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DISCOVERY OF A Lyα GALAXY NEAR A DAMPED Lyα ABSORBER AT $z = 2.3$[1]

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ABSTRACT

We report the detection of a galaxy associated with the damped Lyα absorbing cloud seen at $z = 2.309$ toward the QSO PHL 957 ($z_{\rm em} = 2.681$). The galaxy was discovered in deep Fabry-Perot narrow-band CCD frames and was subsequently imaged spectroscopically. In addition to a strong but narrow Lyα emission line ($F_{\rm Ly\alpha} = 5.6 \times 10^{-16}$ ergs s^{-1} cm^{-2}, FWHM ~ 700 km s^{-1}) and weaker C IV and He II lines, the object shows continuum at $V \sim 24$, with a slope (in F_ν) rising slightly toward the red, similar to what is seen in high-redshift radio galaxies; however, the galaxy does not correspond to any known radio source in the literature. The detected emission lines and continuum are most easily interpreted as light from hot, recently formed stars, implying not only a sizable star formation rate (SFR $\geq 5\ M_\odot$ yr^{-1}) but also a scarcity of dust, which readily quenches Lyα photons. The emission region appears to be marginally resolved spatially and is located 48″ to the NW of the QSO, corresponding to a projected distance of $270h^{-1}$ kpc (for $q_0 = 0.1$); the velocity difference with respect to the damped Lyα cloud is ~ 350 km s^{-1}. The spatial correlation of the absorbing cloud and the companion galaxy supports the interpretation of damped Lyα clouds as objects fundamentally different from the lower column density Lyα forest clouds, which show weak or no clustering. The absorption trough itself shows no Lyα emission, extended or unresolved, in either the Fabry-Perot frames or in deep, moderate resolution (~ 3 Å FWHM), two-dimensional spectra, down to a limiting flux ($3\ \sigma$) for an unresolved line of 2×10^{-17} ergs s^{-1} cm^{-2}, ~ 30 times fainter than the Lyα flux detected from the companion galaxy. The lack of strong Lyα emission from the absorbing cloud can be interpreted as evidence either for a low SFR or for heavy dust obscuration.

Subject headings: cosmology — galaxies: formation — quasars

1. INTRODUCTION

The clouds that produce the damped Lyα systems seen in the spectra of high-redshift QSOs apparently contain at least as much baryonic matter as all spiral galaxies seen today (Lanzetta et al. 1991; Wolfe et al. 1986) and are conjectured to be partially or fully formed galactic disk systems at redshifts $z > 2$ (Wolfe et al. 1986). Observations of the damped Lyα systems may therefore provide clues to the epoch and nature of galaxy formation.

Intense Lyα emission lines have been predicted to be characteristic signatures of young, actively star-forming galaxies at high redshift (Partridge & Peebles 1967; Meier 1976; Cox 1985) prompting searches for emission from the damped systems, including the system studied here, using both narrow-band imaging techniques (Smith et al. 1989; Deharveng, Buat, & Bowyer 1990; Wolfe et al. 1991) and spectroscopy (Foltz, Chaffee, & Weymann 1986; Hunstead, Pettini, & Fletcher 1990; Pettini & Hunstead 1990), especially long-slit. Despite extensive observations by several workers, only two weak (and contradictory) detections have been reported: an unresolved spike of emission in the bottom of the Lyα absorption trough in the spectrum of QSO 0836+113 ($z_{\rm em} = 2.70$, $z_{\rm abs} = 2.47$) (Hunstead et al. 1990); and an extended source around the same damped cloud, reported by Wolfe et al. (1991), who do not confirm the detection of Hunstead et al. These detections, as well as the upper limits of other searches for Lyα emission from high-redshift galaxies (e.g., Lowenthal et al. 1990; Pritchet & Hartwick 1987), are at levels much fainter than expected for an actively star-forming galaxy, if much of the ionizing UV radiation appears in the Lyα line. In contrast to the faintness of the absorbers, large equivalent widths of Lyα emission have been observed from objects associated with high-redshift radio galaxies and QSOs (e.g., Djorgovski et al. 1985; McCarthy et al. 1987; McCarthy 1988; Chambers, Miley, & van Breugel 1990; Heckman et al. 1991; Steidel, Sargent, & Dickinson 1991). The lack of strong detections of Lyα emission from damped Lyα systems and other putative primeval galaxies can be interpreted in two ways: either the star formation rates (SFRs) in normal galaxies at high redshift are considerably lower than predicted (the unconfirmed detection of Hunstead et al. corresponds to SFR $\gtrsim 1\ M_\odot$ yr^{-1}, comparable to Sb galaxies today); or else there is sufficient dust in the observed sources to quench Lyα radiation, which is especially susceptible to dust extinction due to multiple scattering within the optically thick gas. The presence of dust in the damped Lyα clouds has been inferred independently by the observed reddening of QSOs that shine through damped clouds (Pei, Fall, & Bechtold 1991), and Charlot & Fall (1991) find that, depending on the morphology and orientation of the absorber as well as its neutral hydrogen column density, obser-

