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Observational tests of intergalactic enrichment models

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Abstract. We summarise recent results assessing the carbon and silicon abundances of the intergalactic medium (IGM) using the 'pixel optical depth' technique. We briefly discuss the implications of these results for models of intergalactic enrichment, focusing on distinguishing 'early' $z \gg 4$ enrichment by the first generations of stars and objects from 'late' enrichment by $2 \lesssim z \lesssim 5$ Ly-break galaxies. We then discuss the comparison of observed QSO spectra to simulated spectra generated from cosmological simulations that self-consistently include enrichment, and draw qualitative implications for the general picture of intergalactic enrichment at $z \gtrsim 2$.

1. Introduction

The widespread existence of metals outside of galaxies has been known for a decade (e.g. Cowie *et al.* 1995) by their absorption lines in high-z QSO absorption spectra, but their origin remains somewhat of a mystery. Were they created in-situ, or removed from galaxies by winds, galaxy dynamics, dust flows, or some other mechanism? And *when*?

This question has been very challenging in part because of the paucity of *detailed* information on the distribution of intergalactic metals. Fortunately over the past few years several groups have been employing large samples of Keck and VLT high-resolution spectra to infer a more detailed view of the observed enrichment (Schaye *et al.* 2003, hereafter S03; Adelberger *et al.* 2003; Pichon *et al.* 2003; Pieri & Haehnelt 2004; Aguirre *et al.* 2004, hereafter A04; Simcoe *et al.* 2004; Aracil *et al.* 2004). Meanwhile, cosmological simulators have begun to incorporate metal generation and transport in their simulations and make comparisons to the observed absorption spectra (Theuns *et al.* 2002; Cen *et al.* 2004; Aguirre *et al.* 2005, hereafter A05). Herein we will review the findings of our group regarding intergalactic abundances, and discuss in a preliminary way what those findings suggest about the mechanism of enrichment. In this exercise, it is useful to have in mind two basic paradigms.

The first we might call "late enrichment", wherein the relatively massive Ly-break galaxies observed at $z \lesssim 6$ are responsible. This model has the virtue that strong winds are in fact observed in such galaxies (e.g. Pettini *et al.* 1998), and that much more star formation takes place at $z \lesssim 6$ than at $z \gtrsim 6$. Its deficiencies are that the regions near such galaxies comprise a small fraction of the cosmic volume – so spreading metals widely enough may be difficult – and that the high outflow velocities necessary to escape the galaxies' potential wells will lead to high post-shock gas temperatures in the IGM (as well as structural changes in the IGM near galaxies) that may be incompatible with observations of the Lyα forest.

In a second scenario, "early enrichment", the very earliest generation of protogalaxies and stars (including Population III) at $z \gg 5$ pollute the IGM. As these are more numerous than the Ly-break galaxies they might affect a larger filling factor, and they would provide the IGM with more time to recover from the effect of winds and appear relatively undisturbed (e.g. Madau, Ferrara & Rees 2001) by $z \sim 3$. For present purposes we will model such enrichment as metals "sprinkled" into the IGM (without affecting the gas at all) at $z > 5$, with no subsequent metal evolution.

How might we distinguish these scenarios (or others) using observations of the IGM at $z \lesssim 4$? There are a number of ways. 1) If the observed enrichment in a given environment *evolves* then this directly indicates that enrichment by $z < 4$ galaxies is important. 2) The spatial distribution of metals in the two scenarios should differ – though in a way that requires careful modelling. 3) In late enrichment many metals may lie in warm/hot collisionally ionised gas rather than in warm ($\sim 10^4$ K) photoionised gas, so probing the temperature of the observed metals would be very useful. 4) Abundance ratios of the IG metals would aid in determining the enriching sources. 5) The total amount of intergalactic metals may be compared to that expected in different enrichment models.

Fortunately, large samples of data as well as advances in the way the data is analysed now makes this possible. In particular, the "pixel optical depth" method, pioneered by Cowie & Songaila (1998), and tested, extended, and employed by Aguirre *et al.* (2002, hereafter A02), S03, A04, and A05 allows significant progress in all of these directions.

