Dwarf Galaxies: From the Deep Universe to the Present
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Neutral Gas Phase Metallicities Associated with Dwarf Galaxies

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Abstract. Absorption line spectroscopy of foreground gas in the spectra of background quasars has revealed some clear cases where neutral gas is present and associated with dwarf galaxies. Spectroscopy of Lyα and low-ionization metal lines can be combined to derive neutral gas phase metallicities. The damped Lyα absorbers (DLAs) in quasar spectra are the clearest cases of absorption by predominantly neutral gas regions. Here we present some results on neutral gas phase metallicities for cases where the DLA is clearly associated with a dwarf galaxy. We find that the neutral gas phase metallicities in these systems are similar to those in other DLAs. We argue that there may be many unrecognized cases where a DLA is actually associated with a dwarf galaxy even though there is a luminous galaxy within 100 kpc of the quasar sightline.

Keywords. galaxies: dwarf, galaxies: abundances, quasars: absorption lines

1. Background

The metal abundances of neutral gas regions associated with galaxies can be measured by observing and analyzing the absorption lines they produce in the spectra of background quasars. The absorption systems which are damped Lyα absorbers (DLAs) are recognized as ones that correspond to large columns of neutral gas. To determine the type of galaxy associated with the absorption, imaging of the quasar field is done to identify possible associated galaxies. Some method must then be used to make a positive match between the absorption redshift and the galaxy redshift. Once this is done, the impact parameter, b, of the associated galaxy relative to the quasar sightline can be measured. This is an important interpretive parameter which provides a clue about which component of the galaxy causes the absorption, e.g., disk, halo, or circum-galactic medium (CGM), where the CGM may track gas inflow, outflow, fueling, and metal enrichment cycles.

Here we emphasize some cases where the identified galaxies are clearly dwarfs, with luminosities $L < 0.1L^*$, and we present results on the corresponding neutral gas phase metallicities for these cases. We also argue that there may be a significant number of unrecognized cases where a neutral gas absorber should be associated with a dwarf, but is instead mismatched to a nearby luminous galaxy. This is consistent with our finding that neutral gas phase metallicities clearly associated with dwarfs are similar to the broad range of metallicities found in DLAs. This short paper is organized as follows: §2 reviews how quasar spectroscopy is used to derive cosmic neutral gas phase metallicities, §3 outlines how their association with dwarf galaxies is established, and §4 gives a short summary and discussion.

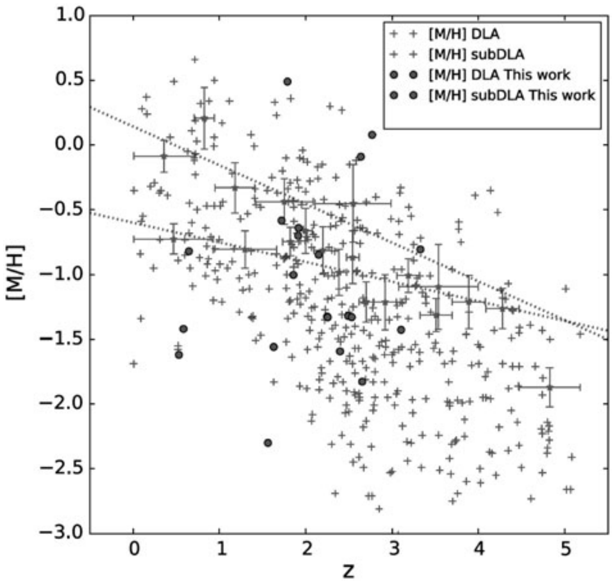

Figure 1. Neutral gas phase metallicities from Quiret *et al.* (2016), who show the color-coding needed to see which are DLAs and which are subDLAs. The DLA (lower) and subDLA (higher) HI-weighted fits to the data are shown. Many galaxy types, including dwarfs, contribute to the results.