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vationally allowed amounts of dust could hide the Lyα emission produced by star formation rates up to two orders of magnitude higher than in the solar neighborhood.

In this *Letter*, we report the discovery of line and continuum emission near the damped Lyα cloud seen at $z_{\rm abs} = 2.309$ toward the QSO PHL 957 ($z_{\rm em} = 2.681$). The damped system toward PHL 957 is an especially well-studied target, and a particularly interesting one for a Lyα emission search: with a neutral hydrogen column density $N_{\rm H\,I} = 2.5 \times 10^{21}$ cm^{-2}, the absorber has been shown to have a metallicity only 4% of solar, with a dust-to-gas ratio only 3% the Galactic value, based on metal absorption-line ratios (Meyer & Roth 1990; Pettini, Boksenberg, & Hunstead 1990); a ratio of molecular to neutral hydrogen five orders of magnitude below Galactic, based on upper limits on H_2 absorption bands (Black, Chaffe, & Foltz 1987); and a ratio of carbon monoxide to neutral hydrogen two orders of magnitude below average Galactic levels, based on upper limits on CO absorption (Levshakov et al. 1990). Taken together, these observations imply an extremely poorly enriched absorber from which Lyα photons might be allowed to escape without substantial obstruction by dust.

2. OBSERVATIONS

2.1. *Fabry-Perot Imaging*

Deep narrow-band CCD images of the PHL 957 field were taken at the KPNO 4 m telescope with the Goddard Fabry-Perot Imager (GFPI; see Caulet et al. 1991 for details on the instrument) on the nights of 1990 January 24–26 (UT) in poor seeing conditions (2".4–3".6 FWHM). Operating in interference order 19, the etalon was tuned to 4023 Å, the wavelength of redshifted Lyα for the damped system at $z = 2.309$; the FWHM of the transmission function was 24 ± 3 Å, corresponding to Lyα in the redshift range 2.299–2.319. Off-band comparison images were taken at a wavelength of 4319 Å with a FWHM of 28 ± 4 Å. The wavelength shift of the transmission function was only 0.6 Å toward the blue at the edge of the field, so the images are essentially monochromatic. Although the GFPI is suceptible to internal reflections from bright sources, the resulting ghost images always appear at repeatable distances and orientations with respect to the original sources, allowing discrimination from genuine detections.

The detector, KPNO's "Tek2," is a Tektronix 512 × 512 CCD with $8e^-$ pixel^{-1} rms read noise and a scale of 0".53 pixel^{-1}, after demagnification of the Cassegrain focus by the instrument's reimaging optics and on-chip binning by a factor of 2, giving a field of view of 2'.3. Dark current was measured to be negligible.

Total integrations of 3 hr on-band and 1.3 hr off-band were obtained in variable conditions over the three nights. The spectrophotometric standard star G191 B2B was observed in both bands for flux calibration. The data were reduced in the usual way, using standard IRAF software routines.

A significant patch of emission is clearly visible in the on-band image 48" to the northwest of the QSO at position angle P.A. = 119°.3 (see Fig. 1 [Pl. L3]). The object appears to be resolved, with two main peaks of emission separated by ~3" at P.A. ≃ 71°; however, the variable seeing over the three nights prevents an accurate estimate of the object's spatial extent. Total flux recorded was $6.5 \pm 1 \times 10^{-16}$ ergs s^{-1} cm^{-2}, corresponding to ~10 σ as measured in nearby patches of blank sky. No extended emission is visible in the immediate vicinity of the QSO line of sight. Due to the blackness and breadth of the damped Lyα absorption line, the QSO all but disappears in the on-band image; the little flux that does appear at the position of the QSO (marked Q in Fig. 1*a*), 1×10^{-16} ergs s^{-1} cm^{-2}, is easily accounted for by leakage of QSO continuum into the broad wings of the Fabry-Perot's Airy transmission function, and so cannot be interpreted as unresolved emission from the damped cloud.

