A $z = 3$ Ly$\alpha$ BLOB ASSOCIATED WITH A DAMPED Ly$\alpha$ SYSTEM PROXIMATE TO ITS BACKGROUND QUASAR

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ABSTRACT

We report on the discovery of a bright Ly$\alpha$ blob associated with the $z = 3$ quasar SDSS J124020.91+145535.6 which is also coincident with strong damped Ly$\alpha$ absorption from a foreground galaxy (a so-called proximate damped Ly$\alpha$ (PDLA) system). The one-dimensional spectrum acquired by the Sloan Digital Sky Survey (SDSS) shows a broad Ly$\alpha$ emission line with a FWHM $\lesssim 500$ km s$^{-1}$ and a luminosity of $L_{\text{Ly}\alpha} = 3.9 \times 10^{43}$ erg s$^{-1}$ superposed on the trough of the PDLA. Follow-up observations using the Keck/LRIS spectrometer confirm that this source has a Ly$\alpha$ nebula with spatial extent exceeding 5″, corresponding to a proper size $> 39$ kpc. Mechanisms for powering the large Ly$\alpha$ luminosity in this nebula are discussed. We use a Monte Carlo radiative transfer simulation to investigate the possibility that the line emission is fluorescent recombination radiation from a kpc-scale PDLA galaxy powered by the ionizing flux of the quasar, but find that the predicted Ly$\alpha$ flux is several orders of magnitude lower than observed. We conclude that the Ly$\alpha$ emission is not associated with the PDLA galaxy at all, but instead is intrinsic to the quasar’s host and similar to the extended Ly$\alpha$ “fuzz” which is detected around many active galactic nuclei. PDLAs are natural coronagraphs that block their background quasar at Ly$\alpha$ and we discuss how systems similar to SDSS J124020.91+145535.6 might be used to image the neutral hydrogen in the PDLA galaxy in silhouette against the screen of extended Ly$\alpha$ emission from the background quasar.

Key words: galaxies: evolution – intergalactic medium – quasars: absorption lines

1. INTRODUCTION

The ionizing radiation emitted by a luminous quasar can, like a flashlight, illuminate hydrogen clouds in its vicinity, teaching us about the size, kinematic structure, and density of the gas which surrounds it (Rees 1988; McCarthy et al. 1990; Heckman et al. 1991a, 1991b; Haiman & Rees 2001). This is because recombinations from photoionized hydrogen ultimately produce Ly$\alpha$ photons—a fraction of the energy in the quasar’s UV continuum is “focused” into fluorescent line radiation and re-emitted, allowing us to study the physical conditions in the emitting gas.

Extended Ly$\alpha$ nebulae with luminosities up to $L_{\text{Ly}\alpha} \sim 10^{44}$ erg s$^{-1}$ and sizes as large as 100–200 kpc have been observed around many quasars (e.g., Djorgovski et al. 1985; Hu & Cowie 1987; Heckman et al. 1991a, 1991b; Lehnert & Becker 1998; Bunker et al. 2003; Weidinger et al. 2004, 2005; Francis & McDonnell 2006; Christensen et al. 2006) and high-redshift radio galaxies (HzRGs; e.g., McCarthy et al. 1990; McCarthy 1993; van Ojik et al. 1996; Nesvadba et al. 2006; Binette et al. 2006; Reuland et al. 2007; Villar-Martín et al. 2007; Miley & De Breuck 2008), but the physical mechanism powering this emission is still unclear. In addition to fluorescent emission powered by photoionization, other mechanisms which have been discussed are recombination emission from material shocked and ionized by radio-jet or starburst-driven outflows (see, e.g., Heckman et al. 1991a, 1991b), or more recently Ly$\alpha$ cooling radiation from gravitational collapse (Haiman et al. 2000; Furlanetto et al. 2005; Yang et al. 2006).

A similar state of confusion surrounds the mechanism powering the so-called Ly$\alpha$ blobs (e.g., Fynbo et al. 1999; Steidel et al. 2000; Francis et al. 2001; Palunas et al. 2004; Matsuda et al. 2004; Dey et al. 2005; Colbert et al. 2006; Nilsson et al. 2006; Smith & Jarvis 2007). The primary difference between the extended “fuzz” around quasars as compared to the nebulae around radio galaxies and Ly$\alpha$ blobs is that a luminous quasar, and hence a potentially large source of ionizing photons, is directly detected in quasars, but not in high-$z$ radio galaxies or Ly$\alpha$ blobs. Obscuration and orientation effects, as are often invoked in unified models of active galactic nuclei (AGNs: see, e.g., Antonucci 1993; Elvis 2000), could be responsible for this difference. Indeed, some evidence for an obscured AGN has been uncovered in several of the Ly$\alpha$ blobs (Chapman et al. 2004; Basu-Zych & Scharf 2005; Dey et al. 2005; Geach et al. 2007; Barrio et al. 2008; Smith et al. 2009).

