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The MUSE QSO Blind Survey: A Census of Absorber Host Galaxies

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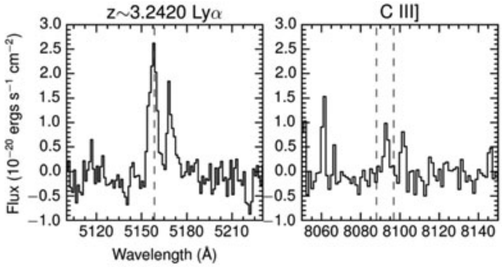
Abstract. Understanding the distribution of gas in galaxies and its interaction with the IGM is crucial to complete the picture of galaxy evolution. At all redshifts, absorption features seen in QSO spectra serve as a unique probe of the gaseous content of foreground galaxies and the IGM, extending out to 200 kpc. Studies show that star formation history is intimately related to the co-evolution of galaxies and the IGM. In order to study the environments traced by absorption systems and the role of inflows and outflows, it is critical to measure the emission properties of host galaxies and their halos. We overcome the challenge of detecting absorption host galaxies with the MUSE integral field spectrograph on VLT. MUSE's large field of view and sensitivity to emission lines has allowed a never-before seen match between the number density of absorbers along QSO sightlines and the number density of emission line galaxies within 200 kpc of the QSO. These galaxies represent a sample for which previously elusive connections can be made between mass, metallicity, SFR, and absorption.

Keywords. galaxies: IGM, quasars: absorption lines, galaxies: formation

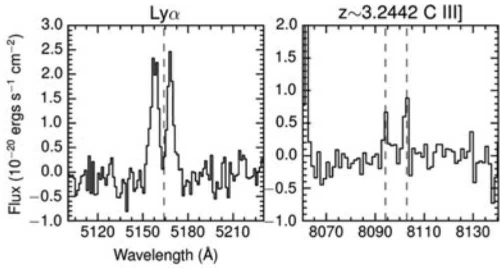
1. Introduction

Gas inflows and outflows are critical ingredients in models for the formation and evolution of galaxies. However, these elements are also the most poorly understood. Models predict the existence of two accretion modes: a cooling flow from a hot, hydrostatic halo and cold ($T \sim 10^4$ K) filamentary streams. The hot and cold modes are thought to dominate accretion onto low- and high-mass galaxies respectively. Galaxies residing in haloes with masses $\sim 10^{12}$ $M_\odot$ benefit from both modes, with cold filaments penetrating the hot halo. Models in which most of the gas that accretes onto galaxies is converted into stars predict far too high stellar masses. It is widely believed that outflows driven by feedback from massive stars and/or AGN are the solution to this overcooling problem. Indeed, observations of starburst galaxies consistently reveal the presence of absorption lines that are blueshifted by hundreds of km s^{-1} relative to the galaxies systemic velocities (Steidel *et al.* 2010), as would be expected if the galaxies drive winds into intergalactic space. Although these outflows are too dilute to be observed in emission (with column densities $N_{HI} = 10^{12} - 10^{22}$ cm^{-2}), observations of QSO absorption lines indicate ubiquitous metal enrichment suggesting gas flows fill a large fraction of the volume (Booth *et al.* 2012).

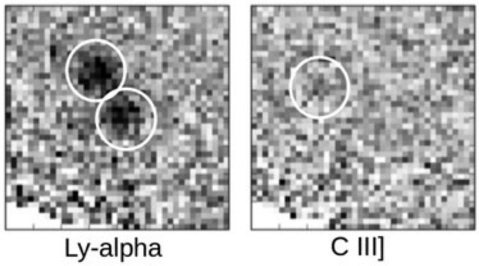
Observing the circumgalactic medium (CGM) where gas flows reside is difficult because of the aforementioned low column densities of the diffuse gas. Absorption line spectroscopy of bright background QSOs allows observers to circumvent this difficulty, is



(a) Redshift determined by peak Lyα emisison.



(b) Redshift determined by C III] emission.



(c) MUSE narrowband image at the redshift of the emitters. Left: Lyα. Right: C III].

