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The global oxygen yield budget followed in hydrodynamic simulations

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Abstract. We present new EAGLE ("Evolution and Assembly of GaLaxies and their Environments", Schaye *et al.* 2015) zoom simulations of a range of Milky Way-like galaxies that can uniquely reproduce the metallicities of galactic stars, the ISM, and now the circumgalactic medium (CGM) as probed by quasar absorption line surveys. The surprising result is that the average L^* galaxy loses more oxygen to the CGM out to hundreds of kpcs from a galaxy than it retains in its stars. These zooms not only follow the nucleosynthetic yields of 11 elements, they follow the non-equilibrium ionization and cooling of 133 ions, which allow direct comparison to observations of the COS-Halos survey of O VI in galactic halos out to 150 kpc (Tumlinson *et al.* 2011). The result is a new understanding of the galactic nucleosynthetic yield budget in simulations where galaxies are dramatically shaped by supernovae and black hole feedback. We are now closer to reconciling observed stellar, ISM, and now CGM metallicities with the nucleosynthetic production of the stellar component.

Keywords. galaxies: formation, intergalactic medium, nucleosynthesis, methods: n-body simulations, quasars: absorption lines

1. Introduction

The supernova nucleosynthetic yields of oxygen integrated over an initial mass function indicate a much larger production of oxygen than can be accounted for in stars and the ISM. Peeples *et al.* (2014) provide a galactic accounting of oxygen and all metals, and added in the contributions of circumgalactic metals observed by the COS-Halos survey (Tumlinson *et al.* 2011). While finding a significant fraction of oxygen in the CGM probed by sight lines out to 150 kpcs around $< z >= 0.2$ star-forming galaxies, Peeples *et al.* could not close the oxygen budget indicating that a significant fraction of oxygen and metals remain hidden, if one is to believe the nucleosynthetic yields.

2. Method

We run a series of cosmological hydrodynamic zoom simulations to confront the COS-Halos observations of strong O VI ubiquitously observed around star-forming, $\sim L^*$ galaxies (Tumlinson *et al.* 2011). We use the EAGLE simulation code (Schaye *et al.* 2015, Crain *et al.* 2015), which is an extensively modified version of the N-body+Smooth Particle Hydrodynamic (SPH) GADGET-3 code with several modifications to overcoming short-comings in classical SPH implementations. The EAGLE subgrid physics routines were calibrated to reproduce the $z = 0.1$ galactic stellar mass functions, the sizes of galactic discs, and the black hole-stellar mass relation. Additionally, the EAGLE-Recal star-formation+black hole feedback prescription (Schaye *et al.* 2015) we apply, reproduces key trends observed in the ISM and stellar metallicities of galaxies, which is critical for a plausible accounting of the global oxygen budget.

We present 10 L^* zooms ($M_{\rm halo} = 10^{11.7} - 10^{12.3}{\rm M}_\odot$) and 10 group-sized zooms ($M_{\rm halo} = 10^{12.7} - 10^{13.3}{\rm M}_\odot$) with SPH particle masses of $2.3 \times 10^5{\rm M}_\odot$ and dark matter

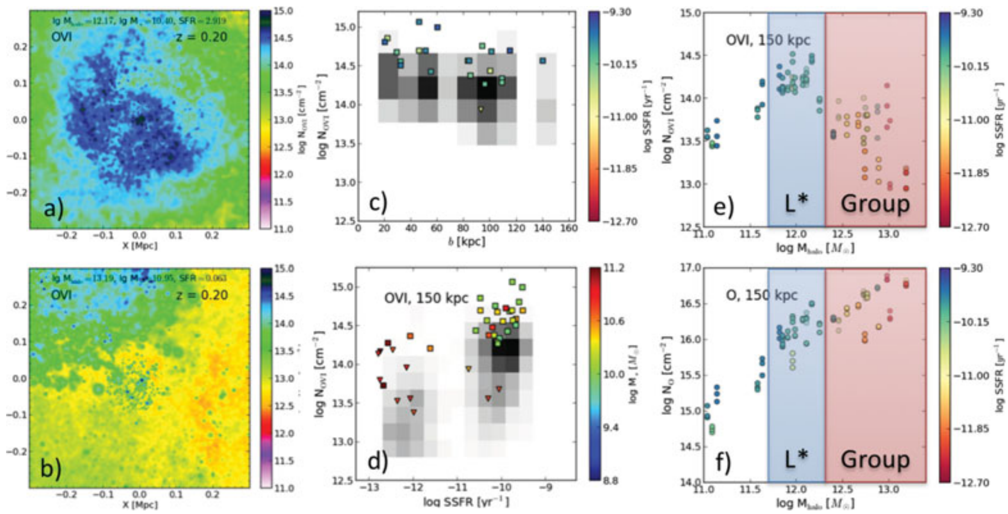

Figure 1. EAGLE simulations confronting COS-Halos results (see text).

particle masses of $1.2 \times 10^6 M_\odot$. We apply a non-equilibrium ionization and cooling module, introduced in Oppenheimer & Schaye (2013), which explicitly follows 133 ionization states of 11 elements at low redshift.

3. Results

Figure 1 shows O VI CGM maps at $z = 0.2$ of a star-forming galaxy in a $10^{12.2} M_\odot$ halo (panel a) and a passive galaxy in a $10^{13.2} M_\odot$ halo (panel b). These halos show the general trend that O VI is $\sim 5 - 10\times$ stronger in the L^* CGM than in the group-sized CGM within 150 kpc. We perform a set of COS-Halos mock surveys and plot the probability distribution of O VI columns (gridded shading) for the blue star-forming COS-Halos sample (squares & reverse triangles for upper limits) in panel c). We find strong O VI columns, although they are $\sim 0.2 - 0.3$ dex weaker than COS-Halos on average. Panel d) shows that our mock surveys confronting the star-forming and passive COS-Halos samples reproduce the bimodality of weak O VI around low-SSFR, passive galaxies, and strong O VI in the high-SSFR, star-forming galaxies.

The EAGLE simulations reproduce the O VI-SSFR bimodality indirectly: passive galaxies live in hotter halos with virial temperatures $> 10^6$ K that are not well traced by collisionally ionized O VI, while star-forming galaxies with virial temperature $< 10^6$ K contain O VI that better traces total CGM oxygen. Panel e) shows the average O VI column within 150 kpc, showing a peak for L^* followed by a decline for group halos, while panel f) shows the average oxygen columns continuing to rise for groups. The implication is that the O VI reservoir probed by COS-Halos indicates a reservoir in excess of the oxygen in the stellar and ISM component of a galaxy. The oxygen mismatch calculated by Peeples *et al.* (2014) is closed in these simulations, because the global O VI CGM ionization correction is much larger than the O/O VI = 5 that is traditionally assumed.

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