A SHOT IN THE DARK: A TECHNIQUE FOR LOCATING THE STELLAR COUNTERPARTS OF DAMPED Lyα ABSORBERS

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ABSTRACT

We present initial results from a Magellan telescope program to image galaxies that give rise to damped Lyα absorbers (DLAs) at 1.63 ≤ z_{DLA} ≤ 2.37. Our program differs from previous efforts in that we target quasars with intervening Lyman limit systems (LLSs) along the line of sight at redshift z_{LLS} > 3.5. The higher redshift LLS is applied as a blocking filter to remove the glare of the background quasar at the rest-frame ultraviolet wavelengths of the foreground galaxy. The complete absence of quasar light offers us an unimpeded view along the sight line to the redshift of the LLS, allowing for an exhaustive search of the DLA galaxy to the sensitivity limit of the imaging data (at or better than 0.25L_∗). In both of our pilot fields (PKS 2000−330 [z_{DLA} = 2.033] and SDSS 0322−0558 [z_{DLA} = 1.69]), we identify an L_∗ galaxy within 5″ of the sight line that has optical colors consistent with star-forming galaxies at z ∼ 2. We examine the correlation between absorption-line properties and galaxy luminosity and impact distance, and we compare the high-redshift galaxy and absorber pairs with those known at z < 1.

Subject headings: quasars: absorption lines — galaxies: general

Online material: color figures

1. INTRODUCTION

Damped Lyα absorption systems identified along the line of sight toward distant quasars offer us an interesting alternative for finding distant galaxies based on their neutral gas content rather than on their apparent brightness or color. Despite a well-established chemical-enrichment history in the damped Lyα absorber (DLA) population (e.g., Prochaska et al. 2003), constraints for different star formation recipes from DLA studies remain limited (e.g., Nagamine et al. 2005) because of a lack of known stellar counterparts. Specifically, the low metal content observed in the DLA population is generally interpreted as supporting evidence for an origin in the dwarf galaxy population (e.g., Pettini et al. 1994), as opposed to an unbiased sample of the galaxy population (Chen et al. 2005). At the same time, studies of the fine-structure transitions in the Si^{+} and C^{3+} ions associated with DLAs (Wolfe et al. 2004) suggest that DLAs may contribute as equally to the star formation rate density as redshift z = 3 as the luminous starburst population selected at rest-frame UV wavelengths (e.g., Steidel et al. 1999).

The nature of DLA galaxies can be determined directly from comparisons between their luminosity distribution function and those of different field populations. Identifying the absorbing galaxies allows us to not only measure their intrinsic luminosity but also study the gaseous extent of distant galaxies based on the galaxy-absorber pair sample. At z < 1, Chen & Lanzetta (2003) showed that the luminosity distribution function of 11 DLA galaxies is consistent with what is expected from the general galaxy population, with a peak at L ∼ 0.4L_∗ and less than 40% arising from L ≤ 0.1L_∗ galaxies. This result clearly argues against a predominant origin of the DLAs in dwarf galaxies. At higher redshift, however, identifying DLA galaxies becomes exceedingly difficult because of their still fainter magnitudes and small angular separation from the background quasar. To date, only six out of the more than 500 known DLAs have been uncovered in stellar emission (see Table 1 of Weatherley et al. 2005 for a summary).

We have initiated a multiband imaging study of quasar fields with known intervening absorbers at z > 1 that exhibit strong Mg ii, Fe ii, and sometimes Mg i absorption features and are therefore promising DLA candidates (>60% likelihood; see Rao et al. 2006). We have targeted our searches specifically in quasar fields that also have an intervening Lyman limit system (LLS) along the line of sight at z_{LLS} > z_{DLA}. In each field, we employ the higher redshift LLS as a natural blocking filter of the background quasar light at the rest-frame ultraviolet wavelengths of the foreground DLA. The complete absence of quasar light allows for an unimpeded search of intervening faint galaxies along the quasar sight line to the redshift of the LLS, substantially increasing the likelihood of finding the DLA galaxies. The goal of our program is to collect a large sample of DLA galaxies at z > 1 for follow-up studies. In this Letter, we present imaging results from two pilot fields of our project. Throughout the Letter, we adopt a Λ cosmology, Ω_m = 0.3 and Ω_Λ = 0.7, with a dimensionless Hubble constant h = H_0/(100 km s^{-1} Mpc^{-1}).

