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Metal abundances in the high-redshift intergalactic medium

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Abstract. Twenty years of high-resolution spectroscopy at the $8-10$ m class telescopes have drastically expanded our view of the gas-phase metallicity in the $z \gtrsim 2$ universe. This contribution briefly summarizes how these studies reveal a widespread metal pollution in the intergalactic medium with a median abundance [C/H] ~ -3.5 at $z \sim 3$ that is increasing by a factor of $\sim 2-3$ from $z \sim 4.3$ to $z \sim 2.4$. At the higher densities that are typical of galactic halos, observations uncover a metallicity spread of five orders of magnitude in Lyman limit systems, ranging from super-solar ([M/H] $\sim +0.7$) to pristine ([M/H] $\lesssim -4$) gas clouds. Finally, the neutral damped Lyα systems are enriched to a median metallicity of [M/H] ~ -1.5 that slowly declines with redshift up to $z \sim 4.5$, at which point it appears to more rapidly evolve as one approaches the end of reionization.

Key words. Techniques: spectroscopic – ISM: abundances – Galaxies: abundances – intergalactic medium – quasars: absorption lines – primordial nucleosynthesis

1. Introduction

The study of metal lines associated to intervening absorption line systems (ALSs) that are detected in the foreground of $z \gtrsim 2$ quasars offers a unique opportunity to trace the history of the metal enrichment of cosmic structures in a redshift-independent fashion, up to the first billion year from the Big Bang. Since the advent of high-resolution echelle and echellette spectrographs at the $8-10$ m class telescopes, observers have been able to map the chemical composition of the intergalactic medium (IGM) and of the denser gas within and around distant galaxies.

In this contribution, after a brief overview of the adopted techniques that may be useful to readers that are not familiar with measurement of gas metallicities in absorption (Sect. 2), we summarize the current status of the study of the metal content in the Lyα forest (Sect. 3), in Lyman limit systems (LLSs, Sect. 4), and in damped Lyα systems (DLAs, Sect. 5). Given the large body of literature on the subject, this article cannot be considered a complete review since we focus primarily on observational results at $z \gtrsim 2$, only briefly referring to theoretical studies. Furthermore, we have decided to highlight empirical findings and their simple interpretation, without however examining in detail the physical processes that are responsible for the observed metal pollution of cos-

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mic structures. Discussions on some of these aspects can be found in other chapters of these proceedings.

2. Technique

2.1. Counting atoms in the distant universe

With absorption spectroscopy, it is straightforward to directly measure the abundances of several elements in different ionization states, provided that lines are not saturated. For each transition, the transmitted flux of a background source is simply $I_{\rm tran} = I_{\rm back}\exp(-\tau(\nu))$, where the optical depth is defined by $\tau(\nu) = \frac{\pi e^2}{m_e c} f N_{\rm kj}\phi(\nu, b)$. Here, f is the oscillator strength, $N_{\rm kj}$ is the ion column density, and ϕ is the frequency-dependent line profile that also depends on the Doppler parameter b (e.g. Spitzer 1978). Differently from studies in emission where detection limits translate into distance-dependent sensitivity on physical quantities, one can notice from the above equations that the detection limits on column densities are conveniently redshift independent. This means that the metal content of intervening ALSs can be measured with equal sensitivity in column density across over 10 Gyr of cosmic history.

While column densities are directly observables, complications arise when metallicities are derived because of ionization corrections. Neutral gas is a dominant component only at the high hydrogen column densities observed in DLAs ($N_{\rm HI} \geq 10^{20.3}$ cm^{-2}) for which metallicities are simply obtained by dividing the measured column densities in neutral or singly ionized ions by the neutral hydrogen column densities. However, for the majority of ALSs at lower $N_{\rm HI}$, the observed ions trace only a (sometimes small) fraction of the underlying hydrogen and metal content. In these cases, ionization corrections are required to translate the observed column densities into metallicities.

For the classes of ALSs that are discussed here, it can be generally assumed that gas is predominantly photo-ionized, as indicated for instance by the line ratios of a same element in adjacent ionization states (e.g. C II, C III, C IV). Standard practice is also to assume that gas is in photoionization equilibrium (but see Gnat et al. 2010; Oppenheimer & Schaye 2013). Ionization corrections are then computed via one-dimensional radiative transfer calculations, with the `cloudy` software package (Ferland et al. 1998) being the code of choice for many authors.