In the course of a survey for damped Ly$\alpha$ absorption proximate to high-$z$ quasars (Prochaska et al. 2008; see also Ellison et al. 2002; Russell et al. 2006), we discovered an extremely luminous Ly$\alpha$ blob coincident with both the redshift of a $z = 3$ proximate damped Ly$\alpha$ (PDLA) system and its background quasar. Although intervening DLAs (δ$v > 3000$ km s$^{-1}$) rarely show Ly$\alpha$ emission (Smith et al. 1989; Möller et al. 2004; Kulkarni et al. 2006), PDLAs appear to preferentially exhibit Ly$\alpha$ emission superimposed on their Ly$\alpha$ absorption trough (Möller & Warren 1993; Möller et al. 1998; Ellison et al. 2002) which is ~5 times brighter than the few intervening detections. Although based on poor statistics and heterogeneous samples, this putative discrepancy suggests that the Ly$\alpha$ emission associated with PDLAs might be powered by its background quasar.

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$^8$ A PDLA is defined as an absorber with $N_{\text{HI}} \geq 2 \times 10^{20}$ cm$^{-2}$ located within $\delta v = 3000$ km s$^{-1}$ of its background quasar.
In what follows, we analyze the basic characteristics of this absorber and discuss several physical scenarios for the origin of this Lyα blob. Finally, we emphasize several novel applications that exploit this unique configuration. Throughout this Letter, we use the best-fit WMAP3 cosmological model of Spergel et al. (2007), with \( \Omega_m = 0.240, \Omega_\Lambda = 0.76, \) and \( h = 0.73. \)

2. OBSERVATIONS

We recently completed a search of the Sloan Digital Sky Survey (SDSS), Data Release 5 (DR5; Adelman-McCarthy et al. 2007) for damped Lyα absorption at small velocity separations from \( z > 2 \) quasars (PDLAs; Prochaska et al. 2008). In the course of this PDLA survey, we identified a damped Lyα system with absorption redshift \( z_{\text{abs}} \approx z_{\text{qso}} \) in the spectrum of the radio-quiet quasar SDSS J1240+1455 (J. F. Hennawi et al. 2009, in preparation), obtained a near-infrared spectrum of the H\( \beta \) line and confirmed by the Ly\( \beta \) profile. Its \( N_{\text{H}_1} \) column density is measured from a Voigt profile fit to the damping wings of the Ly\( \alpha \) and Ly\( \beta \) transitions, \( \log N_{\text{H}_1} = 21.2 \pm 0.15. \) Near the center of the core of the Ly\( \alpha \) profile one notices significant emission which we identify as Ly\( \alpha \).

Contrary to our expectation, we observe significant flux at a redshift \( \approx 3.1092 \pm 0.0014, \) which was precisely determined from the data and corresponds to the absorber’s Ly\( \alpha \) transition. Figure 1 shows the Ly\( \alpha \) and Ly\( \beta \) profiles of the absorber and an estimate of the quasar flux. Overplotted on the data are Voigt profiles assuming a single H\( \alpha \) “cloud” with \( N_{\text{H}_1} = 10^{21.2\pm0.15} \) cm\(^{-2} \) and \( z_{\text{abs}} = z_{\text{qso}}. \) This model is a good representation of the data except for the flux in the core of the Ly\( \alpha \) profile. Because the metal-line transitions and the Ly\( \beta \) data imply a damped Ly\( \alpha \) system, we are highly confident that the emission at \( \lambda \approx 5000 \) Å is not quasar continuum flux, but instead corresponds to line emission from another source.

