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$z \sim 6$ metal-line absorbers as a probe of galactic feedback models

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Abstract. Observations of metal absorption lines in the spectra of QSOs out to $z > 6$ are providing an important probe into the enrichment and ionization state of the intergalactic medium (IGM) at the tail end of reionization. Using simulations with four different feedback models, including the Illustris and Sherwood simulations, we investigate how the overall incidence rate and equivalent width distribution of metal-line absorbers varies with the galactic wind scheme. The low-ionization absorbers are reasonably insensitive to the feedback implementation, with all models reasonably close to the observed incidence rate of O I absorbers. However, all of our models struggle to reproduce the observations of C IV, which is probing overdensities close to the mean at $z \sim 6$, suggesting that the metals are not being transported out into the IGM efficiently enough in these simulations.

Keywords. intergalactic medium, galaxies: high-redshift, quasars: absorption lines, methods: numerical

1. Introduction

As well as regulating star formation, galactic feedback is important for enriching the intergalactic medium (IGM) with metals. There are still many open questions regarding the enrichment of the IGM, such as how and when was the IGM enriched and to which density is the IGM enriched with metals? Metal absorption lines in high-resolution spectra of $z > 6$ quasars are providing important insights into these questions, as they contain a lot of information about the enrichment and ionization state of the high-redshift IGM. These absorption lines also offer a powerful way to test the effect of different feedback prescriptions on the IGM at early times.

2. Modelling the high-z IGM

To test the effect of galactic feedback on the $z \sim 6$ IGM, we look at four cosmological hydrodynamical simulations with different feedback models. This includes the publicly available Illustris simulation (Vogelsberger *et al.* 2014, Nelson *et al.* 2015), run with the moving-mesh code AREPO (Springel 2010). We also look at two simulations run with AREPO that use variants on the Illustris wind physics, previously used to look at properties of damped Ly-α systems (DLAs) and the distribution of C IV around galaxies at $z \sim 2-4$ (first described in Bird *et al.* 2014). We further use a simulation run with P-GADGET3 (Springel 2005) from the Sherwood Simulation Suite, designed for high-resolution studies of the Lyman-α forest in large volumes (Bolton *et al.* 2016). The properties of the simulations are described in Table 1. We find that models with faster

Name	Code	Box Size (cMpc)	$m_{\rm gas}(M_\odot)$	Wind Model
Illustris	AREPO	106.5	1.3×10^6	Vogelsberger *et al.* (2013)
Sherwood	P-GADGET3	59.0	1.5×10^5	Puchwein & Springel (2013)
FAST	AREPO	35.5	2.1×10^6	1.5 × Illustris wind vel
HVEL	AREPO	35.5	2.1×10^6	$v_{\rm wind,min} = 600$ km s^{-1}

Table 1. Parameters of the simulations we use in this work: code that was used to run the simulation, the mass of the gas particle/resolution element ($m_{\rm gas}$) and the wind model used.

