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Identifying physical processes of metal-enrichment in the intergalactic medium at z=3

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Abstract. The enrichment of the intergalactic medium (IGM) with metals is often ascribed to powerful galactic winds emanating from star-forming galaxies during the epoch of peak star-formation ($1 < z < 4$). Actually observed outflows, however, do not appear to reach the distances required to explain the widespread metal enrichment, nor does the low density, metal-enriched IGM show any conspicuous signs of recent outflows. Alternative and/or earlier metal-enrichment processes capable of polluting regions far from bright galaxies may be required. We argue that studying high redshift galactic halos in low level Lyα emission may be a promising approach to search for such metal-enrichment events. It is found that extended, asymmetric Lyα emission often arises in galactic halos hosting young stellar populations and signs of tidal and / or ram pressure stripping characteristic of interacting galaxies. The release of metal-enriched gas during these interactions, possibly facilitated by a combination of stellar feedback and stripping, and enhanced by interaction rates increasing with redshift, may provide a mechanism for enriching the IGM as widely as observed.

Key words. Galaxies: halos – Galaxies: high-redshift – Galaxies: interactions – Galaxies: starburst – intergalactic medium

1. Introduction

Studies of QSO absorption lines have shown the intergalactic medium (IGM) to contain metals out to at least redshift six (e.g. Becker, Rauch, & Sargent 2009). Observations of lines-of-sight to QSOs close (in projection) to foreground galaxies have been used to constrain the gaseous environment of those galaxies and investigate the mechanisms of intergalactic metal-enrichment. Such studies frequently detect physical correlations between the properties of common gaseous ions like HI, MgII, CIV or OVI and the impact parameters to nearby bright galaxies out to hundreds of kpc (e.g. Chen 2012, and references therein). These findings are often referred to as "gaseous galactic halos", or as a "circumgalactic medium" (CGM; e.g. Rudie et al. 2012; Stocke et al. 2013). The question is how and when the metal-enrichment occurred, and what role the nearby galaxy may have played. The frequent finding of blue-shifted absorption lines in the stellar spectra of star-forming galaxies (e.g. Weiner et al. 2009), and the utility of galactic outflows in explaining the mass-metallicity relation (e.g. Erb et al. 2006) and other features of the galactic baryon budget have led to suggestions that QSO metal absorption lines may represent direct observations of galactic outflows enriching the "CGM", and that, in particular, galactic super-winds from bright, star forming $z \sim 3$ galaxies may be the main agents of intergalactic metal-enrichment.

2. The role of galactic winds for the metal enrichment of the IGM

The idea, that by studying QSO absorption lines we may be watching galaxies in the act of blowing halos of metal-enriched gas, may be attractive, but it is not without problems. First, in a dark matter based, hierarchical structure formation picture, halos contain multiple galaxies with a range of luminosities, which may have contributed to the observed metal enrichment at different times and with different efficiency. A nominal association of a particular parcel of gas with the nearest galaxy will be non-unique and will depend on the detection threshold for galaxies (e.g. Rahmati & Schaye 2013), so a distinction between a circumgalactic (directly influenced by a particular galaxy) and a general intergalactic medium may not be particularly helpful. Second, there still is little persuasive observational evidence for galactic winds being able to reach a substantial fraction of the volume claimed for the "CGM" (radii of hundreds of kpc):

1. in the local universe, observations generally show winds ranging only up to a couple tens of kpc (e.g. Veilleux, Cecil, & Bland-Hawthorn 2005).
2. In low redshift galaxies, the formation of typical, asymmetric Lyα emission lines (thought to be shaped by low-ionization, outflowing gas) appears to occur on small scales ranging from individual star-forming knots (e.g. Hayes et al. 2007) up to several kpc (e.g. Mas-Hesse et al. 2003).
3. At high redshift ($z \sim 3$), stacks of surface brightness profiles of Lyα emission centered on Lyman break galaxies (Steidel et al. 2011) show a central depression with a projected radius of $\sim$ 15 kpc for those galaxies with net absorption in their spectra, indicative of the typical range of the low ionization outflows observed in such objects.
4. A correlation between the absorption strength of MgII absorbers and the orientation of the nearest galaxy at intermediate redshifts ($z \sim 0.5 - 0.9$; Bordoloi et al. 2011), possibly due to collimated galactic winds, peters out at a radius of about 50 kpc.