To derive ionization corrections, the observed column densities N_{kj} of elements j in the $k-$th ionization states are compared to grids of column densities that are computed as a function of free parameters, such as the volume density $n_{\rm H}$, the spectrum of the incident radiation field $j(\nu)$, and the chemical composition A_j. For the set of parameters that best describe the observations, the photoionization models yield the desired ionization corrections X_{kj} such that $N_j = N_{kj}X_{kj}$. Metallicities can then be inferred from tracer elements as $[{\rm M/H}] = \log(N_j/N_H) - \log(N_j/N_H)_\odot$.

Although in some cases volume densities can be constrained directly by observations (e.g. by transitions from fine-structure levels) or indirectly (e.g. requiring that gas is in hydrostatic equilibrium), the problem of establishing ionization corrections is often highly under-determined. Standard practice is therefore to assume that the gas clouds are illuminated by the extra-galactic ultraviolet background (EUVB) of a given spectral shape and intensity (e.g. Faucher-Giguère et al. 2009; Haardt & Madau 2012). Further, it is often assumed that the gas has the same chemical abundance pattern of the solar neighborhood. Naturally, all these assumptions introduce systematic uncertainties in the analysis and metallicities become model dependent.

2.2. From absorption systems to cosmic structures

ALSs are broadly classified in three different classes, according to their observed neutral hydrogen column densities. Systems with $N_{\rm HI} \lesssim 10^{16}$ cm^{-2} constitute the Lyα forest (e.g. Lynds 1971), while systems with 10^{16} cm$^{-2} \lesssim N_{\rm HI} <$

$10^{20.3}$ cm^{-2} are defined Lyman limit systems[1] (LLSs; e.g. Tytler 1982) or, at the higher column densities ($N_{\rm HI} \gtrsim 10^{19}$ cm^{-2}), super Lyman limit systems (SLLSs; e.g. Péroux et al. 2002). Finally, systems with $N_{\rm HI} \geq 10^{20.3}$ cm^{-2} are defined damped Lyα systems (DLAs; e.g. Wolfe et al. 2005).

Unfortunately, through absorption spectroscopy alone, observers cannot directly connect the individual gas clouds detected against background sources to the physical structures that host them. However, it is possible to establish a general correspondence between these three classes of ALSs and astrophysical structures by assuming that gas clouds are in local hydrostatic equilibrium (e.g. Schaye 2001). The validity of this assumption, that is also supported by hydrodynamic simulations (e.g. Cen et al. 1994; Rahmati et al. 2013), can be simply understood in the following way. If gas clouds were out of equilibrium, then they would expand until equilibrium is restored with the ambient medium, or collapse and fragment into smaller structures of sizes comparable to the Jeans length L_J. It follows that volume densities and column densities are related by $N_{\rm H} = L_J n_{\rm H}$, where $N_{\rm H} = N_{\rm HI} X_{\rm HI}$ as set by radiative transfer processes. Given these two simple equations, from a theoretical point of view, the Lyα forest can be identified with gas densities $n_{\rm H} \lesssim 10^{-3}$ cm^{-3} that are typical of the cosmic web and voids (e.g. Cen et al. 1994; Hernquist et al. 1996), LLSs with gas densities 10^{-3} cm^{-3} $\lesssim n_{\rm H} \lesssim 10^{-1.5}$ cm^{-3} that are comparable to or above virial densities (e.g. Kohler & Gnedin 2007; Fumagalli et al. 2011a), and DLAs with gas densities $n_{\rm H} \gtrsim 10^{-1.5}$ cm^{-3} that are commonly found in galactic disks or neutral gas clumps (e.g. Nagamine et al. 2004; Pontzen et al. 2008). For reference, the mean cosmic density at $z \sim 3$ is $\bar{n}_{\rm H} \sim 10^{-5}$ cm^{-3}. For this reason, ALSs are powerful probes of the cosmic metal content and its evolution.

[1] Systems with 10^{16} cm^{-2} $\lesssim N_{\rm HI} \lesssim 10^{17.2}$ cm^{-2} are typically classified as partial Lyman limit systems (pLLSs), but we do not make this distinction here.