We rule out the identification of this line as [O\( \text{II} \)] or any other nebular line from a low-redshift galaxy because there are no additional narrow emission lines in the SDSS spectrum, and furthermore the broad emission-line profile does not resemble the [O\( \text{II} \)] doublet. We fit the Ly\( \alpha \) emission with a Gaussian profile and find FWHM = 500 ± 150 km s\(^{-1} \) with a centroid of \( \lambda_{\text{Ly}\alpha} = 3.113 \pm 0.001, \) which is an offset of \( \approx 400 \) km s\(^{-1} \) from \( z_{\text{qso}} \) and \( 100 \pm 100 \) km s\(^{-1} \) offset from \( z_{\text{qso}}. \) A simple boxcar extraction of the line emission gives a flux \( f_{\text{Ly}\alpha} = 4.3 \pm 0.3 \times 10^{-16} \) erg s\(^{-1} \) cm\(^{-2} \) and we derive a luminosity \( L_{\text{Ly}\alpha} = 3.9 \pm 0.4 \times 10^{43} \) erg s\(^{-1} \).

The SDSS fiber spectra are spatially incoherent and only indicate that the source of emission is within the 3′′ diameter fiber. To evaluate the spatial extent, we acquired two short (450 s) exposures of PDLA/SDSS J1240+1455 with the Keck/LRIS spectrometer (Oke et al. 1995). The 600 mm\(^{-1} \) grism was used on the blue side of LRIS, and the resulting spectra have 75 km s\(^{-1} \) per pixel and 3 pixels per resolution element for a point source in our average seeing, or a FWHM = 220 km s\(^{-1} \). The 1′′ long slit was used and the slit was rotated so that two
exposures were taken at ±45° from the parallactic angle. The average seeing for the two exposures at the wavelength of Lyα was 0.75.

We reduced the LRIS spectra using our custom LowRedux9 pipeline written in the Interactive Data Language (IDL). For each reduced exposure, the LowRedux pipeline provides two-dimensional images which are models of the sky and object flux, where the object model is estimated by fitting the spatial point-spread function (PSF) of the quasar spectrum. In Figure 2, we show the two-dimensional LRIS long-slit spectrum of PDLA/SDSS J1240+1455, with both the sky background and the PSF model subtracted off. The spectral direction is vertical, and the horizontal direction is along the slit. A logarithmic stretch has been applied, and this image corresponds to the average of our two exposures which were taken at distinct slit orientations separated by 90°. The model quasar spectrum was not subtracted off in the asymmetric velocity window [−1480, 860] km s\(^{-1}\) about the redshift of the DLA (observed wavelengths 4969–5008 Å). The vertical (red) scale bar indicates the interval corresponding to 1000 km s\(^{-1}\), and the horizontal (blue) scale bar indicates 5° along the slit. The Lyα emission from PDLA/SDSS J1240+1455 is clearly resolved in the 0.75 seeing of these observations, and its spatial extent exceeds 5′, corresponding to a proper size >39 kpc.

Matsuda et al. (2004) have provided a quantitative definition for Lyα blobs as extended Lyα emitting sources with isophotal areas larger than 16 arcsec\(^2\) and fluxes brighter than F_{Lyα} > 0.7 \times 10^{-16} erg s\(^{-1}\) cm\(^{-2}\). Their narrowband imaging survey was also equivalent width limited to EW_{obs} > 80 Å. All of these conditions are satisfied by PDLA/SDSS J1240+1455. Our LRIS spectrum (see Figure 2) implies an isophotal larger than 16 arcsec\(^2\), the flux measured from the SDSS spectrum (in a 3′ fiber aperture) exceeds the Matsuda et al. (2004) flux limit and would have been the fifth brightest emitter in the rich SSA22 protocluster field studied by Matsuda et al. (2004), and the equivalent width of PDLA/SDSS J1240+1455 exceeds EW_{obs} > 82 Å based on the nondetection of continuum flux in the core of the Lyα profile (i.e., at λ \approx 4980 Å) in the SDSS spectrum. We thus conclude that the Lyα emission we detect corresponds to an Lyα blob.

A striking characteristic of the PDLA system is that it exhibits a large N\(\text{v}\) rest equivalent width, W_{\text{r}}(N\(\text{v}\) 1242) = 0.30±0.05 Å (Figure 1). There are only a few examples in the literature of significant N\(\text{v}\) detections in a DLA (Lu et al. 1996; Fox et al. 2007) and nearly all of these are PDLA with z_{abs} > z_{quasar} and with associated Lyα emission (Møller & Warren 1993). The large equivalent widths of the N\(\text{v}\) doublet for PDLA/SDSS J1240+1455 indicate the lines are saturated and we derive a conservative lower limit to the column density of log N(N\(\text{v}\)) \geq 14.4 dex. We also infer a lower limit to the gas metallicity, based on the equivalent widths of low-ion absorption, of 1/10 solar abundance.

