HOW DID THE IGM BECOME ENRICHED?

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Abstract. The enrichment of the intergalactic medium with heavy elements is a process that lies at the nexus of poorly-understood aspects of physical cosmology. We review current understanding of the processes that may remove metals from galaxies, the basic predictions of these models, the key observational constraints on enrichment, and how intergalactic enrichment may be used to test cosmological simulations.

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, and was quite surprising when discovered. It has since become clear that this enrichment is related to many other aspects of physical cosmology, and that the question of “how did the intergalactic medium become enriched?” has a number of components that we would like to understand. Among them:

- The low-density ($\delta \equiv \rho/(\langle \rho \rangle - 1 \lesssim 10$) intergalactic medium (IGM), as probed by the Ly$\alpha$ forest and through C$\text{III}$, C$\text{IV}$, Si$\text{III}$, Si$\text{IV}$, O$\text{V}$, O$\text{VI}$, and other transitions, is at least partly enriched at all redshifts and densities probed (e.g., Songaila and Cowie, 1996; Cowie and Songaila, 1998; Ellison et al., 2000; Schaye et al., 2000; Songaila, 2001; Carswell et al., 2002; Telfer et al., 2002; Bergeron et al., 2002; Schaye et al., 2002; Boksenberg et al., 2003; Pettini et al., 2003; Aguirre et al., 2004; Aracil et al., 2004; Simcoe et al., 2004; Prochaska et al., 2004; Ryan-Weber et al., 2006). How did these metals get where they are?

- The intracluster medium is highly enriched to $Z \sim 0.2 - 0.5 Z_\odot$, with most metals produced in clusters residing in the intracluster medium rather than in the galaxies themselves (e.g., Renzini, 1997). How did such efficient metal ejection occur?

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• Semi-analytic and numerical models of galaxy formation overpredict the stellar masses of (in particular small) galaxies unless they incorporate significant feedback such as would drive material from galaxies (e.g., Kauffmann et al., 1993; Somerville and Primack, 1999). What is the relation between enrichment and galaxy formation?

• The $z \sim 0$ (and $z \sim 2$) mass-metallicity relation is indicative of loss of metals by galaxies (e.g., Tremonti et al., 2004; Erb et al., 2006). How much baryonic mass and metal mass is ejected by galaxies as they form?

• Some galaxies at $z \sim 0$ (Heckman, 2001), and nearly all galaxies at $z > 2$ (e.g., Adelberger et al., 2003), are observed to drive winds that might escape. Do they escape? What is their impact?

In connection with these facts, a general picture has emerged that galactic winds – driven largely from young and/or starburst galaxies – have enriched the IGM both within clusters and the general field. The same feedback may account for the dearth of low-luminosity galaxies (relative to the halo mass function), and also the mass-metallicity relationship of galaxies. However, a detailed understanding of the various feedback processes is lacking, and there are still open questions, and controversies, concerning the time at which various components of enrichment occurred, exactly how, and what this tells us about galaxy formation.

The rest of this article will review recent progress in piecing together this picture. First we schematically review the physics behind outflows, the basic ways of assessing the predictions of these for the observed intergalactic (IG) enrichment, and what general predictions seem to be agreed-upon. We then discuss how the metallicity of the low-density IGM is measured, and the basic results obtained using these techniques. Finally, we discuss what is probably the best way to get a true handle on the enrichment mechanism: direct comparison between detailed feedback simulations and the large data sets now becoming available.

2 Basic physics of galactic winds

While a single supernova explosion cannot blow material out of any but the smallest galaxy, a large set of contemporaneous and co-spatial explosions might. In this case, the overlap of super-heated bubbles can overlap and merge into a “superbubble” that blows out of the galaxy and forms an outflowing large-scale wind (e.g., Heckman et al., 1990). A common way to model this has been to assume that the superbubble will form a “supershell” for which equations of motion can be evolved that include the driving pressure, gravity, the ram pressure of the medium encountered, etc. (e.g., Aguirre et al., 2001; Theuns et al., 2001; Bertone et al., 2003). Even if the shell fragments (as is expected), another shell might form, and the evolution can be followed by encompassing repeated shell-fragmentation in the form of an “entrainment fraction” specifying how much of the ambient material must be carried by the outflow along with the superheated gas.
A second basic mechanism has more recently been proposed by Murray et al. (2005), in which it is momentum deposition by radiation pressure (coupled via dust to the gas\(^1\)), or cosmic ray pressure (Socrates et al., 2006), that drives the outflow.