No corresponding emission is visible in the off-band frame, down to the limiting sensitivity (3 σ) for a point source of 2.7×10^{-17} ergs s^{-1} cm^{-2}, indicating that the flux seen in the on-band image is line emission.

2.2. *Spectroscopy*

Long-slit spectra of PHL 957 were obtained with the Red Channel CCD Spectrograph (Schmidt, Weymann, & Foltz 1989) at the Multiple Mirror Telescope (MMT) on 1989 October 25 UT (before the emission-line object had been discovered) and on 1990 December 8–9 and 1991 January 14–15 UT (after the object's discovery). All observations were made with a 1".5 × 180" slit and either a 1200 line mm^{-1} grating for moderate resolution (2.6 Å FWHM) or a 150 line mm^{-1} grating for low resolution (24 Å FWHM); the pixel scales after binning by a factor of 2 spatially were 0".6 × 0.8 Å pixel^{-1} and 0".6 × 6.4 Å pixel^{-1}, and spectral coverage was ~3700–4300 Å and ~3000–8100 Å, respectively. Seeing conditions ranged from 1".5 to 2".2 (FWHM); total integration times were 7 hr for the initial high-resolution data, 2.5 hr for the low-resolution spectra, and 4.8 hr for the remaining high-resolution spectra. For the 1989 October observing run, before the emission-line object had been discovered, the spectrograph slit was placed north-south. For all subsequent runs the slit was placed at P.A. = 119°.3, to include both the QSO and the companion galaxy; at the telescope, this setting was achieved via a rotational offset from the line connecting the QSO and star "A" in Figure 1.

A strong emission line is clearly detected in both the low- and high-resolution spectra at 4027.3 ± 0.3 Å separated by 48" from the QSO, with a flux of $5.6 \pm 0.1 \times 10^{-16}$ ergs s^{-1} cm^{-2}, consistent with the Fabry-Perot result. Also visible in the low-resolution image is continuum from the object over most of the spectral range covered, at a flux level corresponding to $B \sim 24.2$ (excluding the strong line) and $V \sim 23.6$; although the spectrum includes part of the *R* band, no order blocking filter was used during the observations, so this region of the image may be contaminated by second-order UV light. Two faint but clear emission lines are seen at 5135 ± 4 and 5436 ± 5 Å. We identify the one strong and two weak lines as redshifted Lyα λ1216, C IV λ1549, and He II λ1640, respectively, yielding an emission redshift $z_{\rm em} = 2.3128 \pm 0.0002$, based on the high-resolution spectrum of the Lyα line alone, and confirming that the object is indeed a companion to the damped Lyα cloud. The difference in redshift between the emission and absorption systems, confirmed by examination of narrow metal absorption features in the high-resolution spectrum of the QSO, corresponds to a velocity difference $\Delta v = 346 \pm \sim 20$ km s^{-1}. A one-dimensional spectrum of the galaxy extracted from the low-resolution image is shown in Figure 2, and the two-dimensional high-resolution spectrum is presented in Figure 3 (Plate L3); properties of the emission are summarized in Table 1.

The Lyα line is clearly resolved spectrally in the high-resolution spectrum, showing a FWHM = 9.5 ± 0.5 Å, corre-

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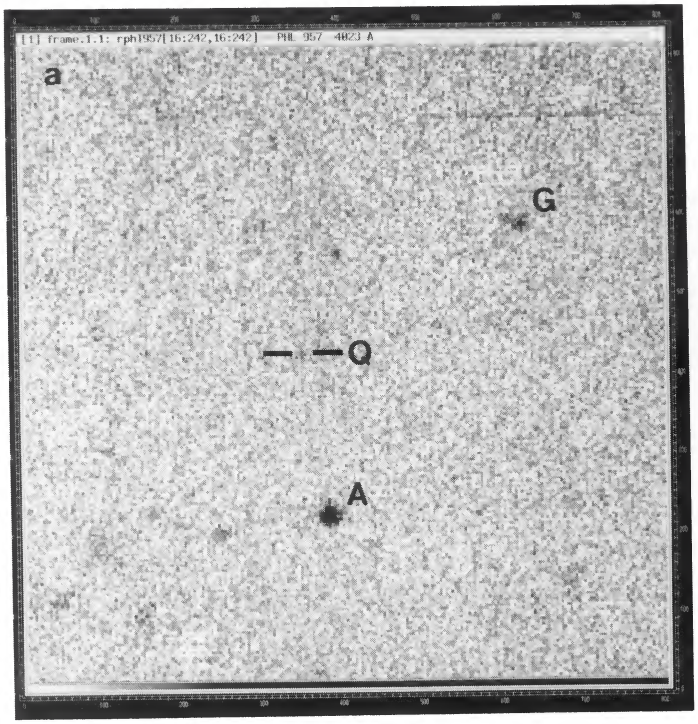

