with simple velocity structure in the heavy elements. In this case Voigt profile fits to corresponding features are shown (dots), as are the blended lines that affect the observed O VI profiles (dash and dot-dash lines show individual blended components).

et al. is real or a result of having only two ions, C IV and O VI, to compare, particularly given the weakness of some of the lines and the uncertainties in allowing for Lyman lines from other systems blended with the O VI. It is interesting that the O VI systems with higher H I column densities tend to fall within the region of the O VI column density/line width diagram expected for a radiatively cooling flow of hot gas (Heckman et al. 2002, their Fig. 1), and so may be similar in nature. For the lower H I column densities, $14.5 < \log N(\mathrm{H\ I}) < 15$, the agreement is not as good, with about half of them having rather lower line widths for their column densities than other objects in that diagram. It is possible that these are the enriched intergalactic regions, which are now less affected by the galaxy that affected them.

The result of these studies has been to establish the presence of highly ionized enriched regions, with the expected densities given the H I column densities. However, the H I column densities correspond to similar overdensities as the higher-redshift C IV studies since the mean density of the Universe is lower in the redshift range where the O VI searches have been undertaken. So we wish to probe to lower H I column densities, and an effective method of doing this is finding some way of improving the S/N by averaging over many systems.

1.5 Stacked Spectra

One way to improve S/N and obtain an average result is by stacking spectra shifted to the Lyα rest position using the observed Lyα wavelengths and to look around at the wavelength regions covering C IV $\lambda\lambda$1548, 1550 and anything else of interest. This has been attempted by several people, starting with an early attempt to detect O VI, in what would now be regarded as rather low-resolution spectra, by Norris, Peterson, & Hartwick (1983), though Williger et al. (1989) failed to confirm their tentative O VI detection in a different sample of objects. Lu (1991) obtained a tentative detection of C IV for systems with $\log N$(H I) $\approx$ 15.3 or more by this method, and suggested on this basis that the C/H ratio might be $\sim 10^{-3.2}$ solar.

Tytler & Fan (1994) used a higher-resolution spectrum to search for C IV by this stacking method and found none for H I column densities in the range $10^{13} - 10^{14}$ cm^{-2}. Keck spectra were analysed in a similar way by Lu et al. (2004), who found that for $13.5 < \log N$(H I) $<$ 14.0 C IV was not detectable at S/N$>$1800. From this they inferred that the abundance of carbon is at most $10^{-3.5}$ solar on average for these systems. Lu et al. (2004) removed a very few systems in which C IV was detectable, so their average value may be biased toward the low side, but not by very much.

However, there are potential problems with this method, as noted by Cowie & Songaila (1998) and investigated further by Ellison et al. (2000). For the high H I column density systems where C IV is seen in individual systems there is significant velocity structure, and the Lyα velocity centroid does not coincide with that of the C IV lines. This will be particularly serious for the earlier lower-resolution studies where blended Lyα features are not well resolved, but even for Keck HIRES spectra Ellison et al. find that there is a velocity offset with a $\sigma = 17$ km s^{-1} between the Lyα and C IV lines. Therefore, any stacking method using the Lyα centroids to determine the C IV position will have reduced sensitivity. How much the sensitivity is reduced depends on the clustering properties of the lines, and to what extent any velocity structure is determined and used for the H I. In Figure 1.4, for example, the Lyα shows a red component that is difficult to separate from the Lyα line alone, but at least that part may be removed if the Lyβ profile is examined as well. If the H I is chosen mainly from clean single systems, as in the Lu et al. (2004) sample, then one is genuinely determining the C IV/H I ratio for those particular systems. The Ellison et al. simulations show that the sensitivity difference is about 0.3 dex in the worst-case C IV/H I velocity spread they adopted, with a sensitivity limit going from C IV/H I = –3.1 to –2.8 for the 67 lines they used with $13.5 < \log N$(H I) < 14.0.

For O VI there is the usual additional complication of Lyman forest blending with the lines of interest. There are two possible approaches to this. One is to treat the blended Lyman lines as an additional source of noise, and estimate this additional noise either by simulations or looking at the fluctuations in the summed spectrum near the O VI lines. Another is to best estimate the contamination from Lyman lines by fitting Voigt profiles and removing them before summing, as has been done by Simcoe, Sargent, & Rauch (2004). In any case, while the heavy element line strength will be affected by velocity offsets and uncertainties in the stacked spectrum the average line strength may be measured against a well-defined local continuum in that spectrum.