3. DISCUSSION

We have discovered an Lyα blob associated with a PDLA system at z \sim 3. We will now discuss several scenarios for the origin of the Lyα emission which also imply distinct configurations for the PDLA system, quasar, and Lyα blob.

3.1. Star Formation from the PDLA Galaxy

Consider first that the Lyα emission arises from H\(\text{II}\) regions associated with star formation in the PDLA galaxy. In what follows, we compare the observed properties of PDLA/SDSS J1240+1455 to two populations of galaxies with significant Lyα emission-line luminosities, namely star-forming galaxies selected via the Lyman break technique (e.g., Steidel et al. 1996a, 1996b; Lowenthal et al. 1997) and the high equivalent width, high-redshift Lyα emitters (LAEs) selected in narrowband imaging surveys (e.g., Cowie & Hu 1998; Hu et al. 1998; Rhoads et al. 2000; Fynbo et al. 2001, 2003; Ouchi et al. 2003).

A strong argument against star formation powering the Lyα blobs is the large physical extent of the line emission \sim 100 kpc. At z \sim 3, star-forming galaxies tend to be very compact with median sizes \sim 3 kpc (e.g., Trujillo et al. 2004). The LAEs are observed to have even smaller sizes (e.g., Pascarella et al. 1998; Westra et al. 2005), although they are somewhat more extended in Lyα than in the continuum (e.g., Møller & Warren 1998). The failure to detect extended continuum sources with comparable sizes to the line emission (see, e.g., Figure 4 of Matsuda et al. 2004) provides further evidence that Lyα blobs are powered by nonstellar processes.

It is worthwhile to estimate the star formation rate (SFR) implied by the large Lyα luminosity in PDLA/SDSS J1240+1455, under the assumption that it is powered by H\(\text{II}\) regions. Using the Kennicutt (1998) relation SFR(M_\(\odot\) yr\(^{-1}\)) = L(Lyα)/1.26 \times 10^{40} erg s\(^{-1}\) and the case B recombination value of the ratio I(Lyα)/I(Hα) = 8.3, we place a lower limit on the SFR of 37 M_\(\odot\) yr\(^{-1}\). This lower limit is conservative because of dust extinction and/or absorption by foreground H\(\text{I}\) gas would imply a much larger SFR. Indeed, the Lyα/Hα ratio in Lyman break galaxies (LBGs, measured from a small subset; Erb et al. 2006) shows an average of only I(Lyα)/I(Hα) = 0.6 with a standard deviation of 0.6. This LBG Lyα/Hα ratio implies an even more extreme SFR \sim 500 M_\(\odot\) yr\(^{-1}\). Along similar lines, Gronwall et al. (2007) compared SFRs inferred from LAE Lyα emission (the same procedure as above) to those inferred from the LAE restframe UV continuum emission, and found that at the bright end (of interest to us here) Lyα SFRs tend

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9 [http://www.ucolick.org/~xavier/LowRedux/index.html](http://www.ucolick.org/~xavier/LowRedux/index.html).
to underestimate the truth by a factor of \(\sim 3\). Thus, the implied SFR if PDLA/SDSS J1240+1455 is an LAE is \(\sim 100\, M_\odot\, \text{yr}^{-1}\).

Even our conservative lower limit exceeds the SFR by an order of magnitude for all but one DLA (Møller et al. 2004; Wolfe et al. 2005). The SFR assuming the LBG Ly\(\alpha/\text{Hz}\) ratio is nearly a factor of two larger than the largest SFRs measured by Erb et al. (2006). In addition, the Ly\(\alpha\) luminosity of PDLA/SDSS J1240+1455 is larger than that of any of the 780 LBGs at \(z \sim 3\) studied by Shapley et al. (2003), and four times larger than the brightest LAEs discovered by Gronwall et al. (2007) selected from an effective survey volume of \(10^5\, \text{Mpc}^3\).

Taking all of these arguments together, we conclude that the Ly\(\alpha\) blob in PDLA/SDSS J1240+1455 is unlikely to be associated with star formation in the PDLA galaxy.