FIG. 1*a*

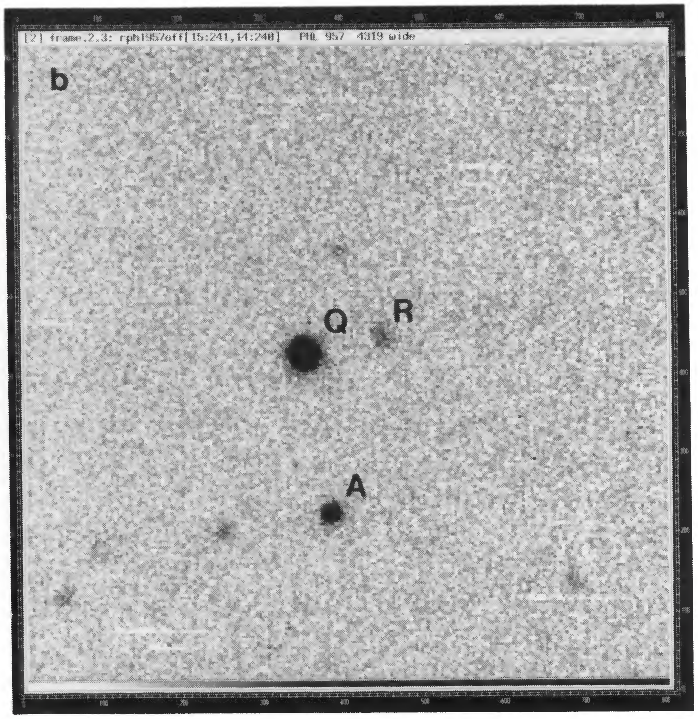

FIG. 1*b*

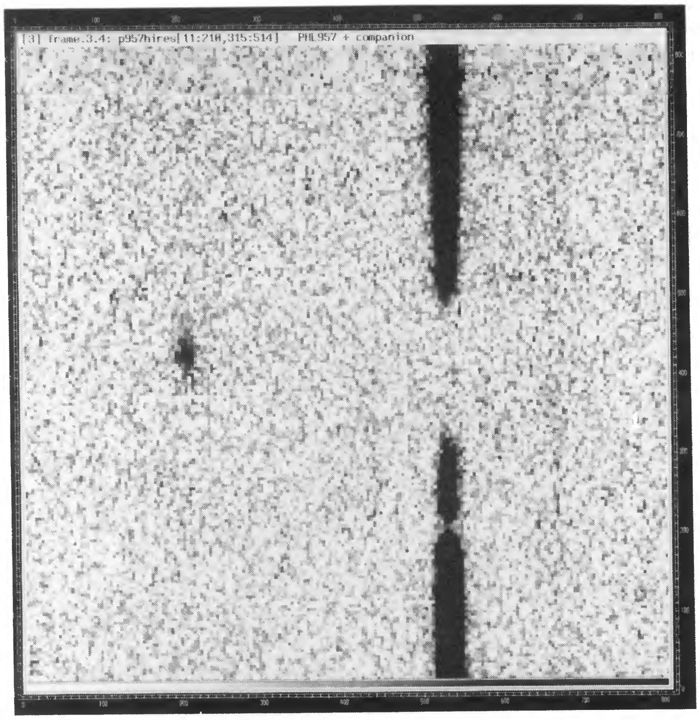

FIG. 3

FIG. 1.—(*a*) On-band Fabry-Perot CCD image of the PHL 957 field. North is up, and east is to the left; the field of view is 2′ × 2′. $\lambda_C = 4023$ Å; FWHM = 18 Å. The position of the QSO is labeled Q, object A is a foreground star, and the companion galaxy is labeled G. (*b*) As in (*a*), but off-band image. $\lambda_C = 4319$ Å; FWHM = 28 Å. Label R indicates a ghost reflection of the QSO.