2. PROGRAM DESIGN

Our survey is designed to search for DLA galaxies in the absence of background quasar light. Therefore, we specifically target those DLA fields for which an intervening LLS also exists along the line of sight. The concept is illustrated in Figure 1, where in the bottom panel we show the spectrum of a quasar at z = 3.778. An intervening LLS is present at z_{LLS} = 3.549, which completely absorbs the photons from the background quasar at wavelengths <4150 Å. A DLA is identified at z_{DLA} = 2.033 based on the presence of a strong Mg ii λ2796, 2803 doublet and Mg i λ2852 at wavelengths >8400 Å (Fig. 2).

Together with the throughput curves of typical broadband
filters, the bottom panel of Figure 1 clearly indicates that the intervening LLS serves as an additional blocking filter of the background quasar light in the \( u' \) band. This particular DLA-LLS-QSO combination along a single sight line offers us a unique opportunity to conduct an exhaustive search for the DLA galaxy in the \( u' \) band without the interference of background quasar light. For an LLS at sufficiently high redshift (i.e., \( z_{\text{LLS}} \geq 3.5 \)), this design allows us to search for ultraviolet emission from DLA galaxies at \( 1.63 \leq z_{\text{DLA}} \leq 2.37 \) with \(<0.001\%\) contaminating quasar flux in the \( u' \) band. We caution that for the technique to be successful, either the \( u' \) filter must suppress red leak to approximately one part in \( 10^4 \) or a red blocking filter must also be used.

Our absorber sample is selected based on the presence of strong metal absorption features that are indicative of a DLA, because the presence of the intervening LLS prevents us from measuring the neutral hydrogen column density \( N(\text{H} \, i) \). Specifically, a combination of strong absorption in both Mg \( \text{II} \) and Fe \( \text{II} \) with a rest-frame absorption equivalent width \( W_{\lambda} > 0.5\, \text{Å} \) (Fig. 2) has also been employed by Rao & Turnshek (2000) and further refined in Rao et al. (2006) for selecting DLAs. We note that these strong metal lines guarantee that the absorbers originate either in a canonical DLA with \( N(\text{H} \, i) \geq 2 \times 10^{20} \, \text{cm}^{-2} \) and an Fe abundance \( [\text{Fe/H}] = -1.0 \) (see, e.g., Prochaska et al. 2003) or in a region with lower \( N(\text{H} \, i) \) but near or greater than solar metallicity. In both scenarios, these strong metal-line absorbers offer us a means of identifying star-forming galaxies at high redshift based on the metal content in their interstellar media rather than their optical brightness or color.

3. OBSERVATIONS

We have completed a multiband imaging program for two pilot fields toward PKS 2000–330 \( (z_{\text{QSO}} = 3.778) \) and SDSS 0322–0558 \( (z_{\text{QSO}} = 3.945) \). The properties of the intervening absorbers along these sight lines are summarized in columns (3)--(6) of Table 1. Absorption-line profiles of metal transitions identified with the candidate DLAs are presented in Figure 2. The spectrum of PKS 2000–330 was obtained using the MIKE (Magellan Inamori Kyocera Echelle) spectrograph (Bernstein et al. 2003) on the 6.5 m Magellan Clay telescope at Las Campanas Observatory. In addition to the prominent LLS found at \( z_{\text{LLS}} = 3.550 \) (Fig. 1), a candidate DLA is found at \( z_{\text{DLA}} = 2.033 \) based on detections of Mg \( \text{I} \), Mg \( \text{II} \), and Fe \( \text{II} \). The presence of Mg \( \text{I} \) indicates that the metal-line transitions trace neutral gas, therefore providing further support for a DLA nature for this absorber. The spectrum of SDSS 0322–0558 was retrieved from the Sloan Digital Sky Survey (SDSS) data archive. In addition to an LLS found at \( z_{\text{LLS}} = 3.764 \) in the SDSS quasar spectrum, a candidate DLA is found at \( z = 1.691 \) based on detections of both strong Mg \( \text{II} \) and strong Fe \( \text{II} \). Because of the low resolution of the SDSS coupled with a poor signal-to-noise ratio in this particular spectrum, we were unable to observe other metal-line transitions.

Optical imaging observations of the two quasar fields were carried out using the MagIC (Magellan Instant Camera) direct imager on the Magellan Clay telescope with the \( u' \), \( g' \), and \( r' \) filters. The optical imaging data presented in this Letter were obtained separately in three different runs in August, Septem-
ber, and October of 2005. All these images were taken under photometric conditions with an exquisite mean seeing of 0.76, 0.5, and 0.7 in the u′, g′, and r′ bands, respectively. Object photometry was calibrated using Landolt standards (Landolt 1992) observed on the same nights as the science frames.

