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Star Formation in Damped Lyman α Selected Galaxies

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Abstract. I present results from an ongoing survey to study galaxies associated with damped Lyman-α (DLA) systems at redshifts $z > 2$. Integral field spectroscopy is used to search for Lyα emission line objects at the wavelengths where the emission from the quasars have been absorbed by the DLAs. The DLA galaxy candidates detected in this survey are found at distances of 10–20 kpc from the quasar line of sight, implying that galaxies are surrounded by neutral hydrogen at large distances. If we assume that the distribution of neutral gas is exponential, the scale length of the neutral gas is ∼6 kpc, similar to large disk galaxies in the local Universe. The emission line luminosities imply smaller star formation rates compared to other high redshift galaxies found in luminosity selected samples.

Keywords. galaxies: formation – galaxies: high-redshift – quasars: absorption lines.

1. Introduction

Statistics of absorption lines in the Lyman-α forest of high redshift quasars show that most of the neutral hydrogen mass resides in the highest column density absorbers, the damped Lyα systems (DLAs) with $\log N(\text{H I}){>}20.3$ cm^{-2}. The amount of gas in high redshift DLAs is comparable to the mass of stars in the local Universe (Storrie-Lombardi *et al.* 1996). Analyses of associated metal absorption lines have shown evidence for a metallicity increase with increasing cosmic time (Kulkarni & Fall 2002). All these studies in combination indicate that DLAs are reservoirs for star formation, and that star formation should occur at the time of observation. However, the type of galaxy in which high redshift DLAs are found is not well known. Significant observing time has been invested in the detection of the DLA galaxies in emission. However, out of more than 500 DLAs at $z > 2$ currently known (Prochaska *et al.* 2005), only three intervening DLA galaxies have been detected in emission, and another three associated DLAs at similar redshifts as the quasars are also detected (Weatherley *et al.* 2005, and references therein).

Previous investigations which aimed to locate emission from DLA galaxies used conventional high spatial resolution images to look for DLA galaxy candidates near the line of sight of QSOs with known DLAs in their spectra. Follow up spectra were needed to determine the redshifts of the candidates in order to confirm or reject them as the DLA galaxies. Alternative methods such as narrow-band imaging (Fynbo *et al.* 1999), or Fabry-Perot imaging (Kulkarni *et al.* 2006) have been used to detect emission line objects at the expected wavelength of Lyα at the redshift of the DLA. Yet another technique that allows one to get spectral as well as spatial information is integral field spectroscopy. Although the total throughput of integral field units (IFUs) is not impressive (typically $\lesssim$10%) they offer the advantage of scanning a range of wavelengths, which is necessary in the case of velocity shifted emission lines. As demonstrated in Christensen *et al.* (2007), the PMAS-IFU (Roth *et al.* 2005) at the 4 m telescope on Calar Alto, can be used to

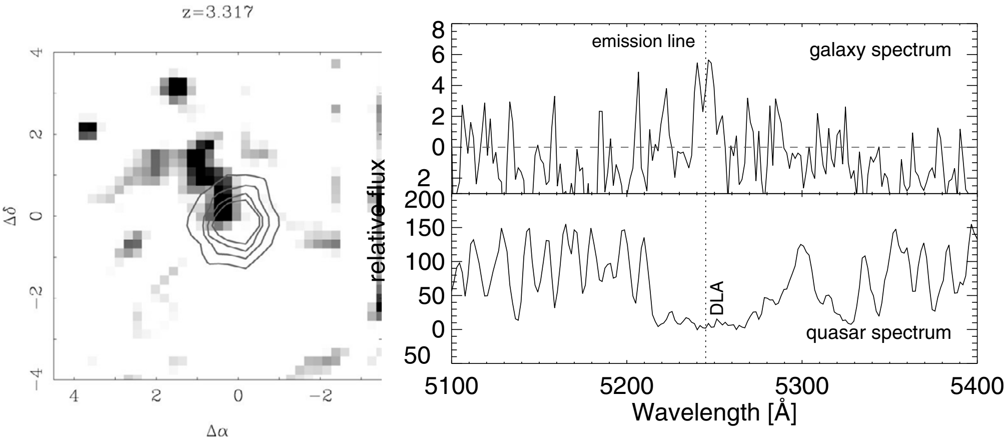

Figure 1. Example of a candidate Lyα emission line from a DLA galaxy at $z = 3.317$ in the line of sight towards PSS J2155+1358. The gray scale narrow-band image is extracted at the wavelength where the QSO emission is absorbed. The corresponding spectrum is shown in the upper panel. The contours on the image indicate the emission from the QSO in adjacent slices of the data cube.

detect emission line candidates with an emission line flux of $\sim 5 \times 10^{-17}$ erg cm^{-2} s^{-1}. This survey is extended to fainter flux limits by including observations from IFUs on 8m class telescopes. Here, preliminary results from the combined sample are presented. The aim of the survey is to determine the star formation rates in DLA galaxies and to probe the extension of neutral gas around proto galaxies.