These two possible mechanisms may coexist and would both result in a rather complicated outflow structure. A first-order model of the effect of these outflows on the host galaxy and the nearby IGM can, however, be generated by assuming that whatever the outflow does at very small radii, it eventually organizes into a wind with some mass outflow rate \(\dot{m}_{\text{sfr}}\), velocity \(V_{\text{wind}}\), and entrainment fraction, and does so in such a way as to conserve some quantity (energy or momentum). The two mechanisms differ in the suggested relation between, in particular, \(\dot{m}_{\text{out}}\) and \(V_{\text{wind}}\). For energy driven winds, it has been argued that \(V_{\text{wind}}\) should be roughly independent of the progenitor galaxy mass (e.g., Heckman et al., 1990). Then if the feedback efficiency is also fixed, equating the energy generation to the energy carried by the wind indicates that:

\[
\dot{m}_{\text{out}} \propto \dot{m}_{\text{sfr}}, \quad V_{\text{wind}} \simeq \text{const.}
\]

For winds driven by radiation pressure, it is more natural for both the wind speed and outflow rate to depend on the progenitor galaxy mass (or velocity dispersion \(\sigma\)), giving a wind possible wind prescription at large radii of (Murray et al., 2005; Oppenheimer and Davé, 2006):

\[
\dot{m}_{\text{out}} \propto \dot{m}_{\text{sfr}}/\sigma, \quad V_{\text{wind}} \simeq 3\sigma,
\]

with the wind momentum outflow \(\dot{m}_{\text{out}}V_{\text{wind}}\) equated to a fixed fraction of the momentum input (i.e. luminosity) of the source.

While these are two interesting perspectives to take, a very great deal happens between an erg of energy (or g cm/s of momentum) being deposited, and the wind several kpc away. In particular, while energy and momentum are certainly conserved in these systems, winds may radiate much of their energy and much of the momentum may cancel out if, as in starbursts, it is generated by a distribution of sources.

That being said, suppose we have some prescription for the wind parameters as a function of galaxy properties. How might we make predictions for intergalactic enrichment?

### 3 Modeling galactic winds

Two basic approaches are used in making predictions for IG enrichment from a given wind model: the semi-analytic, and the numerical.

Semi-analytic approaches (e.g., Aguirre et al., 2001b; Madau et al., 2001; Scannapieco et al., 2002; Thacker et al., 2002; Furlanetto and Loeb, 2003; Bianchi and Ferrara, 2005; Bertone et al., 2005; Pieri et al., 2006a) generally proceed as follows:

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\(^1\)If the dust is somehow not coupled to the gas, then an outflow of dust could ensue and contribute to IG enrichment; see Aguirre et al. (2001a), Bianchi and Ferrara (2003).
1. A cosmological simulation is used to determine galaxy locations, halo masses, and gravitational potentials.

2. The simulations outputs themselves (for hydrodynamic simulations) or semi-analytic prescriptions overlaid on the halos (for dark matter simulations) are used to determine galaxy star-formation rates, metallicities, gas properties, inflow rates, etc.

3. A prescription based on a simplified wind model is applied to the galaxy properties to determine how far a wind would propagate during a “time step” and how the expelled metals would be distributed. These metals are then “painted on” to the gas or dark particles.

4. The metallicity of particles is then tracked, to yield the metallicity distribution at later cosmological epochs.

In the numerical approach (e.g., Cen and Ostriker 1999; Theuns et al. 2002; Thacker et al. 2002; Aguirre et al. 2005; Cen et al. 2005; Oppenheimer and Davé 2006), one instead:

1. Directly simulates gas physics anew for each trial.

2. Uses prescriptions for star formation, feedback of both energy and metals into the gas surrounding star-forming regions, and possibly for the launching of winds.²

3. Tracks metals accumulating in the gas particles, and potentially uses these metallicities in the cooling rates of the gas.