Optical u′, g′, and r′ images of the field around SDSS 0322−0558 were obtained in 2005 September through cirrus, and object photometry was calibrated using common sources identified in the SDSS field. The mean seeing in the final stacked u′, g′, and r′ images are, respectively, 0.76, 0.7, and 0.7.

Near-infrared images of the field around SDSS 0322−0558 were also obtained in 2005 October, using Persson’s Auxiliary Nasmyth Infrared Camera (PANIC; Martini et al. 2004) on the Magellan Baade telescope with the H filter. The images were taken under photometric conditions with a mean seeing of 0.74. Object photometry was calibrated using several Persson infrared standards (Persson et al. 1998) observed on the same nights of the science frames.

All imaging data were processed using standard pipeline techniques. The processed individual images were registered to a common origin, filtered for deviant pixels, and stacked to form a final combined image using our own program. For each field, we detect objects separately in the u′ and g′ frames due to the absence and presence of the background quasar in these two bandpasses, respectively, using the SExtractor program (Bertin & Arnout 1996). A segmentation map is produced that defines the sizes and shapes of all the objects found in the stacked images. Object fluxes were measured by summing up all the photons in the corresponding apertures in the segmentation map. Flux uncertainties were estimated from the mean variance over the neighboring sky pixels. The dominant error in object photometry, however, is in the photometric zero-point calibration. We estimate that the uncertainties in optical and near-infrared photometry are 0.1 and 0.05 mag, respectively.

4. RESULTS AND DISCUSSION

The results for PKS 2000−330 and SDSS 0322−0558 are presented in Figures 1 and 3, respectively. Galaxies identified at angular distance θ < 5′ are summarized in columns (7)–(12) of Table 1.

In the field of PKS 2000−330, two extended sources, X and G, are found close to the sight line and above the 5 σ limiting magnitude AB(u′) = 26.9 over a 1′′ diameter aperture. Both X and G have a similar u′-band brightness, AB(u′) = 25.4 ± 0.1, and u′ − g′ color, AB(u′ − g′) = 0.4. Object X is located 2.8′′ from the sight line, not resolved from the quasar in the r′-band image, and object G is located 4.7′′ from the sight line. We note that galaxies X and G are not likely associated with the strong LLS at zLLS = 3.2 that produces the strong Lyα absorption feature at λ ≈ 1500 Å, because at z = 3.2 nearly all the photons at λ < 3800 Å (rest-frame 912 Å) are absorbed, and the abundant fluxes observed in the u′ band would imply an enormous ultraviolet flux intrinsic to these galaxies. Figure 4 shows that the observed colors of galaxy G are consistent with star-forming galaxies at 1.9 < z < 2.7 (Adelberger et al. 2004). We therefore consider galaxy G (and possibly X) as the DLA galaxy

![Fig. 3.—Stacked images of the field around SDSS 0322−0558 (zSDSS = 3.945) in the u′, g′, and r′ bands, where the quasar light is again completely missing in the u′ band due to the presence of an intervening LLS at zLLS = 3.764. The images are 20″ on a side. We have identified a galaxy G at a 2.1′′ angular distance from the quasar sight line. [See the electronic edition of the Journal for a color version of this figure.]

![Fig. 4.—Optical u′ − g′ vs. g′ − r′ colors of galaxies at z ≈ 2. Observations of the candidate DLA galaxy G in each of the science fields toward PKS 2000−330 and SDSS 0322−0558 are shown as open stars with error bars, together with random galaxies found in the two fields (dots). The color criteria for selecting 1.9 < z < 2.7 galaxies from Adelberger et al. (2004) are marked as dashed lines. The solid curves are the predicted optical colors for starburst galaxies at high redshift under a no-evolution scenario, starting at z = 1 through z = 5 in steps of Δz = 0.5. Both candidate DLA galaxies have observed colors consistent with the selection criteria for z ≈ 2 star-forming galaxies. [See the electronic edition of the Journal for a color version of this figure.]