FIG. 3.—Two-dimensional high-resolution (2.6 Å FWHM) sky-subtracted spectrum of PHL 957 (*right*) and the Lyα companion galaxy (*left*), showing the core of the damped Lyα absorption line in the QSO and the Lyα emission line (FWHM ∼ 9.4 Å) in the galaxy. The image covers the spectral range 3946–4105 Å, with red at the top; the horizontal axis covers 2′, with northwest to the left.

LOWENTHAL et al. (see 377, L74)

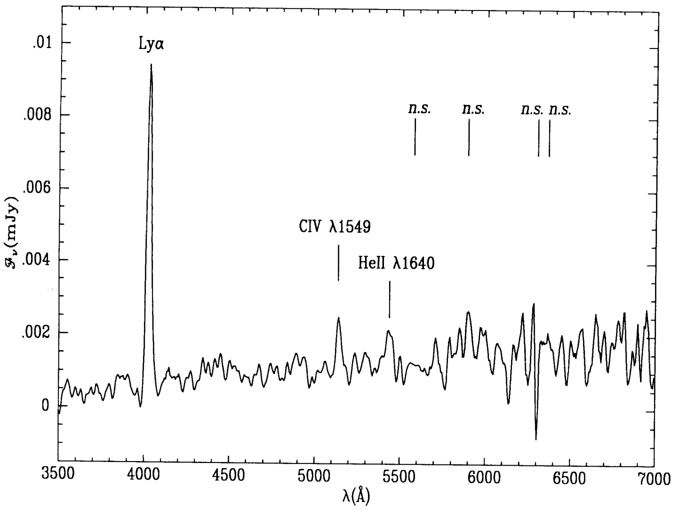

FIG. 2.—Low-resolution (24 Å FWHM) spectrum of the companion galaxy to the damped Lyα cloud toward PHL 957. Important emission features are indicated, as are the locations of residual night sky lines (marked n.s.). The spectrum has been smoothed by 3 pixels ≃ the spectral FWHM, to suppress the noise.

sponding to ~700 km s^{-1}. Although the emission appears to be marginally resolved spatially, the variable seeing conditions again prevented an accurate measurement; more observations are necessary to determine the true spatial extent.

No emission is detected from the damped Lyα cloud itself at either of the two position angles, down to a limiting flux (3 σ) in the high-resolution data for an unresolved source $F \leq 2 \times 10^{-17}$ ergs s^{-1} cm^{-2}, ~30 times fainter than the Lyα emission observed from the companion galaxy and a factor of ~4 lower than the previous upper limit, set by Pettini et al. (1990). A very slight excess of flux (~2 σ as measured in circular apertures approximating the FWHM of an unresolved source) is measured in the 1989 October data at a position coincident with the QSO PSF and the centroid of the Lyα absorption trough, but confusion with cosmic-ray hits and the absence of emission in the later images convinced us that it was spurious.

TABLE 1

PROPERTIES OF THE COMPANION GALAXY TO THE $z = 2.309$ DAMPED LYMAN-α CLOUD TOWARD PHL 957

PARAMETER	VALUE $q_0 = 0.1$	 $q_0 = 0.5$
R.A.(1950)	$01^h00^m30\overset{s}{.}55$	
Decl.(1950)	$+13°00'33\overset{''}{.}6$	
$\lambda_{Ly\alpha}$	4027.3 ± 0.3 Å	
Δλ(FWHM)	9.4 ± 1 Å	
z_{em}	2.3128 ± 0.0004	
$F(Ly\alpha)$[a]	5.6×10^{-16} ergs s^{-1} cm^{-2}	
$W_{E,rest}(Ly\alpha)$	140 Å	
C IV/Lyα	0.1	
He II/Lyα	0.1	
V	~23.6	
$B-V$	~0.6	
L(Lyα)	$1.1 \times 10^{43}h^{-2}$	$5.3 \times 10^{42}h^{-2}$ ergs s^{-1}
SFR[b]	$11h^{-2}$	$5h^{-2}$ $M_\odot$ yr^{-1}
Size	$\leq 17h^{-1}$	$\leq 12h^{-1}$ kpc
Projected distance from damped cloud	$270h^{-1}$	$190h^{-1}$ kpc
Velocity separation from damped cloud	346 ± 19 km s^{-1}	

[a] Error may be ±30%.