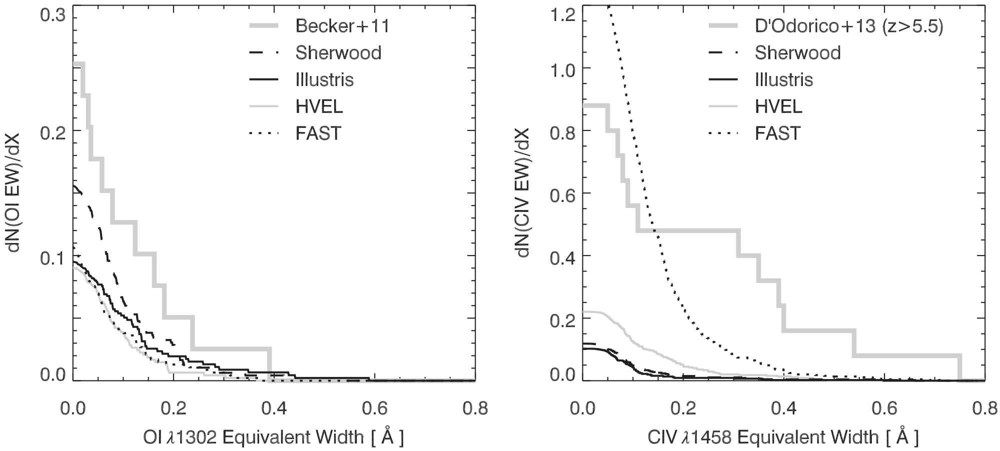

Figure 1. Left: Cumulative distribution of O I equivalent widths for the four feedback models (thin lines), compared to data from Becker *et al.* (2011) (thick line). Right: Cumulative distribution of C IV equivalent widths for the four feedback models (thin lines), compared to data from D'Odorico *et al.* (2013) (thick line). This figure is adapted from Figure 10 of Keating *et al.* (2016).

winds are able to enrich the IGM more efficiently with metals. As the wind velocity is increased, the volume filling factor of metals increases. The mean mass-weighted metallicity is also higher at a given gas overdensity for models with higher wind velocities.

To model the ions which we are interested in, we generate a set of interpolation tables for each ionic fraction in density and temperature space using the photoionization code CLOUDY (Ferland *et al.* 2013). We assume a uniform UV background (while aware that this is likely to be a poor approximation at $z \sim 6$), using the Haardt & Madau (2012) model. We also test the effect of increasing the amplitude of this model to account for the contribution of local sources. We account for self-shielding of dense, cold gas by including a frequency-based attenuation of the UV background based on the Rahmati *et al.* (2013) prescription, as described in Bird *et al.* (2015).

3. Comparison with Observations

To compare our simulation with observations of O I and C IV at $z \sim 6$, we constructed synthetic spectra along different sightlines through the simulation. From these, we identified the absorbers and measured their equivalent widths. As the observations are not complete, we apply a completeness correction to our data based on estimates of completeness from Becker *et al.* (2011) and D'Odorico *et al.* (2013). Our resulting equivalent width distributions are shown in Figure 1. We find that the distribution of O I absorbers is reasonably insensitive to the hydrodynamic solver and feedback implementation used in the simulations. All our models fall short of the incidence rate measured by Becker

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et al. (2011), but this could be matched by rescaling the metallicity by a factor of ~ 3, increasing the resolution of the simulations (which would produce a larger number of weak systems) or by changing our treatment of the self-shielding in the simulations.

Matching the C IV, which is probing the low density gas at $z \sim 6$, is much more challenging. Only the extreme HVEL model, which has a minimum wind velocity of 600 km s^{-1}, can produce the total number of observed absorption systems. However, this model and all the other feedback prescriptions fail to produce enough strong systems (with equivalent widths greater than 0.2 Å). The question then is, where is the missing C IV? Are these wind models not enriching the IGM out to low enough densities? As a test, we assume that all carbon below a self-shielding threshold is in the form of C IV. Even for this extreme test, all of our models still struggled to reproduce the observed incidence rate and equivalent width distribution of C IV absorbers. We also investigated the effect of changing the UV background. Having a harder UV background or increasing the amplitude by a factor of six (to mimic inhomogeneous amplification of the UV background by local sources) does help, but still fails to produce the strongest absorbers. This is investigated in more detail in Keating *et al.* (2016).

4. Conclusions

We find that while the incidence rate of O I absorbers is reasonably robust to the choice of hydrodynamic code and wind implementation, looking at high-redshift C IV absorbers puts interesting constraints on wind models. It is not entirely clear whether this points to missing physics in the simulations, such as stronger winds at high redshift, or if the galactic winds in the simulations require a different numerical implementation. We emphasise that it is critical to test feedback models at the highest possible redshift, as models which fail to reproduce observations at early times will also fail at later times, or may appear to succeed for the wrong reasons. Modelling metal-line absorbers provides an interesting way to test the effect of feedback models on the IGM. These constraints will become even tighter as new observations of metal absorption lines are delivered by the current and next generation of spectrographs.

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