3.2. Fluorescent Recombination Radiation Powered by the Quasar

An optically thick gas cloud illuminated by a nearby quasar will emit Ly\(\alpha\) photons at a rate which is \(\eta \sim 0.6\) times the ionizing flux impinging upon it (Gould & Weinberg 1996). If this is the mechanism responsible for the Ly\(\alpha\) emission in PDLA/SDSS J1240+1455, then one can estimate its distance from the quasar as follows. Suppose that the emitting region has an angular diameter \(\theta\) which covers a fraction of the area of the 3\(^\prime\) SDSS fiber, so that \(f_{\text{Ly}\alpha} = \Phi_{\text{Ly}\alpha} \pi \theta^2/4\), where \(\Phi_{\text{Ly}\alpha}\) is the Ly\(\alpha\) surface brightness. At a distance \(d\) from the quasar, the DLQ galaxy absorbs an ionizing photon flux of \(F_{\text{c}} = (1/4\pi d^2) \int (L_{\nu}/h\nu) d\nu = (1/4\pi d^2) (L_{\text{Ly}\alpha}/h\alpha_Q)\) where the last equality assumes that the quasar spectral energy distribution obeys the power-law form \(L_{\nu} = L_{\text{LL}} (v/v_{\text{LL}})^{-\alpha_Q}\) blueward of the Lyman limit \(v_{\text{LL}} = 13.6\, e\text{V}/h\), where \(L_{\text{LL}}\) is the specific luminosity at the Lyman limit and \(\alpha_Q = 1.57\) (Telfer et al. 2002).

We estimate \(L_{\text{LL}} = 1.0 \times 10^{31}\, \text{erg s}^{-1}\, \text{Hz}^{-1}\), by combining the SDSS optical photometry of the quasar SDSS J1240+1455 with the assumed power-law spectral shape. The fluorescent surface brightness is given by \(\Phi_{\text{Ly}\alpha} = \eta h v_{\text{Ly}\alpha} F_{\text{c}} / (4 \pi d^2)\), so we arrive at an estimate for the distance \(d = 186(\eta/0.60)(\theta/3\, \text{\prime})^2\) kpc adopting the measured Ly\(\alpha\) flux in the 3\(^\prime\) aperture from the SDSS spectrum. The maximum possible distance is \(d < 186\) kpc because (1) we have assumed the fluorescent emission fills the entire 3\(^\prime\) SDSS fiber, and (2) we have assumed a “full moon” configuration (front-side illuminated) where our scenario is more likely to approach a “new moon” (backside) illumination pattern. We will address this latter issue in greater detail below.

Intriguingly, the above distance estimate of a few hundred kpc matches the upper limit on the gas distance implied by the observed N\(\nu\) column density, if we assume the quasar is photoionizing the outer layers of the PDLA system. This is the most likely origin because the extragalactic UV background and local sources are too weak or too soft to yield such a large N\(\nu\) column density and N\(\nu\) is very rarely observed in DLA systems (A. J. Fox et al. 2009, in preparation). We have estimated the distance of the quasar from the PDLA system by performing a series of calculations with the Cloudy software package (v.6.0.2; Ferland et al. 1998) assuming a plane-parallel slab of gas with \(N_{\text{HI}} = 10^{11.3}\, \text{cm}^{-2}\), metallicity [N/H] = -1, and a range of ionization parameters \(U = F_c/n_{\text{HI}}\). To match the observed N\(\nu\) equivalent width, we require \(\log U > -2\) and, therefore, an upper limit to the separation between the quasar and DLA of \(d_{\text{N}\nu} < 700\, \text{kpc}(n_{\text{HI}}/1\, \text{cm}^{-3})^{-1/2}\). We draw two important conclusions: (1) the gas is located within approximately 1 Mpc of the quasar; (2) the majority of PDLA systems lying within 1 Mpc of the quasar should also show significant N\(\nu\) absorption.

We explore the fluorescence scenario further by performing the following numerical simulation. The PDLA system is modeled as a singular isothermal sphere with a dark matter halo mass of \(10^{11}\, M_\odot\) and a quasar located directly behind it. The top panel shows the predicted Ly\(\alpha\) image for this configuration taking into account self-shielding effects and the radiative transfer of fluorescent Ly\(\alpha\) photons. The one-dimensional spectra for two 0.73\,\prime\,0.73 apertures (labeled A1 and A2) are shown in the lower panel where Ly\(\alpha\) at \(z = 3\) corresponds to 0 km s\(^{-1}\). The one-dimensional spectrum of the fluorescent radiation from the optically thick region of the cloud (A1) shows the characteristic double-peaked profile expected for Ly\(\alpha\) photons diffusing in frequency out of an optically thick medium. The emission from the optically thin outer region of the cloud (A2) is a single peak centered at \(\Delta v = 0\, \text{km s}^{-1}\) with much lower surface brightness. Although the shape of the line profile for the SDSS aperture is in reasonable agreement with the observations, the predicted flux is several orders of magnitude fainter than observed.