Taken together, these findings do not preclude that galaxies may deposit a large fraction of their metals in their immediate neighborhood, well outside of their interstellar medium, but to explain the metallicity of the IGM further than a few tens of kpc away from bright galaxies one may have to look for alternative modes of metal enrichment. For example, the widespread presence of high-ionization, metal-enriched gas, most easily observed at high redshift in absorption by the CIV 1549 Å doublet, is unlikely to have been produced by galaxies close to the time when the gas is observed. Measurements of the kinematics of CIV gas at $z \sim 3$ (Rauch et al. 1996; Rauch, Sargent, & Barlow 2001) reveal it to be relatively quiescent, unlike gas currently being stirred by galactic winds. The earliest cosmological hydro-simulations of QSO metal absorbers, not yet including feedback and with metals added ab initio, were able to model the thermal, kinematic, and ionization properties of CIV absorbers as the products of an earlier phase of nucleosynthesis and metal enrichment, settling into the potential wells of future Milky-Way-type halos (Rauch, Haehnelt, & Steinmetz 1997). Simulations including feedback suggest that it is difficult to produce the spatially widespread carbon enrichment of the IGM with outflows from $z \sim 3$ star-forming galaxies in situ (Kawata & Rauch 2007). The clustering properties of CIV absorption lines and the greater ease of distributing metals at earlier epochs (e.g. Pichon et al. 2003; Porciani & Madau 2005; Scannapieco 2005; Scannapieco et al. 2006) support the view that the carbon metal enrichment may predate the bright galaxies that now appear spatially associated with it.

3. Using Lyα emission to pinpoint high z galactic halos

With increasing redshift, the metal enrichment of the IGM must be occurring in an increasingly denser environment, with a correspondingly larger role expected for galactic interactions, and lower mass galaxies, perhaps in a way analogous to the interactions happening in massive galaxy clusters at lower redshifts. At redshift 3, however, it is difficulty to even just ascertain the halo membership of satellite galaxies (which may be important agents of metal enrichment); any emission from the halo gas is too faint to study with narrow band imaging, and absorption line studies, while highly sensitive, lack spatial information. We argue here that spectroscopically detecting galaxies embedded in extended Lyα emitting halos may be a way of pinpointing galactic halos during assembly. Supplementing the spectroscopy with HST imaging helps to make sense of the spatial arrangement and physical state of the halo constituents.

We have performed several blind, spectroscopic long-slit searches for Lyα emitters that have yielded a number of detections of $z \sim 3$ Lyα emitting halos. The significance of this approach consists in its unprecedented depth, and its combination of velocity information and at least some spatial resolution (along the slit). The strong suppression of the sky background afforded by the spectroscopic approach together with large exposure times of between 40 and more then 90 hours on large telescopes allow us to detect individual extended Lyα halos powered by star-formation rates as low as $1\ M_\odot\ \mathrm{yr}^{-1}$ out to several tens of kpc. Among the usual contingent of ordinary, compact Lyα emitting galaxies similar to those seen in narrowband Lyα surveys, there are a number of extended, asymmetric objects.