3. Metals in the Lyα forest

3.1. The metallicity of the IGM

The metal content of the IGM can be inferred from the analysis of the Lyα forest that is comprised by gas clumps with $N_{\rm HI} \lesssim 10^{16}$ cm^{-2}. Three independent techniques have been adopted in the past to measure the IGM metallicity: the pixel optical depth method (POD; e.g. Cowie & Songaila 1998; Ellison et al. 2000; Schaye et al. 2003), the study of individual Lyα forest lines (e.g. Davé et al. 1998; Carswell et al. 2002; Simcoe et al. 2004; Simcoe 2011), and the analysis of composite quasar spectra (e.g. Lu et al. 1998; Pieri et al. 2010, 2013).

The POD method relies on a statistical analysis of multiple quasar sightlines (see e.g. Schaye et al. 2003). At first, the optical depths of the C IV ion $\tau_{\rm CIV}$ and of the associated neutral hydrogen $\tau_{\rm HI}$ are measured at each spectral pixel inside the wavelength windows where C IV absorption lies. After applying corrections for noise and contaminants, temperatures and densities are assigned to each value of $\tau_{\rm HI}$ using cosmological hydrodynamic simulations. It should be noted that this type of simulations are fairly robust (Theuns et al. 1998; Regan et al. 2007) and less dependent on the often unknown sub-grid physics that is adopted in simulations of galaxy formation. Therefore, the use of simulations is not a source of large and uncontrolled systematic uncertainties.

The last step in the derivation of the Lyα forest metallicity is to apply ionization corrections $X_{\rm CIV}$ and $X_{\rm HI}$ to infer the total carbon abundance:

$$[{\rm C/H}] = \log\left(\frac{\tau_{\rm CIV}\lambda_{\rm CIV}f_{\rm CIV}X_{\rm CIV}}{\tau_{\rm HI}\lambda_{\rm HI}f_{\rm HI}X_{\rm HI}}\right) - ({\rm C/H})_{\odot}\,. \quad (1)$$

This last step is the most prone to non-negligible systematic uncertainties (see Simcoe 2011), also because C IV is a subdominant ion at most densities, being $\lesssim 10\%$ of all the carbon present inside the IGM at $z \sim 2.5$. Furthermore, ionization corrections systematically vary as a function of the assumed EUVB spectral shape, which is uncertain at the energies that are responsible for the photoionization of doubly and triply ionized carbon. Therefore, for the same observed C IV distribution, an EUVB with harder spectral shape (e.g. Haardt & Madau 2001) implies higher carbon abundances at low densities compared to what one would infer using a softer spectrum (e.g. Faucher-Giguère et al. 2009).

Following this procedure, Schaye et al. (2003) measured the distribution of carbon within the Lyα forest as a function of overdensity $\delta = n_{\rm H}/\bar{n}_{\rm H}$ between $z \sim 2 - 4$, with most of the data lying at $z \sim 3$. For the assumed Haardt & Madau (2001) EUVB and solar carbon abundance $({\rm C/H})_\odot = -3.45$ (Anders & Grevesse 1989), the median IGM metallicity is $[{\rm C/H}] = -3.47^{+0.07}_{-0.06} + 0.08^{+0.09}_{-0.10}(z-3) + 0.65^{+0.10}_{-0.14}(\log\delta - 0.5)$ with a log-normal scatter $\sigma([{\rm C/H}]) = 0.76^{+0.05}_{-0.08} + 0.02^{+0.08}_{-0.12}(z-3) - 0.23^{+0.09}_{-0.07}(\log\delta - 0.5)$.

The second method to establish the metal content of the IGM relies on the identification of individual metal lines that are associated to distinct "clouds" in the Lyα forest. By fitting the hydrogen Lyman series and the associated strong metal lines such as C IV and O VI, this analysis provides a more direct constraint on the IGM metal enrichment than the POD method. However, these types of study are limited to overdensities $\delta \gtrsim 2$ because of the minimum hydrogen column densities that can be detected even in the highest resolution and signal-to-noise spectra. Similarly, detection limits hamper the direct measurement of very low metallicities (e.g. $[{\rm O/H}] < -3$) in individual ALSs, although the underlying metal distribution of the IGM can be inferred using survival analysis.

With direct measurements, Simcoe et al. (2004) obtained a median IGM metallicity of $[{\rm O/H}] = [{\rm C/H}] = -2.82$ with ~ 0.75 dex scatter at $z \sim 2.5$, after applying ionization corrections using an unpublished version of the Haardt & Madau EUVB (HM1.80) and assuming that the observed gas clouds are in local hydrostatic equilibrium. It should be noted that the agreement between the median oxygen and carbon abundances does not imply that $[{\rm C/O}] = 0$ in the IGM, as this ratio depends on the assumed shape of the EUVB, with softer spectra yielding lower [C/O] ratios. Compared to the results of Schaye et al. (2003), the analysis of Simcoe et al. (2004) favors a weaker density dependence for the IGM metallicity, although the distributions of carbon that are inferred either by direct detection of individual lines or by the POD method lie in satisfactory agreement once systematic variations due to the different choices of EUVB are taken into account.