![Figure 3](image.png)
from this surface-brightness image to illustrate the flux level and the expected emission-line profiles. Although the one-dimensional spectrum through the 3" SDSS fiber aperture has roughly the observed line width, it has an integrated flux that is several orders of magnitude lower than observed. The low flux results from the fact that we are observing the illuminated galaxy in a "new moon" configuration; the optically thick regions which give rise to the Lyα emission also serve to shield the radiation from our vantage point. The observed flux is instead dominated by the outer regions of the fiber which cover optically thin regions of the gas in the halo surrounding the galaxy (aperture A2 in Figure 3). Based on this calculation, we conclude that the observed Lyα emission in PDLA/SDSS J1240+1455 is unlikely to be fluorescent recombination radiation from the PDLA galaxy.

3.3. Extended Lyα "Fuzz" from the Quasar Host Halo

We consider the most plausible hypothesis to be that the Lyα emission is not associated with the PDLA galaxy at all, but instead is intrinsic to the quasar’s host galaxy. Indeed, Lyα emission has been detected as an extended "fuzz" around many but instead is intrinsic to the quasar’s host galaxy. Indeed, Lyα is unlikely to be fluorescent recombination radiation from the quasar emission nebula. The physical mechanism responsible for the fuzz could be fluorescent recombination radiation from the gas in the quasar host halo powered by the quasar’s large ionizing flux (Rees 1988; Heckman et al. 1991b; Haiman & Rees 2001; Weidinger et al. 2004), or it could be among other mechanisms put forth to explain the extended Lyα halos around quasars’ Lyα blobs, and HzRGs, such as recombinations from shock-heated gas in a large-scale outflow (e.g., McCarthy et al. 1990; Heckman et al. 1991a, 1991b; Taniguchi & Shioya 2000; Colbert et al. 2006) or cooling radiation from gravitational infall (Haiman et al. 2000; Fardal et al. 2001; Furlanetto et al. 2005; Yang et al. 2006).

It is important to explain the distinction between the fluorescence from the DLA galaxy which was considered in the previous section and the fluorescent Lyα fuzz from quasar host halos that we refer to here, since both are potentially powered by photoionization from the quasar. For the former case the emission comes from a large, kpc-scale self-shielding cloud (the DLA galaxy) and a large fraction $\eta \simeq 60\%$ of the ionizing continuum impinging on the surface of the DLA is converted into Lyα recombination photons. We showed that very few of these Lyα photons escape to our vantage point and so this scenario is unlikely to power PDLA/SDSS J1240+1455.

In the latter fuzz case, the emission is presumed to be coming from very small dense self-shielding clouds of gas which permeate the quasar halo but have a small ~0.5% covering factor (McCarthy et al. 1990; Heckman et al. 1991b), which can be deduced from the fraction of the ionizing continuum which is being absorbed (Heckman et al. 1991b). If this is indeed the mechanism operating in PDLA/SDSS J1240+1455, we estimate a similar covering factor $c_f = N_{\text{Ly}\alpha}/(0.60 \times n_{\text{Ly}\alpha})/Q = 0.4\%$, where $N_{\text{Ly}\alpha}/h \nu_{\text{Ly}\alpha}$ is the rate the nebula emits Lyα photons, the factor of 0.60 accounts for the fact that only 60% of the ionizations result in an Lyα photon for an optically thick cloud, and $Q = 9.8 \times 10^{56}$ photons s$^{-1}$ is our estimate for the rate at which the quasar emits ionizing photons.

In the context of the photoionization-powered fuzz, an intriguing possibility is that the PDLA absorption is not from a kpc-scale galaxy at all, but rather from one of the dense self-shielding clouds responsible for the small $c_f \sim 0.5\%$ covering factor which reprocesses the ionizing luminosity of the quasar into an Lyα nebula. For any given quasar, the small covering factor indicates that the probability that our sightline intercepts such a cloud is very small; however this probability $\sim 0.5\%$ is comparable to the probability of a quasar having a PDLA at $z \sim 3$ which is $\sim 1\%$ (Prochaska et al. 2008). Thus, some fraction of PDLAs could arise from very small dense self-shielding clouds in the quasar interstellar medium (ISM), rather than from large kpc-scale galactic columns of H1. The density of the gas emitting the Lyα fuzz around quasars and HzRGs is highly uncertain, ranging from several tens to several thousands of cm$^{-3}$ (McCarthy et al. 1990; Heckman et al. 1991b). However, Nesvadba et al. (2006) recently constrained the density in the emission-line nebula of MRC 1138–262, a powerful radio galaxy at $z = 2.16$, finding $n_e \sim 400$ cm$^{-3}$. If we assume a representative value of $n_H \sim 100$ cm$^{-3}$, then the implied cloud sizes are extremely small. For an $N_H$ column density comparable to that of PDLA/SDSS J1240+1455, $d \sim N_H/n_H = 6$ pc. As the broad-line region is expected to have a size of $\sim 1$ pc (Osterbrock & Ferland 2006), it might be possible to rule out higher density and hence smaller neutral clouds based on the lack of PDLAs showing partial covering effects.