There are two basic means of proceeding in this aim; inferring abundances from the observations as directly as possible and comparing to these models, or generating models and comparing these directly to the observations. We have taken both approaches, as described in Sections 2 and 3, respectively.

2. The inferred intergalactic abundances

The pixel technique is described in detail in A02, S03, and A04. At the most basic level, one plots the optical depths for pixels in a wavelength region where some transition is expected, against those in wavelengths corresponding to absorption by the same gas in another transition. Correlation implies detection: for example, correlation between CIV optical depth $\tau_{\rm CIV}$ and Lyα optical depth $\tau_{\rm Ly\alpha}$ indicates the presence of carbon. The results – and implications for the enrichment scenarios – of applying a suite of techniques based on this idea to a sample of 19 Keck and UVES spectra is summarised below.

Metallicity is inhomogeneous and density-dependent. By assuming an ultraviolet background (UVB) model (our fiducial choice is that of Haardt & Madau 2001 including both quasars and galaxies), and that the relation between $\tau_{Ly\alpha}$ and gas overdensity δ is as given by hydrodynamics simulations, we can covert $\tau_{\rm CIV}/\tau_{\rm Ly\alpha}$ vs. $\tau_{\rm Ly\alpha}$ into [C/H] versus δ (see A02). The result (S03) is that the median [C/H] depends on density:

$$[{\rm C/H}] = -3.47^{+0.07}_{-0.06} + 0.65^{+0.10}_{-0.14} \times (\log \delta - 0.5),$$

where here and elsewhere errors are 1σ. Whether enrichment is early or late, it is unsurprising that high-density regions are more enriched, but this trend had not previously been established. This result (as well as some others below) does depend on the UVB model chosen; for example, a harder UVB (e.g. as from quasars only) would imply a higher metallicity overall, and less of a trend of metallicity with density. However, UVBs very different from our fiducial model are strongly disfavoured. For example, if the UVB is much harder, then the inferred Si/C ratio (see below) is implausibly high, and the *mean* metallicity of the IGM actually increases with decreasing density, which seems unlikely; or if the UVB is much softer, the inferred O/C or O/Si will be implausibly high.

Beyond the medians, the *full* distribution of $\tau_{\rm CIV}/\tau_{\rm Ly\alpha}$ for a given $\tau_{\rm Ly\alpha}$ can be used to determine the scatter in [C/H] at a given density (S03). This reveals that [C/H] is well-fit by a normal distribution with a width of $\approx 0.8\,$dex. This rules out any truly uniform enrichment scenario, and can provide strong constraints when compared in detail to enrichment models (see below).

Metallicity does not appear to evolve significantly. Perhaps even more interestingly, [C/H] at a given gas density appears independent of redshift (S03): a simultaneous fit of the $\delta-$ and $z-$ dependence for all data yields $[\mathrm{C/H}] \propto (0.08 \pm 0.10) \times (z-3)$, and for any given cut in density our results are compatible with no evolution†. Clearly this suggests early enrichment and indicates that the metals we see were in place by $z \sim 4$. Metals could in principle be added to the IGM after $z \sim 4$, but only in such a way that they cannot be observed in CIV absorption.

The observed metals are largely in warm, photoionised gas. The CIII and SiIII lines fall in the Lyα forest and, lacking doublets, are difficult to identify using line-fitting. They can, however, be measured using the pixel technique – the forest appears as a contaminant that can be reliably subtracted. Because the ratios CIII/CIV and SiIII/SiIV are quite sensitive to both the density and temperature of the absorbing gas (but rather insensitive to the spectral shape of the UVB), we can use them to strongly constrain the state of the gas giving rise to the observed absorption. Our results (S03; A04) indicate that the relatively high-density CIV- and SiIV- absorbing gas is at $T < 10^{4.9}$ K. Moreover, the observed $\tau_{\mathrm{CIII}}/\tau_{\mathrm{CIV}}$ and $\tau_{\mathrm{SiIII}}/\tau_{\mathrm{SiIV}}$ ratios are fully compatible with those predicted from numerical simulations with *no* feedback in which metals are added to the IGM in accord with the carbon distribution inferred from the observations (S03; A04; A05). As for the metallicity vs. redshift, this indicates that our results are compatible with the early enrichment "sprinkled metals" model; if carbon or silicon is added to the IGM by later generations of galaxies, then it must not absorb strongly in CIV (i.e. it must be too hot and/or too low-density, and/or too low-metallicity).