All combined, these studies reveal a widespread metal pollution of the IGM at $z \sim 2.5 - 3$, with non-zero metallicity extending to under-dense regions with $\log\delta = -0.5 - 0.0$. However, about 30% of the Lyα forest lines detected above $\delta \gtrsim 1.6$ exhibit a metallicity $[{\rm C,O/H}] \lesssim -3.5$, which excludes the presence of a metallicity floor in the IGM. By mass, $40 - 60\%$ of the universe is enriched above $[{\rm O/H}] \gtrsim -3$ while, by volume, only 20% of the overdense universe has a metallicity $[{\rm C/H}] \gtrsim -3$. Integrated over the density distribution predicted by numerical simulations between $\log\delta = -0.5 - 2.0$, the carbon density of the $z \sim 3$ universe is $\Omega_{\rm C} \sim 2.3\times10^{-7}$, for an assumed baryon density $\Omega_{\rm b} = 0.045$ and a mass-weighted metallicity $[{\rm C/H}] = -2.80 \pm 0.13$. These estimates bear significant uncertainties related to ionization corrections, as well as extrapolations outside the range of densities directly probed by observations.

More recently, Simcoe (2011) has extended the analysis of the chemical properties of the overdense ($\delta > 1.6$) Lyα forest to $z \gtrsim 4.0$, finding a median $[{\rm C/H}] = -3.55$ with log-normal scatter $\sigma \sim 0.8$ dex for the assumed Grevesse & Sauval (1998) solar abundances. While ionization corrections still constitute a source of systematic uncertainty, C IV traces $\sim 50-60\%$ of all the carbon present in the IGM at $z \gtrsim 4$ for the mean H I column density that is detectable in the Lyα forest. And in fact, consistent median abundances are found for either the Haardt & Madau (2001) or the Faucher-Giguère et al. (2009) EUVB. Compared to carbon and oxygen abundances at similar overdensities in the lower redshift universe, the median IGM metallicity at $z \gtrsim 4-4.5$ is a factor of $\sim 2-3$ lower than what observed at $z \sim 2.5$. As this evolution is only weakly dependent on the assumed EUVB, this analysis implies that half of the metals seen in the IGM at $z \sim 2.5$ are ejected from galaxies between $z \sim 2.5 - 4.3$. This value is indicative of a substantial pre-enrichment of the IGM, and it implies that the observed metal content of the Lyα forest at a given redshift is not entirely attributable to co-eval star-formation episodes.

3.2. The structure of metals within the IGM

The study of the small-scale metal distribution in the IGM offers interesting clues to the processes that are responsible for the observed metal enrichment. A direct way of establishing the small-scale spatial distribution of metals in the IGM is to analyze the variation in the metal line profiles along closely-spaced quasar sightlines with projected separations between ~ 10 pc and a few kpc. By examining spectra of multiple images of strongly lensed quasars, Rauch et al. (1999) and Rauch et al. (2001) concluded that low-ionization lines at $z \sim 2 - 3.5$ (e.g. C II, Si II) arise from very compact clouds with sizes as small as ~ 30 pc. Conversely, metal lines of triply-ionized carbon or silicon appear featureless on scales of few hundred parsecs, and they retain a coherence in velocity up to a few kpc. Similar sizes are also found in photoionization modeling of metal lines detected in individual quasar spectra (e.g. Schaye et al. 2007; Pieri et al. 2013).

Compared to the Jeans scale of the high-redshift Lyα forest (~ 100 kpc), the existence of enriched gas clumps with sizes of few hundred parsecs implies that metals are not fully mixed with the surrounding hydrogen distribution, at least on timescales that are comparable to the lifetime of the enriched clouds. Given that the implicit assumption to any metallicity determination is that the observed metal and hydrogen column densities arise from the same phase, it follows that the inferred metallicities in the Lyα forest are often smoothed on the larger spatial scales of hydrogen.