2. Data

The target selection of the original PMAS survey did not take into account the metallicity of the DLAs or the detection of molecular hydrogen absorption lines associated with the DLAs. However, information from absorption lines could point out DLAs that are most likely associated with the strongest star forming galaxies. DLAs which have a strong C II* fine structure absorption are also expected to be located in a strong radiation field, and could be close to a region with a high star formation rate (Wolfe *et al.* 2003). Alternatively, star formation occurs in regions that contain a significant fraction of molecular hydrogen apart from neutral hydrogen. If DLAs arise in star forming regions one should expect a high molecular fraction. Yet only few DLAs show absorption from molecular hydrogen (Ledoux *et al.* 2003). Nevertheless, the selection of systems with either H_2 detection or strong C II* absorption could help to preferentially select DLA galaxies with strong emission lines.

The sample of DLAs observed with IFUs have now been doubled by means of these new selection criteria. As of mid-2007, the total sample investigated with integral field observations consists of 13 DLAs and 8 sub-DLAs (with column densities $19 < \log$ NH I $<$ 20.3 cm^{-2}) from the PMAS survey, and 14 DLAs observed with IFUs on the VLT and Gemini telescopes.

3. Results

The reduced data cubes are investigated systematically for the presence of emission lines close in wavelengths where the QSO emission is absorbed by the DLAs. For an emission line object to be considered as a good candidate it is required to be detected at

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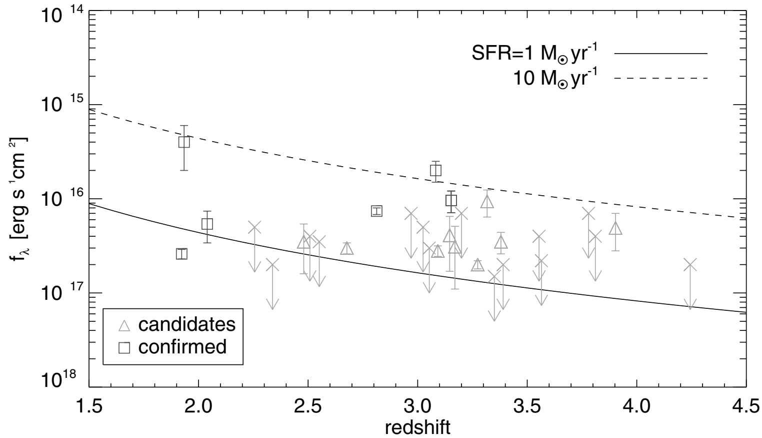

Figure 2. Emission line flux as a function of the redshifts of the DLA systems. Squares represent DLA galaxies that have been confirmed previously (taken from Møller *et al.* 2002). Triangles denote emission line candidates detected in this survey, and crosses 3σ upper detection limits. The lines show the relation between the fluxes and SFRs.

the 3σ level in both narrow-band images and associated spectra extracted from the IFU data cubes as demonstrated in Fig. 1 (see also Christensen *et al.* 2007).

In total six candidate Lyα emitters are detected in the PMAS survey and three candidates are found in the IFU data from the VLT. Fig. 2 shows the emission line fluxes of the candidates as a function of redshifts. This figure also includes DLA galaxies confirmed through conventional techniques (see Møller *et al.* 2002). The luminosity is found using a set of parameters H_0, Ω_m, and Ω_Λ. Then the star formation rate (SFR) is calculated using a conversion factor between the Hα luminosity and the SFR (Kennicutt 1998), and the Lyα/Hα emission line ratio for case B recombination. Fig 2 shows that both the candidates and the confirmed DLA galaxies have SFRs between 1 and 10 $M_\odot$ yr^{-1}, while the upper limits indicate that many DLA galaxies have even smaller SFRs.

The projected spatial offset between the emission line candidate and the QSO line of sight can be used as a proxy for the extension of the neutral gas around the DLA galaxies. Fig. 3 shows the DLA column density as a function of the measured impact parameter b for the candidates and for DLA galaxies taken from the literature. Assuming that the gas distribution around proto galaxies can be described by simple disks, we can fit an exponential profile N(H I)= N(H I)$_0$ $\exp(-b/h)$ to the observations. A fit to the candidates only gives the scale length $h \approx$6 kpc, which is similar to large disk galaxies in the local Universe. A fit to the confirmed objects only gives h=4.5 kpc. The central column densities given by the fits are N(H I)$_0$ $\approx 3-5\times10^{21}$ cm^{-2}.

4. Discussion

Beyond the detection of the candidates we are faced with biases concerning the interpretation of what type of galaxy a high redshift DLA resides in. Since the selection of emission line objects will most easily point out the brightest galaxy present in a group, it is impossible to determine whether or not the candidate is the true DLA galaxy. This could bias the results, and possibly explain the discrepancy from numerical simulations which suggest that most DLA galaxies have impact parameters smaller than 5 kpc (Nagamine *et al.* 2007). In no case do we find two good candidate emission line galaxies associated with a single DLA.