1.6 Pixel Optical Depths

A method that does not rely as much on line parameters, and in particular does not require stacking at estimated redshifts from Lyman lines, was introduced by Cowie & Songaila (1998). They correlate pixel optical depths of Lyman and heavy element species, and so avoid any aspect of profile fitting, and find that the mean Lyα to C IV optical depth ratio is roughly constant down to a detection limit corresponding to N(H I) $\approx 10^{13.5}$ cm^{-2}. This gives abundances about an order of magnitude higher than the stacking method, in an interesting contrast with the Lu et al. (2004) result. Ellison et al. (2000) comment that a velocity offset between the Lyα and C IV lines should, as we have seen, only partly account for the difference even in the worst case.

Cowie & Songaila (1998) did not detect O VI by this method in their sample, which was generally at redshifts $z > 3$, but subsequently Schaye et al. (2002) found a signal corresponding to O VI for redshifts $2 < z < 3$. A detailed description of the method and its effectiveness when used on cosmological simulations is given by Aguirre, Schaye, & Theuns (2002). They also give a recipe for how to implement the method, which in summary (for O VI to be specific) is:

- Measure residual flux relative to continuum in Lyα, and take as $\tau = -\log$(relative flux). For saturated lines, use $\min(\tau_{\mathrm{Ly}n} f_\alpha \lambda_\alpha / f_n \lambda_n)$ for Lyman series, else τ is ill-determined.
- Determine τ(O VI) at $\lambda\lambda$1032, 1038 Å in corresponding pixels, and choose $\min[\tau(1032), 2 \times \tau(1038)]$ to minimize contamination.
- Correct for contamination by removing pixel optical depths appropriate for other lines, e.g. in the Lyman series.
- Bin into H I values (in log space), and take median τ(Lyα) and τ(O VI) in each bin.

Then, τ(O VI) is O VI optical depth plus perhaps an offset that is independent of τ(H I), which may arise particularly from errors in the continuum estimate. The continuum estimate is especially uncertain in the Lyα forest, where even in relatively uncrowded spectra at $z \approx 2-2.5$ errors of order 2% are not uncommon, and even for the C IV regions the presence of broad emission lines (not to mention small flux calibration errors causing small ripples and even jumps in the spectra) may result in continuum uncertainties of up to about 0.5%, even in spectra with S/N$\approx$ 80 per pixel. Typical results for O VI are shown in Figure 1.6. Note the detections of O VI, down to apparent optical depths $\sim 10^{-1}$ for redshifts $z < 3.2$, and possibly up to $z \approx 3.5$, as revealed by the correlated O VI and H I optical depths.

This method shows the presence of O VI, but converting the measured quantities to abundances involves calibration via simulations. Even then, uncertainties in the continuum levels in the individual spectra can be important. A statistician might be concerned at taking a minumum optical depth from several lines and converting that to an optical depth at Lyα, or the strongest heavy element transition, when there is noise present, and of omitting those pixels where there is apparent emission rather than absorption. Comparison of the results from those from the same analysis applied to simple simulated spectra is all that is needed to make allowance for any such biases. Another possible source of bias is the difference in intrinsic line widths between the O VI and corresponding H I lines if thermal broadening is important, as it appears to be in those systems where O VI and C IV are strong enough to be measured directly. For pure thermal broadening the O VI lines have velocity widths $\frac{1}{4}$ that of H I, so in individual cases the H I optical depth may still be a significant fraction of the peak value, while for the corresponding O VI this is not true.