TABLE 1

| FIELD | zSDSS | zLLS | zDLA | W(Å) (Mg II) | W(Å) (Fe II) | θ (arcsec) | ρ (h−1 kpc) | AB(u′) | AB(g′) | AB(r′) | AB(H) |
|-------|-------|------|------|-------------|-------------|------------|-------------|-------|-------|-------|-------|
| PKS 2000−330 (X) | 3.778 | 3.550 | 2.033 | 0.958 ± 0.008 | 0.513 ± 0.006 | 2.8 | 16.4 | 25.4 | 25.0 | ... | ... |
| PKS 2000−330 (G) | ... | ... | ... | ... | ... | 4.7 | 27.5 | 25.4 | 25.0 | 24.9 | ... |
| SDSS 0322−0558 | 3.945 | 3.764 | 1.690 | 4.3 ± 0.39 | 1.7 ± 0.2 | 2.1 | 12.4 | 23.8 | 23.3 | 23.0 | 22.08 |

Notes:
1. Uncertainties in galaxy magnitude are dominated by systematic uncertainties in the photometric zero-point calibration. We estimate that the uncertainties in optical and near-infrared photometry are 0.1 and 0.05 mag, respectively.
2. The error on this measurement is possibly higher, due to a noise spike in the absorption feature.
at $z_{\text{DLA}} = 2.033$, and the $\nu'$-band magnitude of G indicates that it is nearly an $L_*$ galaxy [AB($\nu'$) = 24.54 for $z = 3$ galaxies in Adelberger & Steidel 2000]. At $z_{\text{DLA}} = 2.033$, the corresponding impact parameter of X and G is $r = 16.3$ and 27.5 $h^{-1}$ kpc, respectively.

In the field of SDSS 0322−0558, we identify a single compact source G at $\theta = 2^\circ.1$ to the quasar with AB($\nu'$) = 23.8 ± 0.1, and no other sources brighter than the $5 \sigma$ limiting magnitude AB = 26.8 in the $\nu'$ band. In Figure 4, we show that this object has observed colors consistent with star-forming galaxies at $1.9 < z < 2.7$. We therefore consider this object the most likely candidate for the DLA at $z_{\text{DLA}} = 1.69$. At $z = 1.69$, the galaxy is at $r = 12.4$ $h^{-1}$ kpc, and its $H$-band magnitude also indicates a nearby $L_*$ galaxy (e.g., Chen et al. 2005).

We have shown that in the absence of quasar light, the $\nu'$-band image of each field offers us an unimpeded view along the line of sight to the redshift of the LLS, allowing for a complete search of the DLA galaxy to the sensitivity limit of the imaging data. The consistent optical colors of these candidate galaxies summarized in Table 1 strongly support their identification as absorbing galaxies, despite a lack of redshift measurements. We note that the sensitivity of the $\nu'$-band images allows us to uncover galaxies fainter than $L_*$ (>0.25$L_*$ in PKS 2000−330 and >0.06$L_*$ in SDSS 0322−0558) at the redshift of the DLA, but no fainter galaxies are found. Our identification is further strengthened by the number of random galaxies that we expect to find within the small angular radius from the quasar along the quasar sight line. Adopting a nominal galaxy luminosity function from Ellis et al. (1996), we expect to find <0.1 galaxies with AB($\nu'$) ≤ 25.4 within $\theta \leq 5^\circ$ over the redshift interval $\Delta z = 0 - z_{\text{LLS}}$.

Our survey results based on two Mg $\Pi$-selected DLAs at $z > 1.5$ agree with previous studies at $z < 1$ in that strong Mg $\Pi$ absorbers are commonly found to arise in typical $L_*$ galaxies (Bergeron 1986; Steidel et al. 1994). Their intrinsic luminosities are also comparable to the few DLA galaxies known at $z > 1.9$ (Møller et al. 2002). However this is at odds with the null results reported by Colbert & Malkan (2002) and with recent work by Rao et al. (2003), who argued that strong Mg $\Pi$-selected DLAs at $z < 1$ most likely originate in <0.1$L_*$ dwarf galaxies.

Using the two galaxy-absorber pairs established in our pilot study, we also find that the $W$(Mg $\Pi$ λ2976) versus $\rho$ distribution at $z > 1.6$ is qualitatively consistent with the anticorrelation observed at $z < 1$ (Lanzetta & Bowen 1990; Churchill et al. 2000). The agreement suggests that the size of extended Mg $\Pi$ gas around luminous galaxies has not evolved significantly since $z = 1.6$. A larger sample is necessary for investigating the extent of neutral gas in high-redshift galaxies as well as for a statistical comparison between the luminosity distribution of the DLA galaxies and that of the field galaxy population.

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