Figure 1. Two interacting Lyα emitters with associated C III] emission detected with VLT/MUSE. The vertical dashed lines indicate the wavelength used to determine the redshift. The difference in emission lines between frames a) and b) is due to slight overlap in the extraction aperture centered on each of the Lyα emitters.

luminosity independent and therefore less biased towards high gas densities, and provides us with an accurate and sensitive probe of the CGM. As the strongest absorption lines are ubiquitous in the rest-frame UV, this work can be done with high resolution spectrographs on ground-based telescopes at high-z and with HST/COS at low-z. Such high resolution spectra can provide critical information on the column density, kinematics, metallicity, and physical state of the gas being probed. However, though great progress has been made in detecting QSO absorption host galaxies (e.g. Chen *et al.* 2010; Péroux *et al.* 2012; Straka *et al.* 2015), the relationship between these absorption properties in the halo and the emission properties of the central host galaxies remains an open question. Understanding the luminosity, star formation rate, position angle, and morphology (to name a few) of QSO absorption host galaxies is a critical step to formulate a complete picture of gas flows in and around galaxies and their role in galaxy formation and evolution.

2. Galaxy Detection

Traditionally, detecting QSO absorption host galaxies has involved several steps, including deep imaging, frequently in multiple filters, and followup spectroscopy (multi-object or long-slit) of the galaxies detected photometrically. These techniques are also biased towards the most luminous galaxies, relying on their detection in imaging. Although surveys around $z \sim 1$ QSOs have yielded thousands of galaxy redshifts using these techniques, nearly all of the galaxies have impact parameters of many Mpc, far exceeding the extent of the CGM and hence limiting the science to studies of large-scale

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structure (Tejos *et al.* 2014). At ultra-low redshift, $z \sim 0.01$, there are currently redshifts for $\sim 10^2$ galaxies with impact parameters ~ 350 kpc from QSOs for which HST spectra are available (Liang & Chen 2014). However, as these galaxies are nearly all dwarfs ($M< 10^9$ $M_\odot$), these separations far exceed the size of the galaxies haloes. At high redshifts, spectroscopic surveys yield fewer than 4 galaxies per unit redshift compared to 30 metal line absorption systems seen along the QSO line of sight (Steidel *et al.* 2010). With the onset of the integral field spectroscopy age, we are able to address these problems with a more efficient observing strategy.

3. The MUSE QSO Blind Survey

The MUSE QSO Blind Survey is a blind survey for galaxies within 200 kpc of QSO sight lines without prior knowledge of their absorption properties. The survey is designed to utilize the large $1' \times 1'$ field of view of the Multi Unit Spectroscopic Explorer (MUSE) on the Very Large Telescope (VLT) (Bacon *et al.* 2010). MUSE is sensitive to emission from even faint galaxies that might not otherwise be detected in continuum through deep imaging, allowing us to simultaneously determine redshift and impact parameter with the QSO line of sight. Our survey searches for galaxies in 24 fields centered on QSO sight lines, with the aim to cross correlate these galaxies with absorption systems cataloged from high-quality archival QSO spectra (from HST/COS and VLT/UVES). The sample is divided into two categories, 16 QSOs at $0.4 < z < 1.5$ and 8 QSOs at $z \sim 3.8$, in order to probe [O II] and Hα emission correlated with absorption at $z < 1.5$ and Lyα emitters correlated with absorption at $2.9 < z < 3.8$.

Figure 1 shows for example a pair of Lyα emitters detected with MUSE which show corresponding C III] emission. Assuming a systemic redshift measured from C III] of $z = 3.2442$, the Lyα emission is shifted ~ 430 km s^{-1} from systemic. In addition, this system exhibits corresponding C IV and Si IV absorption ~ 550 km s^{-1} from systemic. We have successfully used MUSE to find hundreds of emission line and continuum galaxies along these lines of sight, probing physical impact parameters ranging from 50 kpc at $z = 0.1$, to 250 kpc at $z = 1$, and up to 225 kpc at $z \sim 3$. MUSE has allowed us to establish a sample of galaxies for which SFR, metallicity, galaxy orientation (position and inclination angles), and kinematics are known and for the first time matched in number density to that of absorbers along QSO sight lines.

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