4. Interacting galaxies as sources of IGM enrichment

Inspection of archival HST ACS broad band images shows that these emitters correspond to small groups of interacting galaxies, possibly satellites in a common halo (fig. 1). Elongated structures, reminiscent of tidal tails and /or ram pressure stripped galactic wakes are seen (first three rows in the figure). Blue colors and the presence of what appears to be high equivalent width Lyα emission suggest young stellar populations, partly residing in the tails. Star-formation in tidal dwarfs or ram-pressure stripped galactic wakes would not only occur far away and up in the halo of the main galaxy, it may also more easily evacuate the shallow potential of metals. Thus, these sites may be candidates for IGM metal enrichment outside of the zone-of-influence of the main galaxy. Such features have, of course, been seen before in the local universe, often in cluster environments, but it is striking that they can be picked out in extended Lyα emission at higher redshifts as well. In addition, Lyα is also useful as a tracer of the production of ionizing photons. The second row of panels in fig. 1 shows a situation, where ionizing radiation appears to spill out of a breach in the neutral hydrogen halo of an interacting galaxy, illuminating in-falling gas (Rauch et al. 2011). In general, the same features that accompany the ejection of metals (shallow potential wells with lower density gas; stripped stellar populations, young stars, possibly fueled by the metal-poor halo gas) may facilitate the escape of ionizing radiation as well. Thus galactic interactions may be responsible for the sources of both, early metal-enrichment, and ionizing radiation during the epoch of reionization. Extended Lyα emission can have a variety of origins, and one of the objects in our Lyα selected sample happens to be an AGN. The situation in the bottom row of the figure shows the Lyα emission region of an obscured QSO at z=3.045. Two small emission regions embedded in the QSO halo and visible in both Lyα emission and broad band light appear to host a stellar population with an age of only 2 Million years. The coincidence of the short-lived AGN activity with a very young stellar population may suggest that the star-formation is triggered by the AGN. Of course, this, too, is a form of interaction between galaxies, potentially leading to similar consequences in terms of a metal-enrichment of the QSO environment, and the escape of ionizing photons (Rauch et al. 2013a).

5. Conclusions

QSO absorption lines show a complex enrichment history of the intergalactic medium

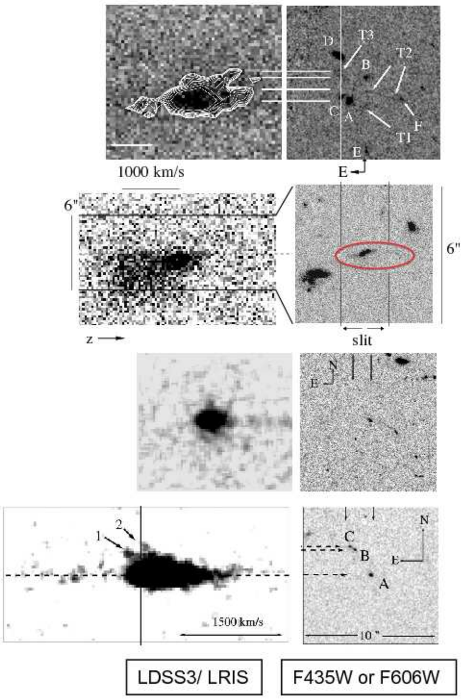

Fig. 1. Four extended, asymmetric Lyα emitters at $z \sim 3$. The left panels give the 2-dimensional spectra (with the spectral direction horizontal, the slit vertical), the right panels consist of HST ACS broad band images of the underlying galaxies. The top three rows all show halos with multiple galaxies and evidence for young/stripped stellar populations, the bottom row depicts an obscured AGN with two extremely young stellar clumps in its halo.

that is not fully accounted for by the idea that wind-driven bubbles around bright star-forming galaxies establish a "circum-galactic" medium. Widespread metal enrichment far from bright galaxies, beyond the range of know types of galactic winds, may require a earlier phase of metal enrichment or metal loss from a spatially distributed population of sources, possibly aided by the release of metals during ram-pressure or tidal stripping, or by the destruction of satellites during mergers. We have argued that we can study such processes with deep spectroscopic observations of Lyα emitting galactic halos. Blind spectroscopic searches for faint, extended Lyα emitters can pinpoint the location of galactic halos undergoing assembly at ~ 3 and help understand the release of metals and ionizing photons from the halo constituents. Preliminary results show that this approach appears to result in the detection of galactic halos with their satellites in various stages of interactions, as shown by the presence of young stellar populations, disturbed Lyα emission characteristic of anisotropic gas flows, tidal and ram pressure stripped features, and secondary star-formation outside the main halo galaxy. A combination of moderate stellar or SN feedback with such stripping mechanisms may unbind the metals in the interstellar medium of galaxies, when they move through the gaseous large scale filaments in the IGM, and within the gaseous envelopes of more massive galaxies. For more details, please see Rauch et al (2011; 2012, 2013a,b).

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