2. Neutral Gas Phase Metallicities

Some quasar absorption line surveys, such as those done using the massive database of Sloan Digital Sky Survey (SDSS) spectra, have been performed to specifically identify tracers of foreground cosmic neutral gas, such as a subset of strong MgII absorption line systems. See Rao *et al.* (2017) and references therein for details. For any strong MgII absorber at redshift $z < 1.6$, UV spectroscopy (e.g., with the Hubble Space Telescope) is required to measure its HI column density, N(HI). This is done by fitting Lyα absorption with a Voigt damping profile. Those found to have logN(HI) $\geqslant 20.3$ are classically called damped Lyα absorbers (DLAs); those with $19.0 \geqslant$ logN(HI) > 20.3 are called subDLAs. Results from spectroscopy of corresponding unsaturated metal-line transitions due to singly ionized elements can then be combined with N(HI) values to derive metallicities. Even moderate-resolution SDSS spectroscopy can provide metallicities for elements like Zn, Cr, Si, Fe, and Mn. High-resolution spectroscopy can often provide more details, such as information on the number of absorption components at different velocities that make up a metal-line absorption profile. Figure 1 shows a compilation of metallicity results for neutral-gas absorbers from Quiret *et al.* (2016).

3. Association with Galaxies

Once a DLA absorption system with measured HI column density, N(HI), is found, imaging is used to identify candidate associated DLA galaxies at various impact parameters, b, and luminosities, L. Slit spectroscopy may be used, photo-z techniques may be employed, or a good reason must exist (e.g., the existence of a galaxy at small-b with no other plausible candidates) to claim that the absorption redshift and the galaxy redshift match. However, if there is a dwarf galaxy at low impact parameter along a bright quasar sightline, this would hinder any identification, and it might make an actual dwarf galaxy

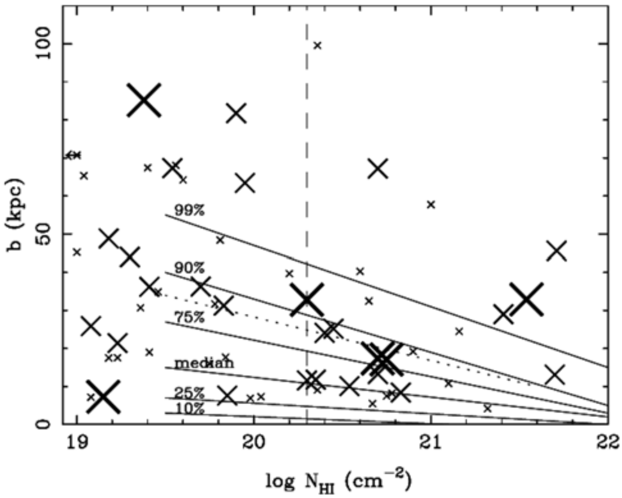

Figure 2. Luminosities and impact parameters, b, of associated DLA and subDLA galaxies at $z < 1$ from Rao et al. (2011). Large Xs represent ∼L* galaxies; medium Xs are sub-L* galaxies; small Xs are dwarf galaxies. However, for some large-b cases, one might infer that neutral-gas absorption is due to unseen dwarfs with smaller b, and their detection is lost in the glare of the bright quasar along the sightline. The lines are a representation of findings from local 21 cm emission studies, and indicate the percentage of gas found interior to b as function of N(HI).

absorber undetectable. At high redshift, it is often impossible to find any reasonable candidate absorbing galaxy. At low redshift, candidate absorbing galaxies are usually found, but it is often not possible to find a luminous one at a reasonably low impact parameter; sometimes no luminous galaxies are found. Figure 2 shows some results on N(HI), b, and L for galaxies matched to neutral-gas absorbers at $0.1 < z < 1.0$ by Rao *et al.* (2011).

When any galaxy is found near the redshift of the DLA, the DLA absorption could still be due to an undetected dwarf galaxy at lower impact parameter. Importantly, Figure 3 shows some examples where only dwarf galaxies are present at reasonable impact parameters. Thus, they are clear examples of dwarf galaxies associated with DLAs at $z < 1$. These examples are from Turnshek *et al.* (2001), Turnshek *et al.* (2004), and Rahmani *et al.* (2016), respectively.