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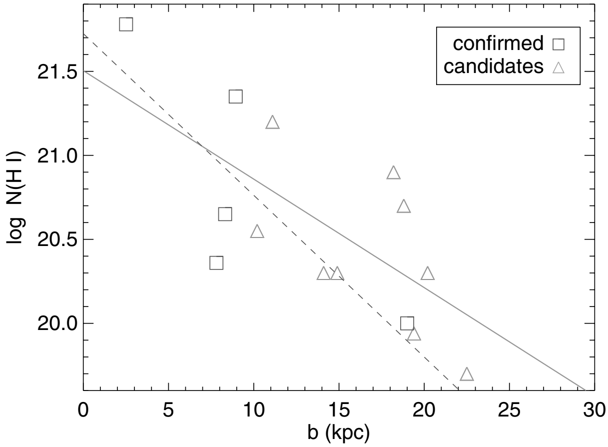

Figure 3. Column density of the DLA as a function of the impact parameter measured in the data cubes. There is a clear correlation that higher column density DLAs are found closer to the emission line galaxies. The solid line shows a fit of an exponential profile to the candidates only, while the dashed line is a fit to the confirmed objects. The exponential scale lengths are 6 and 4.5 kpc, respectively.

Another complication is that the SFRs derived from Lyα emission lines are very uncertain. Resonant scattering in a dusty environment will effectively quench all Lyα photons and the derived SFRs are strictly lower limits. This could be a minor problem as DLA clouds themselves do generally not contain much dust, although this may not be the case for the emission line region detected at a 10–20 kpc distance. For a couple of DLA galaxies, the corresponding optical emission lines suggest similar SFRs as those derived from Lyα (Weatherley *et al.* 2005).

The fit of one single exponential profile to the neutral gas distribution assumes that the average DLA galaxy disk is observed face on. In case of an edge on disk, a higher column density DLA could be found at larger impact parameters. Correspondingly the scatter in the figure would increase. It is not reasonable to expect that the neutral gas in proto galaxies fits a similar exponential disk in all cases since individual galaxy disks have different scale lengths. At low redshifts a sample of 14 confirmed DLA galaxies do not show a clear correlation between the column density and impact parameter (Chen *et al.* 2005). Another effect that could cause a considerable scatter in Fig. 3 is tidal interactions between individual galaxies in groups, which can distribute high column density clouds far from the host galaxy.

4.1. *DLA galaxy types*

Returning to the question of what type of galaxy DLAs reside in, we may use the information from the fit in Fig. 3. The total neutral gas mass of such an exponential disk is M(H I)$\approx 5 \times 10^9$ M$_\odot$, which is similar to that of our Galaxy, and certainly larger than the neutral gas mass in dwarf galaxies.

The total baryonic mass of a DLA galaxy including stars is difficult to estimate based on these observations. However, various arguments suggest that DLA galaxies are likely low-mass, and low-luminosity objects. Firstly, at $z = 3$ the galaxies have not had the time to build up a significant stellar mass component, so the total mass may be significantly below the Milky Way mass. Secondly, since DLA metallicities are typically 1–10% solar, and taking into account the mass-metallicity relation observed for galaxies, the DLA hosts must be low mass galaxies provided that the DLA metallicity is representative of

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the host. Such low mass galaxies are also expected to be sub-luminous relative to L^* galaxies. Further, the Schmidt-Kennicutt law is shown not to be valid for DLAs (Wolfe & Chen 2006), so the expected average SFR for a DLA galaxy is smaller than 1 $M_\odot$ yr^{-1}. Since the detection limit of the current survey is a SFR of a few solar masses per year, we cannot conclude that DLA galaxies are dark based on the non detections. Very likely an increase in efficiency of future IFUs will help to detect the emission lines from the DLA galaxies.

The selection of high redshift galaxies based on their neutral gas cross section avoids the biases that affect other surveys for high redshift galaxies, that just pick up the most luminous objects with the highest SFRs. While Lyman break galaxies, which have typical SFRs of 10–100 $M_\odot$ yr^{-1} (Steidel *et al.* 1996) and are relatively rare, are progenitors of present day luminous ellipticals, the present day galaxy counterparts to DLAs could be both normal spiral galaxies and dwarf galaxies. Studies of abundance patterns in DLAs combined with chemical evolution models have shown that DLAs reside in galaxies with a range of star formation histories, typical for dwarf galaxies or quiescent spirals (Dessauges-Zavadsky *et al.* 2007). The fact that the DLA galaxy candidates have very modest SFRs, and that most of them remain undetected at the flux limit of this survey, supports this scenario. Selecting galaxies based on their absorption properties probes a different population of galaxies than those drawn from high redshift surveys, and a complete picture of high redshift galaxy formation needs to take these different populations into account.

Further analysis of the candidate emission line objects involves a comparison with properties of DLA absorption lines such as the C II* or H_2 detections and the velocity components of the absorption lines. This will help to understand the correlation between the absorption line studies and the type of galaxy the DLA resides in.

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