Abundance ratios are consistent with no evolution. We can use ions of different elements to infer relative abundances: for example, from $\tau_{\mathrm{SiIV}}/\tau_{\mathrm{CIV}}$ we can infer [Si/C] and from $\tau_{\mathrm{OVI}}/\tau_{\mathrm{CIV}}$ we can infer [O/C]. In addition, the distribution of $\tau_{\mathrm{SiIV}}/\tau_{\mathrm{CIV}}$ at a given τ_{CIV} constrains the *scatter* in [Si/C]. If a Haardt & Madau (2001) UVB is assumed, the analysis yields $[\mathrm{Si/C}] = 0.77 \pm 0.05$. (As for the carbon abundance, this result depends on the UVB: a Haardt & Madau UVB with no galaxies would yield $[\mathrm{Si/C}] \simeq 1.5$, and softer UVBs would lead to $[\mathrm{Si/C}] < 0.75$.) There is no evidence for evolution, density-dependence, or scatter in [Si/C]. The [Si/C] value we obtain is probably within systematic errors‡ of the $[\mathrm{Si/C}] \sim 0.5$ expected from Type II supernovae; alternatively, the high value *might* suggest some contribution from massive, metal-free Pop. III stars which can (according to theoretical models), give as high as $[\mathrm{Si/C}] \sim 1.3$ (see the compilation by Qian & Wasserburg 2005). Note that making the UVB softer would be an easy way to reconcile our [Si/C] with type II yields, but that preliminary analysis indicates super-Solar [O/C] for the same UVB, and [O/C] would *increase* with a softer UVB; so it seems that either O and/or Si is highly overabundant with respect to C.

What does this say about the enrichment scenario? Type II yields would be unsurprising from either early or late enrichment (as both would probably lack significant contributions from Type Ia or AGB enrichment) while Pop. III yields would be expected

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† Note that even if all enrichment were completed by $z = 4$, metallicity would still evolve because over-dense regions increase their over-density with time, and this would cause a flattening of the [C/H] vs δ trend. This effect is compatible with our measurements and is in fact suggested by our analysis, but only at $\approx 1\sigma$ significance (see S03, section 8.1).

‡ Specifically, there are uncertainties in the recombination rates of SiIV (A04) and in the importance of local sources of UV photons (Schaye 2004) that could affect the result at this level.

only to contribute significantly in the early scenario. The lack of evolution in [Si/C] is more evidence against anything evolving significantly, as predicted by the early scenario. Finally, the lack of scatter in [Si/C] suggests that the observed carbon and silicon result from the same nucleosynthetic sources, and are distributed by the same processes.

There is a lot of metal in the IGM. By combining the centre and width of the metallicity distribution at a given density with the fraction (as predicted by simulations) of the IGM at each density, we can add up the contribution of the observed metals to the total metal content of the IGM. Performing this calculation for our observations over the density range $-0.5 \leqslant \log\delta \leqslant 2.0$ yields $\Omega_{\rm C} = 2.3 \times 10^{-7}$ for our fiducial UVB. Using also a uniform value of [Si/C]=0.77 gives $\Omega_{\rm Si} = 3.4 \times 10^{-7}$.