Relative to the numerical method, the primary advantage of the semi-analytic method is speed: many realizations can be computed on a desktop computer in the time that one simulation can be run on a supercomputer. Another advantage is that semi-analytic methods allow a clearer connection to be made between the physical ingredients of the model and the results, possibly leading to a better understanding of the actual physics that is responsible for particular effects.

Numerical methods, in contrast, treat the gas physics much more accurately and can, for example, assess the impact of feedback on the thermal state of the gas. Depending on the resolving power of the simulations, fewer prescriptions for physics need to be used than in the semi-analytic method, since the physics can be directly simulated. Simulations naturally allow a self-consistent treatment of the effect of feedback on star formation. Finally, they easily allow for the generation of mock observations.

There is a fairly large literature on IG metals using both approaches, so we here focus on what appear to be general and (fairly) well-agreed upon findings:

²Of course, in principle, the wind – if driven by energy injection – should launch itself. That this generally does not occur without some sort of assistance is generally attributed to insufficient resolution.
• Galaxies at \( z > 2 \) essentially all drive winds: Whether winds are launched “automatically” or via a prescription, if the mechanism is consistent with winds from low-\( z \) starburst galaxies, then it will also predict that most high-\( z \) galaxies drive them, since the specific SFRs are so much higher then.

• Wind propagation and escape is quite sensitive to the entrainment fraction and to \( v_{\text{wind}} \). This occurs because the two primary forces limiting wind propagation are the galaxy’s potential well (if the wind speed is not much higher than the escape velocity) and the ram pressure of the (potentially infalling) gas that must be swept up even if the wind is fast. Moreover, if entrainment is significant, then the mass over which the wind energy and momentum must be shared may be much greater.

• The metallicity of the IGM resulting from enrichment by galactic winds is highly inhomogeneous and probably has a filling factor \( \lesssim 10\% \).

• Higher-redshift enrichment tends to lead to more homogeneous enrichment at lower-redshift. This is somewhat contentious and depends in detail on the assumptions made, but appears to be borne out by numerical calculations. It occurs because high-\( z \) galaxies are relatively smaller and more numerous, and because the winds have more time to propagate. It appears to occur in spite of the fact that the earliest galaxies of any given mass tend to form in highly biased and highly-clustered regions.

• There is a strong correlation between the gas metallicity and the gas density, which follows simply from the fact that galaxies form preferentially in high-density regions.

The numerical treatments of IGM enrichment reinforce many of these conclusions. In addition they seem to generically suggest that:

• A significant fraction of the metals ejected end up in hot (\( \gtrsim 10^5 \text{K} \)) gas, especially when metal-line cooling is not included, but also even when it is.

• Except at the highest redshifts and with the smallest sources, winds tend to preferentially propagate outside and in-between filaments, and also have a low filling factor, so that there is little overall disruption of the structure or statistical description of the Ly\( \alpha \) forest itself.

4 Assessing metals spectroscopically

Nearly everything we know about the enrichment of the IGM at \( z \gtrsim 2 \) is via optical C\textsc{iv}, C\textsc{iii}, Si\textsc{iv}, Si\textsc{iii}, O\textsc{v}, and O\textsc{vi} absorption-line spectroscopy of distant quasars. Below we briefly review how these assessments are performed, and the basic results obtained to date.
4.1 Techniques

The standard technique is to fit line profiles to a set of absorption features to derive (where the line is not too saturated) column densities and (where the line is resolved) line-widths. This technique works well in the IGM for relatively high-column lines where there is relatively little contamination. Given extremely good data, this can probe gas densities at only a few times the cosmic mean \cite{Simcoe2004}. Once determined, the ionic column densities can might be converted into metallicities as described below. The prime advantages of line-fitting over the pixel-based techniques described next are that it (a) is familiar and straightforwardly interpreted, (b) treats high column-density lines well, and (c) gives information on line widths. Its main disadvantages are that it (a) is unsuitable for statistical searches for absorption that is weak compared with the noise or contamination; (b) is subjective in the sense that decompositions in Voigt profiles are non-unique; (c) is slow and dependent on prior identification of lines, making it unsuitable for application to large datasets and simulations.