As for the origin of the observed enrichment, the compact and metal-rich clouds ([C/H] > -1) that are uncovered by the analysis of Schaye et al. (2007) outnumber galaxies by several order of magnitudes. Also, these clouds are likely to be short-lived ($\sim 10^7$ yr), either because they lack pressure support from an ambient medium or because of the hydrodynamic instabilities. It is therefore plausible that a significant fraction of the metals seen in the IGM has been carried from galaxies in the form of compact and enriched clumps that subsequently mix with the surrounding hydrogen. Multi-phase galactic winds (e.g. Creasey et al. 2013) or stripped gas clouds (e.g. Rauch et al. 2013) are two possible channels for the IGM pollution.

4. Metals in Lyman limit systems

The study of the metal content of LLSs ($N_{\rm HI} \sim 10^{16} - 10^{20.3}$ cm^{-2}) provides valuable insights into the chemical properties of gas at the densities that are comparable to or higher than the virial densities. A detailed analysis of the metallicities of LLSs is therefore a powerful way to probe the flows of metals in galaxy halos, at the interface between galactic disks and the IGM (e.g. Fumagalli et al. 2011a; Faucher-Giguère & Kereš 2011; van de Voort et al. 2012; Rudie et al. 2012; Fumagalli et al. 2013b). However, the chemical abundances of LLSs have been analyzed in sufficiently large samples only at $N_{\rm HI} \gtrsim 10^{19}$ cm^{-2}, the column densities that are typical for SLLSs (e.g. Péroux et al. 2003; Kulkarni et al. 2007). Between $N_{\rm HI} \sim 10^{16} - 10^{19}$ cm^{-2}, where the bulk of the LLS population resides, only the metal properties of few individual systems or small samples have been reported so far (e.g. Steidel 1990; Prochaska 1999; Fumagalli et al. 2011b, 2013a). Such a lack of comprehensive studies (which are however underway) is imputable to the fact that high signal-to-noise and resolution data are required to measure $N_{\rm HI}$ in systems which have most of the Lyman series lines saturated.

Fumagalli et al. (2013a) have recently obtained a composite spectrum of a small statistical sample of LLSs at $z \sim 2.6 - 3.0$ (see also Prochaska et al. 2010), which is characterized by prominent absorption lines of triply-ionized carbon and silicon with equivalent widths in excess to 0.5Å. Higher-ionization lines, e.g.

C IV and Si IV, are weaker with equivalent widths of $\sim 0.1 - 0.2$ Å, while lower-ionization lines (e.g. O I, Si II, C II) are mostly undetected to limits of $\sim$ 0.05 − 0.1 Å below $N_{\rm HI} \lesssim 10^{19}$ cm^{-2}. All combined, these properties are indicative of an highly ionized[2] ($\log U \gtrsim -3$) and likely metal poor gas phase ([M/H] $\lesssim -1.5$), as confirmed by photoionization modeling under the assumption that LLSs are illuminated by the Haardt & Madau (2012) EUVB and have solar abundance ratios (Asplund et al. 2009). Metallicities between $-3 \lesssim$ [M/H] $\lesssim -1.5$ are also commonly found in the analysis of individual LLSs (Steidel 1990).

Although we currently lack a well sampled metallicity distribution, a striking peculiarity of this class of absorbers is the observed range of five orders of magnitude in the LLS metal content. At one extreme of the metallicity distribution, Prochaska et al. (2006) found a SLLS with metallicity [M/H] $\sim +0.7$, a value that only moderately depends on ionization corrections (with amplitude ~ 0.3 dex) given the observed column density of $N_{\rm HI} = 10^{19}$ cm^{-2}. At the other extreme, Fumagalli et al. (2011b) reported the discovery of two gas clouds without any associated heavy metals. In the absence of metal lines, the ionization state of the gas is unconstrained but, under the conservative assumption that these gas clouds have $\log U \gtrsim -3$, the metallicities of these two pristine systems are [M/H] $\lesssim -4$. Notably, one of the two clouds also has a deuterium abundance of primordial composition. This clump is therefore a relic of the gas that formed during the Big Bang nucleosynthesis and remained uncontaminated for two billion years.

Besides the large metal variation from system to system, LLSs also exhibit heterogeneous chemical properties within individual absorbers. Few examples of LLSs with multiple line components that are separated by only a few hundreds km s^{-1} but have metallicity differences up to 2 dex are accumulating in the literature (e.g. D'Odorico & Petitjean 2001; Prochter et al. 2010; Crighton et al. 2013). Such a diversity of chemical composition both in individual systems and within the population suggests that the denser ambient gas in proximity to galaxies, from which LLSs likely arise, is composed by multiple co-existing but distinct gas phases, such as chemically-pristine inflows and metal-enriched outflows or galactic fountains.