4. Summary and Discussion

We have shown four clear examples where neutral gas associated with a dwarf galaxy gives rise to a DLA absorption system (Figure 3); three have metallicity measurements. In these three cases neutral gas phase metallicities are $-1.34 \leq [X/H] \leq -0.58$, i.e., between about 4% and 26% solar. Other such cases can be found in the literature, but we have emphasized these because they are ones that we have previously studied. We have noted that these metallicities are typical of the current observed range of DLA metallicities at $z < 1$ (Figure 1), and we have pointed out that in cases where luminous galaxies at large impact parameter have been identified as being matched to the DLA (Figure 2), it is possible that the actual galaxy associated with the DLA is a dwarf lost in the glare of the background quasar's light.

Observations of DLA neutral gas regions are thought to be closely related to star formation processes since neutral gas may transition to molecular gas, and then star formation occurs. At the same time, understanding the metallicities and other properties

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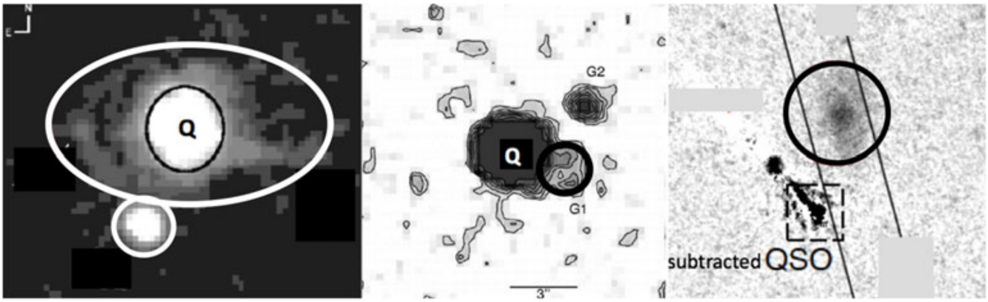

Figure 3. The **left panel** shows an IRTF image of the Q0738 + 313 sightline with two DLAs from Turnshek et al. (2001). It shows two white-circled dwarf galaxies. One DLA has z = 0.091, logN(HI) = 21.2, and neutral gas phase metallicity [X/H] = −1.34; it is matched to a LSB dwarf galaxy with L = 0.08L* and b< 3.6 kpc, which lies almost on top of the background quasar. The second circled dwarf galaxy with L = 0.1L* and b = 19 kpc is matched to a z = 0.221 DLA with logN(HI) = 20.9. The **middle panel** shows an IRTF image of the Q1727 + 5302 sightline from Turnshek et al. (2004). The DLA has z = 0.945, logN(HI) = 21.2, and neutral gas phase metallicity [X/H] = −0.58; it is matched to the black-circled dwarf galaxy with L = 0.08L* and b = 25 kpc. The galaxy to the upper right of the quasar is at an unrelated redshift. The **right panel** shows a HST ACS prism image of the Q1204 + 0953 sightline from Rahmani et al. (2016). The DLA has z = 0.640, logN(HI) = 21.0, and neutral gas phase metallicity [X/H] = −0.72; it is matched to the black-circled dwarf galaxy with L∼0.1L* and b = 12 kpc. The quasar's dispersed light is mostly subtracted, with only artifacts remaining; red galaxies with little UV don't show dispersed light.

of dwarfs is important as they may be significant building blocks of luminous galaxies. We believe that future observational work should explore cases where L^* and sub-L^* galaxies at large impact parameters are identified as the putative DLA aborbers. Indeed, this might reveal more cases of dwarfs associated with DLAs. Such dwarfs might be the agent for eventually fueling (via merging) some of the more luminous galaxies that have been mistakenly identified as the sole galaxies associated with the DLAs.

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