In contrast with the low cloud covering characteristic of the Lyα fuzz, Hennawi et al. (2006) and Hennawi & Prochaska (2007) have argued for a high covering factor $\sim 30\%$ of optically thick clouds in the halos $\sim 100$ kpc of quasars, based on the frequency of high column density absorbers observed transverse to the line of sight in close quasar pairs. Unlike PDLAs which are always illuminated by their background quasar, several independent lines of evidence suggest that these transverse absorbers are not illuminated (Hennawi et al. 2006; Hennawi & Prochaska 2007; Prochaska & Hennawi 2008). Prochaska & Hennawi (2009) conducted a detailed study of a single system, deducing cloud sizes $\sim 10–100$ pc and densities $n_H \sim 1–10$ cm$^{-3}$, and they argued such clouds would likely be photoevaporated if illuminated by a bright quasar. It is then tempting to speculate that optically thick clouds with a range of densities exist in the host ISM and halo of quasars. In the absence of ionizing photons, the low-density $n_H \sim 1–10$ cm$^{-3}$ population of “transverse” absorbers, characterized using close pairs of quasars (Hennawi et al. 2006; Hennawi & Prochaska 2007; Prochaska & Hennawi 2009), dominate the H1 covering factor $\sim 30\%$, whereas the denser clouds ($n_H \sim 100$ cm$^{-3}$) cover only a tiny fraction $\sim 0.5\%$ of the line of sight. The lower density (high covering factor) clouds are photoevaporated by the intense quasar radiation, whereas the dense clouds (low covering factor) can self-shield and survive. It would be these dense clouds which are responsible for the Lyα fuzz emission from quasars, HzRGs, and Lyα blobs, and it is possible that absorption from them accounts for some PDLAs. Furthermore, it is intriguing that detailed spectroscopic modeling of extended emission-line nebulae around quasars and FR II radio galaxies at low redshift $z \lesssim 0.5$ similarly show evidence for two-phase media composed of an abundant low-density medium ($n_H \sim 1$ cm$^{-3}$) and much rarer high-density clouds.
\( n_{\text{H}} \sim 400 \text{ cm}^{-3} \) (Stockton et al. 2002, 2006; Fu & Stockton 2007, 2009).

4. FUTURE DIRECTIONS AND APPLICATIONS

We have reported on the discovery of a \( z = 3 \) Ly\( \alpha \) blob associated with a quasar that also exhibits a PDLA system. Five other quasars are known which show a similar coincidence of quasar, DLA, and extended Ly\( \alpha \) nebula: PKS 0528–250 (Møller & Warren 1993), PHL 1222\(^{10}\) (Møller et al. 1998; Fynbo et al. 1999), B 0405–331 (Ellison et al. 2002), and Q 2059–360 (Pettini et al. 1995; Leibundgut & Robertson 1999); although SDSS J1240+1455 has the largest Ly\( \alpha \) luminosity of them all. We argue that the line emission in PDLA/SDSS J1240+1455 is not associated with star formation in the PDLA galaxy nor is it fluorescent recombination radiation from the back side of a kpc-scale PDLA galaxy illuminated by the quasar.