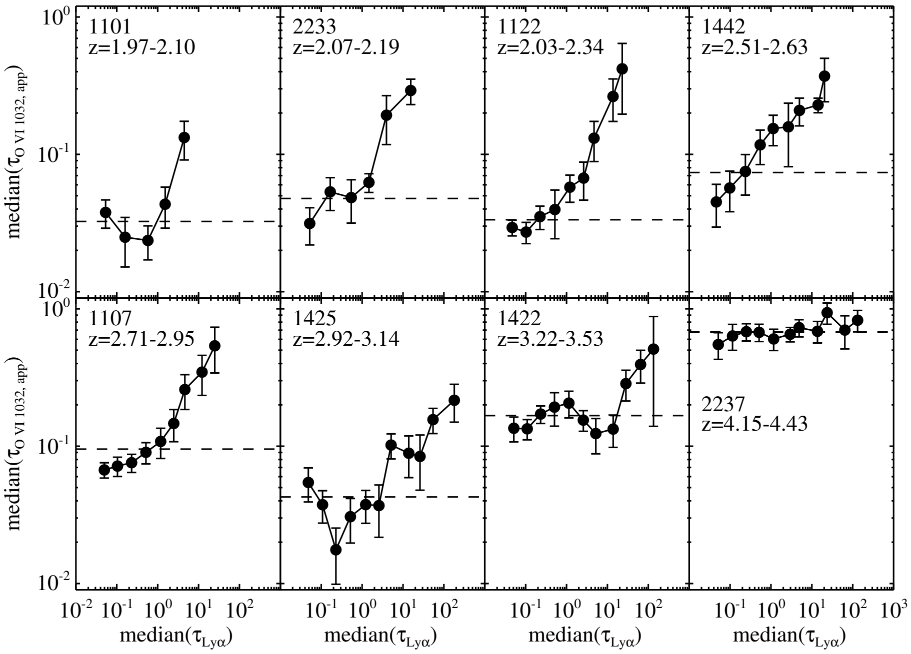

Fig. 1.6. Results from a pixel analysis search for O VI. H I-O VI pixel pairs were binned in H I optical depth, and the data points indicate the median optical depth in each bin. The dashed lines represent O VI detection limits. (Reproduced from Schaye et al. 2000.)

1.7 Anomalous Abundances

Much of the discussion above has been aimed at addressing the question of average abundances in the intergalactic medium, and seeing if there are trends with H I column density and the matter density in the regions. There will, of course, be a spread in the abundances for any simple parameterization such as this, but there is little information yet on how large this spread is. However, there are a few anomalously high-abundance regions that may be telling us something, even if it is not clear what.

The Carswell et al. (2002) compilation of O VI systems contained one that shows O VI and C IV, at redshift $z = 2.030096$ toward HE 1122−1648, which is unusual in two ways: the Lyα is very weak and, unlike the other systems studied, N V is clearly present. An examination of other spectra at similar redshifts suggests that, while such systems are by no means common, this particular example is not unique. The narrow heavy element lines again point to temperatures that are too low for collisional ionization to be effective, and if they are photoionized by the intergalactic background then the density is $\log n_{\mathrm{H}} \approx -4$ to -3.5 cm^{-3} and the heavy element abundances $\sim$solar. In particular, the nitrogen-to-carbon ratio is $\sim$solar or even higher. Size estimates based on these models suggest a length scale $\sim$ 100 pc. There are no nearby high H I column density systems in this case, so if it is enriched material it is not close to a galaxy with a significant interstellar medium. This could be due to local ionization or dynamic effects, or geometry, so may not be a significant problem. However, the nitrogen overabundance does set such systems apart, and leads one to speculate that it is not normal galaxy ejecta but that from a QSO. This could be either the background object, though the velocity is then $\sim 30,000$ km s^{-1}, or from a foreground active galactic nucleus.

While such systems may only be of marginal importance in the overall scheme of things, their existence has to be allowed for in the various stacking techniques that are used to search for heavy elements at low H I column densities. One such contaminant in a sample of a few hundred systems could lead to an average abundance $\sim 10^{-2}$ solar while the "typical" abundance could be much less. The use of median, as opposed to average, values for pixel or stacked spectra, as is common, should avoid such problems.

1.8 Conclusions

The direct detection of highly ionized heavy elements corresponding to neutral hydrogen at H I column densities $> 10^{14}$ cm^{-2} reveals that parts of the higher-density intergalactic medium has been enriched by outflow of material from galaxies. The heavy element abundances, where they have been determined, suggest that the lower-density regions have lower element abundances. For systems with $N(\text{H I}) > 10^{15}$ cm^{-2} the abundance of oxygen is $\sim 10^{-1.5}$ solar, while for $10^{14.5} < N(\text{H I}) < 10^{15}$ cm^{-2} estimates are $\sim 10^{-2.5}$ solar. At lower column densities less direct techniques, such as stacking by redshift or pixel optical depth, are required. These techniques each suffer from some biases and uncertainties, and we are still at the stage where these have not been explored fully. Uncertanties in ion velocity relative to the H I position reduce the sensitivity of the redshift stacking method, and for pixel stacking the results should be compared with simulations. The two techniques can give raw abundance estimates that are almost an order of magnitude apart in the worst cases, and estimated corrections to both do not yet make them fully compatible. So, on the basis of what we know so far, for the low-density regions the true intergalactic medium is far from galaxies, and the heavy element abundances could be anywhere below a rather uncertain value of $10^{-2.5}$ solar. Any constraints on the large-scale feedback from galaxies into the intergalactic medium are not very tight.

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