The pixel optical depth (POD) method \cite{Cowie1998,Songaila1998,Ellison1999,2000Schayeetal,Aguirre2002,Telfer2002,Schave2003,Arai2004,Aguirre2004,Pieri2004,Songaila2005,Pieri2006b} is a complementary approach that has certain advantages, particularly when applied to weak, widespread absorption that may be easily confused with contaminating lines or when applied to large date sets or simulations.

The key steps in the POD search are:

1. Compute arrays of apparent pixel optical depths, $\tau_{\text{app}}(z) = -\ln \frac{F(z)}{F_{\text{cont}}(z)}$, where $F$ and $F_{\text{cont}}$ are the transmitted flux in the pixel and the local continuum, respectively. Sophisticated methods have been developed \cite{Aguirre2002,Schave2003} to correct for contamination, noise, continuum fitting errors, etc. in these “apparent” optical depths, taking advantage of the fact that many ions generate multiplets (e.g., $\text{H}^i$) or doublets (e.g., $\text{C}^\text{IV}$, $\text{N}^\text{V}$, $\text{O}^\text{VI}$, and $\text{Si}^\text{IV}$), with known optical depth ratios.

2. Choose a “base” and a “target” transition and bin the pixel pairs according to the recovered POD of the former (e.g., $\text{C}^\text{IV}$ as a function of $\text{H}^i$). The combinations that have so far proved to be most useful are $\text{C}^\text{IV}(\text{H}^i)$ \cite{Cowie1998}, $\text{O}^\text{VI}(\text{H}^i)$ \cite{Schave2000}, $\text{Si}^\text{IV}(\text{C}^\text{IV})$ \cite{Aguirre2004}, $\text{C}^\text{III}(\text{C}^\text{IV})$ \cite{Schave2003}, and $\text{Si}^\text{III}(\text{Si}^\text{IV})$ \cite{Aguirre2004}.

3. Compute the median (or any other percentile) of the target transition POD as a function of the binned base transition POD. A correlation reflects a detection. The method can be generalized to measure the full distribution of target optical depths by simultaneously measuring multiple percentiles \cite{Schave2003}.

While elemental abundances are desired, we can only measure ion abundances, whether from optical depth ratios or column density ratios. This is unfortunate in
that uncertainties in the ionization balance are currently the limiting factor in the study of intergalactic abundances. But it is also good news, because it means that we can constrain the physical conditions in the gas, since the ionization balance depends in general on the radiation field, the gas density, and the gas temperature.

The radiation field (if uniform), can be described in terms of a normalization (in the form of the H I ionization rate) and a spectral shape (determined by the type of sources, and the transfer of radiation through the IGM). The UV background (UVB) models of Haardt and Madau (2001) have become fairly standard, (which is not to say they may not be quite incorrect!) and provide a useful benchmark.

In photo-ionization equilibrium, the gas density is closely related to the H I optical depth: \( n_{\text{HI}} \propto \rho^2 \Gamma_{\text{HI}}^{-1} \), and the H I ionization rate \( \Gamma_{\text{HI}} \) can be measured. A similar (but more detailed) relation can be obtained using mock spectra drawn from hydrodynamics simulations. This relation can be used both to perform ionization corrections, and to indicate the density of gas being probed.

If the gas is very hot and/or dense, then collisional ionization may dominate over photo-ionization, in which case the ionization balance will depend only on the temperature. If photo-ionization dominates, then the ion fractions are still weakly dependent on the temperature because the recombination rates are. However, as long as \( T \sim 10^4 \) K, as is usually assumed, the temperature is not the main source of uncertainty in the analysis.