It is interesting to compare this to a rough estimate of the amount of silicon expected to be produced by stellar nucleosynthesis at $z \gtrsim 3$:

$$\Omega_{\rm Si,exp} = 10^{-6}\left(\frac{Y}{0.02}\right)\left(\frac{f_{\rm Si}}{0.05}\right)\left(\frac{\Omega_*}{0.001}\right),$$

where Y is the metal mass/stellar mass formed, $f_{\rm Si}$ the the metal mass fraction in silicon, and Ω_* is the stellar density at $z \sim 3$. This indicates that a substantial fraction of all metals expected to be produced by $z \sim 3$ reside in the IGM. Note that this may cause difficulties if all of the enrichment happened at $z \gg 4$, as the total stellar mass formed at such early times may be insufficient to produce the requisite metallicity unless the early star formation rate is assumed to be extremely high (e.g. Qian & Wasserburg 2005).

3. Comparing observed to simulated spectra

The abundances inferred from the CIV and SiIV optical depths are clearly compatible with the early model in which metals are sprinkled into the gas at $z \gtrsim 4$ without affecting the gas. However, the conversion of optical depths into C and H densities makes use of simulations *without feedback*; it is therefore self-consistent only in the early scenario.

It is thus useful to employ a complementary approach of generating spectra from simulations with enrichment – including the effect of the outflows on the IGM – and comparing these to the observed spectra using the pixel technique. In a first investigation of this sort (A05) we have performed this analysis using two sets of high-resolution particle-based hydrodynamic simulations (Theuns *et al.* 2002; Springel & Hernquist 2003) with different feedback prescriptions that drive strong winds at $z \gtrsim 2$ as per the late enrichment scenario. This led to several general and qualitative conclusions:

Simulations with feedback under-estimate CIV and CIII absorption. As mentioned above, the observed CIV/HI and CIII/CIV ratios are well-reproduced by non-feedback simulations if we impose a metallicity distribution on the gas as inferred from the observations. For CIV/HI, this is just a consistency check, but the CIII/CIV comparison is a genuine success. However, when spectra are generated from self-consistent enrichment simulations, they produce far too small values of $\tau_{\rm CIV}/\tau_{\rm HI}$ and $\tau_{\rm CIII}/\tau_{\rm CIV}$, for all of our UVB models (though softer UVBs make the discrepancy smaller).

Metal rich gas in the simulations is too hot and too low-density. The problem arises because essentially all of the intergalactic and enriched gas in both simulations exists in low-density, high-temperature ($10^5\,K \lesssim T \lesssim 10^6\,K$) bubbles. Since both the CIV/C ratio and the CIII/CIV ratio fall off quickly with both increasing temperature $T \gtrsim 10^5$ K, and decreasing density $\delta \lesssim 10$ the gas becomes nearly invisible in CIV, and where CIV is detected there is virtually no accompanying CIII.

Metal line cooling should be important. There is a potentially important effect that could ameliorate the aforementioned problem, which is that cooling by metals was not included in the simulations, but could be important due to the high metallicity of the gas in the bubbles. Calculating the cooling time using the Sutherland & Dopita (1996) tables indicates that much of the metal-rich gas could plausibly cool. Correctly treating metal cooling in cosmological simulations will be quite challenging because it depends on the very local metallicity (and thus crucially on how well metals mix) and equilibrium cooling may not be a good approximation. But it can be crudely modelled by assuming that gas cools to $T \approx 10^4$ K if its (Sutherland & Dopita) cooling time is shorter than the Hubble time. In this case much more CIV absorption is present and the *median* $\tau_{\rm CIV}/\tau_{\rm HI}$ observed could plausibly be matched by the simulations.