[2] The ionization parameter U is defined by the ratio of hydrogen ionizing photons to the total hydrogen density.

5. Metals in damped Lyα systems

At the highest neutral hydrogen column densities of $N_{\rm HI} \gtrsim 10^{20.3}$ cm^{-2}, quantum mechanic effects imprint a characteristic shape to the hydrogen Lyα profile that can be used to precisely measure $N_{\rm HI}$ in individual systems. Furthermore, at these densities, gas is almost fully neutral, thus neutral or singly ionized ions are the dominant species that trace the bulk of the gas. For these reasons, measurements of metallicities in DLAs are generally reliable, being unaffected by the uncertainties that arise from ionization corrections. Many studies have investigated in detail the metal content of DLAs, their redshift evolution, and their abundance ratios (e.g. Pettini et al. 2002; Prochaska et al. 2003a; Rafelski et al. 2012; Neeleman et al. 2013; Jorgenson et al. 2013).

These studies, and in particular recent work by Rafelski et al. (2012), have revealed a metallicity distribution that is well described by a Gaussian with mean [M/H] $= -1.51$ and dispersion $\sigma = 0.57$. This distribution lacks extended tails either towards super-solar or pristine values, as also confirmed by dedicated searches for very low-metallicity DLAs (e.g. Penprase et al. 2010) that consistently found gas enriched at or above a floor of [M/H] ~ -3. Further, the hydrogen-weighted mean metallicity of DLAs $\langle Z \rangle$, a quantity which describes the cosmic metal content of neutral hydrogen, exhibits a statistically-significant redshift evolution that Rafelski et al. (2012) modeled as $\langle Z \rangle = (-0.22 \pm 0.03)z - (0.65 \pm 0.09)$ between $z \sim 0 - 4.5$, although other parametrizations can be found in the literature (Jorgenson et al. 2013). Further, the study of the handful of DLAs known beyond $z \sim 4.5$ reveals that the cosmic metal content of neutral gas evolves much more rapidly in the first Gyr of cosmic history (Rafelski et al. 2013). This trend suggests a rapid chemical enrichment of the first cosmic structures or that a second population of more metal-poor DLAs becomes progressively important towards the epoch of reionization.

Since ionization corrections are not needed, the intrinsic abundance patterns in DLAs can be reliably measured (e.g. Prochaska et al. 2003b). For the subset of systems in which both iron and $\alpha-$elements are measured, DLAs are found to be $\alpha-$enhanced with a median $[\alpha/\mathrm{Fe}] \sim +0.3$ (Rafelski et al. 2012). Furthermore, the [M/H] and $[\alpha/\mathrm{Fe}]$ distributions in $z > 2$ DLAs with $[\mathrm{M/H}] \lesssim -1$ agree with those observed for Galactic halo stars. Similar abundance patterns between DLAs and halo stars are also found in the most metal-poor DLAs at $[\mathrm{M/H}] \lesssim -2$ (e.g. Cooke et al. 2011), hinting that there exists a connection between DLA gas and the sites where Galactic halo stars form. The study of abundance patterns of DLAs also provides important clues about the stellar populations that are responsible for the observed metal enrichment. For instance, a recent analysis by Becker et al. (2012) in candidate DLAs at $z > 5$ revealed a remarkable similarity in the abundance ratios of DLAs from $z \sim 2$ to beyond $z \sim 6$. Given the age of the universe at $z \sim 6$, these observations indicate that supernovae type-II from population-II stars and prompt type-I supernovae are the major contributors to the observed metal enrichment in DLAs.

6. Summary

Over two decades of absorption line studies have dramatically improved our view of the cosmic enrichment in the distant universe. Although a complete picture of the cosmic chemical evolution is yet to be drawn, this brief review outlines a possible sketch towards this goal. Galaxies are rapidly and continuously polluted by the yields of population II stars starting from the first few hundred million years of cosmic histories, and the relics of this enrichment are possibly seen today in the older stellar population within our Galaxy. Metals are also dispersed outside galactic disks, either through galactic winds or via more violent processes (e.g. tidal or ram-pressure stripping), in a heterogeneous, poorly mixed, and possibly short-lived gas phase. And this pollution is ultimately responsible for the widespread metal content that is visible in the overdense regions of the IGM.

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