4.2 Observations of IG metals at \( z > 2 \)

Using the spectral data and ionization-correction modeling just discussed, in the past decade or so we have assembled a reasonably detailed assessment of IG enrichment – albeit with some large outstanding questions.

Basic results thus far include:

- The carbon abundance (probed via C IV) is inhomogeneous: at fixed overdensity \( \delta \) and redshift \( z \), the p.d.f. for \([C/H]\) is a gaussian of width \( \sim 0.5-1.0 \) dex, i.e. the distribution is lognormal (Schaye et al., 2003; Simcoe et al., 2004). Similar results hold for oxygen as probed via O VI (Simcoe et al., 2004).

- The median carbon abundance \([C/H]\) (and also the width of the p.d.f.) increases with density (Schaye et al., 2003), and there is (some) carbon in (some) underdense gas (corresponding to \( N_{\text{HI}} \lesssim 3 \times 10^{13} \)) (Schaye et al., 2003).

- For a standard choice of the UV background (HM01 Q+G UVB), the median \([C/H]\) does not evolve from \( z \sim 4 \) to \( z \sim 2 \) (Schaye et al., 2003). In addition, metals exist at \( z \gtrsim 5 \) (Songaila, 2001; Pettini et al., 2003; Ryan-Weber et al., 2006; Simcoe, 2006).

- The IGM is alpha-enhanced relative to the sun: \([\text{Si}/C] \sim 0.2-1.5 \) (Aguirre et al., 2004), \([\text{O}/C] \gtrsim 0.0 \) (Telfer et al., 2002; Simcoe et al., 2004). This suggests
enrichment by predominantly Type II supernovae, perhaps even with a contribution by hypernovae (see, e.g., Qian and Wasserburg, 2005, and other contributions to this volume).

- Results are UVB-dependent. A Haardt and Madau (2001) UVB model with galaxies and quasar light included, and 10% escape fraction from galaxies seems plausible: a much harder or softer does UVB does not (Schaye et al., 2003; Aguirre et al., 2004; Simcoe et al., 2004).

- Using detected SiIII and CIII absorption, it can be shown that most strong SiIV and CIV absorption arises in photoionized gas (Schaye et al., 2003; Aguirre et al., 2002).

- Metals are correlated with themselves and with galaxies (Adelberger et al., 2005; Pieri et al., 2006b; Scannapieco et al., 2006).

4.3 Basic Implications of derived abundances

A basic implication of the above findings is that essentially all of the results are explainable by metals “sprinkled” onto simulations with no winds, at $z \gtrsim 5$. But does it mean that all metals in the IGM come from such an early enrichment period? There are some reasons to think not.

First, a substantial fraction of all metals generated by stars at $z \gtrsim 3$ appear to reside in the diffuse IGM: $[C/H] \sim -2.8$, $[Si/H] \sim -2.0$, $[O/H] \sim -2.3$ (for HM01 Q+G) imply $f_{Z,IGM} = 10 - 30\%$ (Bončê et al., 2006).

Second, because their ionization fractions fall quickly with temperature above $\sim 10^5$ K, CIV and SiIV cannot probe very hot gas – metals in such gas would simply be invisible to probes using these ions.

In general, the rough amount of metals present in the IGM can be reproduced by models that include galactic winds (though not with models that do not include winds). However, the observations summarized above present a detailed and challenging target for the next generation of models. In the next section we summarize some recent work comparing cosmological simulations – including enrichment – in detail to the observed spectra.

5 Confrontation with simulations

While much can be inferred using observations directly, it is very useful to compare them to synthetic spectra generated from simulations with enrichment – including the effect of the outflows on the IGM. In one investigation of this sort, Aguirre et al. (2005) analyzed two sets of high-resolution particle-based hydrodynamic simulations (Springel and Hernquist, 2003; Theuns et al., 2002) with different feedback prescriptions that both drive strong winds at $z \gtrsim 2$ as per the late enrichment scenario. Four general and qualitative conclusions of this study were as follows.