Nonetheless metals appear too low-density and too inhomogeneous. While including metal cooling might lead to a sufficient increase in CIV absorption, it does *not* appear to fix the difficulty in reproducing CIII/CIV. This can be traced to the fact that the metal-rich gas has too low density to produce the observed ratios. This problem may also be lessened by a proper treatment of metal cooling, as the cooling would also affect the gas dynamics, allowing gas to contract as it cools. But there is yet another problem, which is that although the *median* $\tau_{\rm CIV}/\tau_{\rm HI}$ can be roughly reproduced by the simulations, the spread in $\tau_{\rm CIV}$ at a given $\tau_{\rm HI}$ cannot. This can be traced to the fact that metals in the simulations are *too inhomogeneous*, which in turn results from a relatively small fraction of gas particles being enriched. This problem seems unlikely to improve from a correct treatment of metal cooling.

4. Conclusions

What are we to make of the question of early vs. late enrichment? Our analysis presents a bit of a conundrum. On the one hand, all of our observations of intergalactic enrichment appear perfectly consistent with metals being in place in the IGM at $z \gtrsim 4$ without disturbing the IGM (with the possible exception of the overall metal mass, which may be challenging for $z \gg 4$ enrichment to reproduce). Moreover, simulations of enrichment caused by strong feedback fail to reproduce the observations in a number of ways. On the other hand, essentially all $z \gtrsim 2$ galaxies appear to be driving winds that seem likely to escape into the IGM – where do their metals go? Furthermore, groups and clusters at $z \sim 0$ exhibit a metallicity of $Z \sim \frac{1}{3} Z_\odot$ that is much higher than that of the IGM at $z \sim 3$, some Lyα clouds have $Z \sim 0.1 Z_\odot$ at $z \lesssim 0.5$ (Prochaska *et al.* 2004), and reasonable estimates of the mean $z = 0$ metallicity are $\sim 5-10\times$ higher than that inferred at $z \sim 3$ (Finoguenov *et al.* 2003†). Thus it seems that either metallicity evolution occurs between $z \sim 3$ and $z \sim 0$, or we are failing to detect some metals at $z \sim 3$, or both.

Can this conflict be reconciled? Perhaps. It seems plausible that galaxies forming at *all* redshifts $z \gtrsim 2$ contribute to intergalactic metallicity: the metals we *see* in the Lyα forest via quasar spectroscopy were almost entirely in place by $z \sim 4$ and result from a rather early enrichment phase that left the IGM relatively undisturbed, while metals added at $2 \lesssim z \lesssim 4$ are largely hidden from view in hot, low-density gas with a relatively small filling factor that preferentially avoids the dense filaments. This latter enrichment could, through gravitational infall, later appear as a portion of the high metal mass gas in clusters and groups (the rest being provided by processes occurring after the groups/clusters can be said to have formed). Whether such a scenario can be made to work in detail is an open question.

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† They calculate $\Omega_{Z,IGM} = 3.3 - 7 \times 10^{-5}$ in clusters, OVI systems, and the Lyα forest, corresponding to $Z \approx 0.05 - 0.1 Z_\odot$ in the IGM.

While a lot of progress has been made in understanding the mechanism of intergalactic enrichment, there are a number of important avenues to pursue toward assembling a comprehensive picture of the process:

- Where possible, more ions (e.g. OVI and NV) should be analysed to provide stronger constraints on the UVB model, on relative abundances, and on the possible importance of collisionally ionisation. Such work is currently underway.
- Simulations of 'late' enrichment that include metal cooling must be evaluated, with particular attention to how well metal cooling is captured, and what effect it has on the observed ionic ratios. It would be advantageous to compare grid-based with particle-based simulations of enrichment as well. Several groups will undoubtedly be performing such analyses over the next several years.
- Modelling and simulations of individual wind-driving galaxies embedded in a realistic IGM are vital for understanding how winds will really propagate into the IGM, and the link between enrichment and galaxy formation processes.
- More work on 'early' enrichment is also important: is it really possible to enrich the IGM without any real effect on the gas? What role could population III play?
- Enrichment mechanisms differing from the canonical supernova-driven wins are worth investigating. For example, what about outflows of dust (Aguirre *et al.* 2001; Bianchi & Ferrara 2005) or driven by dust (Murray *et al.* 2005)? And how much of the group/cluster metals could be explained by dynamical processes rather than outflows?

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