Instead we believe that Ly\( \alpha \) emission in PDLA/SDSS J1240+1455 (and the five other similar systems) is just the extended Ly\( \alpha \) fuzz which has been observed around many quasars. If this fuzz is powered by photoionization, it differs from the fluorescent emission considered in Section 3.2, because the clouds which reprocess the ionizing radiation are likely very small \( \sim 10 \text{ pc} \), dense \( n_{\text{H}} \sim 100 \text{ cm}^{-3} \), and cover a small fraction \( \sim 0.5\% \) of the line of sight. It is possible that the PDLA absorption which we detected results from such small dense clouds, rather than from a much lower density, much larger kpc-scale galaxy thought to be responsible for the intervening DLA population. Detailed study of an echelle spectrum of PDLA/SDSS J1240+1455 is in order, as it could constrain the physical properties of the PDLA such as the cloud size, density, temperature, enrichment, and the radiation field impinging on it (Prochaska 1999; Rix et al. 2007; Prochaska & Hennawi 2009). This would yield important information about the nature of the gas in the quasar ISM and halo, and would provide an interesting comparison with the properties of the transverse optically thick absorbers, thought to be unilluminated, which are detected in close quasar pairs (Hennawi et al. 2006; Hennawi & Prochaska 2007; Prochaska & Hennawi 2009). A particularly exciting possibility would be to compare the physical properties of the PDLA absorbing gas, inferred from absorption line techniques, with the physical properties of the emitting gas in the Ly\( \alpha \) nebula (Nesvadba et al. 2006), deduced from the detection of additional emission lines.

Indeed, with additional deep optical and near-IR spectroscopy, one could detect additional emission lines providing important constraints on the mechanism powering the emission. Specifically, H\( \beta \) lies in a relatively clear transmission window near 2 \( \mu \text{m} \) as does H\( \gamma \) near 1.8 \( \mu \text{m} \). The relative flux of these Balmer lines to Ly\( \alpha \) is sensitive to the amount of dust extinction, the hardness of the photoionizing spectrum, and resonant scattering of the Ly\( \alpha \) photons. These Balmer line ratios could thus further distinguish between the emission mechanisms discussed in Section 3. Furthermore, the detection of high excitation lines, most notably N\( \text{v} \), C\( \text{v} \), or [He \( \text{ii} \)] 1640 would demand that the nebula is powered by a hard spectrum, because a stellar continuum is too soft to produce strong emission in these lines.

The coincidence of a damped Ly\( \alpha \) system and a quasar (PDLA) provides unique opportunities for future research. A PDLA acts like a natural coronagraph in the core of the damped Ly\( \alpha \) absorber, blocking the background quasar’s bright Ly\( \alpha \) emission and allowing one to conduct a sensitive search for diffuse extended fuzz from the quasar, albeit in a relatively narrow spectral window (\( \lambda \approx 10–30 \text{ Å} \)). At the faintest flux levels, star formation from the PDLA galaxy and/or the quasar host galaxy could contribute to the detected emission, but for very bright Ly\( \alpha \) emission as in SDSS J1240+1455 it is very unlikely that star formation contributes significantly.

Because the bright Ly\( \alpha \) nebula likely originates in the quasar host halo, and hence behind the PDLA, it is possible to image the PDLA in silhouette against the extended screen of Ly\( \alpha \) emission to infer the spatial distribution of the PDLA H\( \text{I} \) gas. A “hole” in the Ly\( \alpha \) emission will indicate the region where the H\( \text{I} \) gas is optically thick to Ly\( \alpha \) radiation, corresponding to column densities \( N_{\text{HI}} \gtrsim 10^{14} \text{ cm}^{-2} \). The size of this hole would thus indicate the extent of the lower column density “halo” of the PDLA, and a seeing-limited, integral field unit (IFU) (or narrowband) observation would be sensitive to sizes of 5 kpc and greater. If the cloud responsible for the PDLA is kpc-scale, as is expected for intervening DLAs, a hole would be detected, whereas if a much smaller denser cloud is responsible for the absorption (as suggested in Section 3.3), then the \( \sim 10 \text{ pc} \) hole would be impossible to resolve. At present, the only other means of assessing the size of absorption line systems is by observing coincident absorption in close quasar pairs (e.g., Smette et al. 1995; Ellison et al. 2007), but this technique provides measurements which are statistical in nature. Of the five other known PDLAs which also exhibit extended Ly\( \alpha \) emission, two, PKS 0528–250 (Møller & Warren 1993) and PHL 122 (Fynbo et al. 1999), have been imaged with narrowband filters centered on the cores of the DLAs. These observations were probably too shallow to rule out the detection of the PDLAs’ Ly\( \alpha \) shadow. Furthermore, PHL 122 is a binary quasar, and significant contamination from the second quasar’s Ly\( \alpha \) emission (it has no PDLA) makes the detection of a shadow even more difficult. Future IFU or narrowband imaging observations with 8–10 m class telescopes could detect the Ly\( \alpha \) shadows of PDLAs providing important constraints on the size and nature of these absorbers.

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\(^{10}\) PHL 1222 is also a binary quasar and hence more complicated since both quasars could contribute to the ionizing flux.