First, the feedback simulations produce far too small values of $\tau_{CIV}/\tau_{HI}$ and $\tau_{CIII}/\tau_{CIV}$, for all UVB models employed.
Second, metal-rich gas in the simulations is too hot and too low-density: essentially all of the intergalactic and enriched gas in both simulations exists in low-density, high-temperature (\(10^5 \text{ K} \lesssim T \lesssim 10^6 \text{ K}\)) bubbles. Since both the \(\text{C} \text{ IV}/\text{C} \text{ III}\) ratio and the \(\text{C} \text{ III}/\text{C} \text{ IV}\) ratio fall off quickly with both increasing temperature \(T \gtrsim 10^5 \text{ K}\) and decreasing density \(\delta \lesssim 10\), the gas becomes nearly invisible in \(\text{C} \text{ IV}\), and where \(\text{C} \text{ IV}\) is detected there is virtually no accompanying \(\text{C} \text{ III}\).

Third, metal line cooling, which was not included, should be important. If crudely modeled (by assuming that gas cools to \(T \approx 10^4 \text{ K}\) if its cooling time is shorter than the Hubble time), much more \(\text{C} \text{ IV}\) absorption is present and the median \(\tau_{\text{CIV}}/\tau_{\text{HI}}\) could plausibly match the observed one.

Finally, metals nonetheless appear too low-density and too inhomogeneous: While including metal cooling might lead to a sufficient increase in \(\text{C} \text{ IV}\) absorption, it does not appear to fix the difficulty in reproducing \(\text{C} \text{ III}/\text{C} \text{ IV}\). 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 \(\tau_{\text{CIV}}/\tau_{\text{HI}}\) can be roughly reproduced by the simulations, the spread in \(\tau_{\text{CIV}}\) at a given \(\tau_{\text{HI}}\) cannot: the metals in the simulations are too inhomogeneous. This problem seems unlikely to improve from a correct treatment of metal cooling.

In a more recent study, Oppenheimer and Davé (2006) have compared simulated spectra from a large suite of feedback simulations to observed line and pixel data. (See also contributions by Davé and Oppenheimer in the present volume for more details; here we just mention a few points.)

The Oppenheimer & Davé simulations include metal-line cooling, and wind prescriptions chosen to correspond to “momentum driven” and “energy driven” winds as discussed in Sec. 2. In comparison to Aguirre et al. (2005), there are two findings of note. First, Davé et al. find much better agreement in \(\text{C} \text{ IV}/\text{H} \text{ I}\) and \(\text{C} \text{ III}/\text{C} \text{ IV}\) optical depth ratios between their simulations and the data than do Aguirre et al. (2005). This is very likely due to the inclusion of metal line cooling. Second, in models for which the \(\text{C} \text{ IV}\) optical depths are compatible with observations, the overall cosmic carbon abundance is higher than that inferred by Schaye et al. (2003) based on the same data. This indicates that (as argued by Davé et al.) metals are being hidden in relatively hot gas not probed by the observations.

It would be very interesting to see how the Davé et al. simulations fare when applied to \(\text{O} \text{ VI}\), which is much more sensitive to the presence of hot gas, and when applied to percentiles in \(\text{C} \text{ IV}\) other than the median – which Aguirre et al. (2005) found difficult to reproduce using simulations, even with cooling included.

6 Concluding facts and opinions

We will conclude with some facts, and some opinions. The key facts are:

- Both observations and simulations of IG enrichment are getting drastically
better, and the former are, finally, strongly constraining the latter.

- Comparisons between observations and simulations have to be done with care.
- Observations of IG metals strongly constrain models of feedback from star formation (a crucial ingredient of simulations and galaxy formation models).

Some opinions:

- Enrichment is unlikely to be purely “contemporary” or “primordial”: Enrichment almost surely occurs at $z < 4$, perhaps mostly hidden in hot gas. However, it is unclear that $z < 6$ enrichment can account for all measurements.
- It seems likely that a galaxy-mass-dependent $V_{\text{wind}}$ is necessary – but it is not clear that this requires radiation-pressure-driven winds.
- There is a dearth of high-quality, high-resolution simulations of individual wind-driving galaxies in a cosmological background. Please do some!

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