[b] Assuming no dust and Case B recombination.

3. DISCUSSION

The emission-line object does not correspond to any previously reported X-ray, radio, or optical source in the literature. We interpret the observed continuum radiation as evidence that the source contains stars, as opposed to being a passive cloud excited by an external source of radiation; we assume it represents some form of galaxy in a group or cluster also containing the damped Lyα cloud and compare the properties of the companion with three possible types of galaxy: (1) Seyfert 2 galaxies, (2) radio galaxies, and (3) giant extragalactic H II regions or starburst galaxies at an early stage of star formation. The width of the Lyα emission line (FWHM ~ 700 km s^{-1}) is comparable to the most narrow lines seen in Seyfert 2 galaxies, and extended Lyα emission has recently been observed around high-redshift QSOs (Heckman et al. 1991). However, despite the presence of He II and C IV, emission lines from other high-ionization species generally seen in AGN spectra, notably N V, are absent.

Our detection exhibits line ratios and a continuum slope strikingly characteristic of high-redshift radio galaxies, such as the 3CR sample studied by McCarthy (1989). Chambers & McCarthy (1990) argue that the rest-frame UV continua of such objects match well the continua of the hottest O-type stars studied with *IUE*, suggesting that a major portion of the light seen in such radio galaxies is starlight. However, the present galaxy is considerably fainter than most of those sources, both in continuum and line flux, and it also does not appear in any all-sky strong radio-source surveys. Unfortunately, C III] λ1909, which is commonly seen in high-redshift radio galaxies, falls near a strong night sky line in our spectra and cannot be measured accurately. VLA observations are planned to address the possibility that the source is a faint radio galaxy.

Finally, we consider the hypothesis that the object is an isolated region of strong star formation, without an embedded nonthermal radiation source. While the equivalent width of Lyα emission (W_E ~ 140 Å in the rest frame) is substantial, it is not outside the realm of possibility for active star formation (e.g., Elston 1988; Spinrad 1989). Of greater concern is the presence of He II and C IV, which implies an abundance of photons corresponding to the peak of a blackbody curve at $T > 10^5$ K; only the most massive stars, such as Wolf-Rayet stars, can produce such radiation in substantial amounts. However, both C IV λ1549 and He II λ1640 are seen in absorption or with P Cygni profiles in *IUE* spectra of some nearby extragalactic H II regions (e.g., Hartmann et al. 1988), and other lines of C IV and He II are seen in emission from the nebulae surrounding some Wolf-Rayet stars (e.g., Polcaro et al. 1991; Niemela, Heathcote, & Weller 1991), indicating that a nonthermal source is not necessary for such species to exist. Furthermore, the strength of the Lyα line argues strongly against the presence of large amounts of dust, a condition that should also increase the escape probability of other line radiation in the UV. Certainly, the Lyα flux resembles the early, optimistic predictions of Partridge & Peebles (1967) more than the discouragingly low equivalent widths observed by *IUE* in nearby star-forming regions, including those with metallicity as low as one-tenth solar (e.g., Hartmann, Huchra, & Geller

1984; Meier & Terlevich 1981), the most likely interpretation being extremely low levels of dust.

If we assume that there is in fact negligible destruction of Lyα radiation by dust, then the observed Lyα luminosity is a direct indicator of flux of ionizing UV photons which can in turn be used to estimate a star formation rate, under the assumption that all the UV radiation is produced by hot stars. Assuming Case B recombination, we expect Lyα/Hα ∼ 10. We then follow Kennicutt (1983), who parameterized the total star formation rate (SFR) of local spiral galaxies in terms of the total observed Hα luminosity as $\mathrm{SFR}(M_\odot\ \mathrm{yr}^{-1}) \sim L(\mathrm{H}\alpha)/10^{41}$ ergs s^{-1}, assuming a modified Miller-Scalo/Salpeter initial mass function, and find that for our observed Lyα flux, $\mathrm{SFR} \sim 5\text{–}11h^{-2}\ M_\odot\ \mathrm{yr}^{-1}$ for $q_0 = 0.5$ and 0.1, respectively. This rate is certainly not extraordinary; indeed it corresponds to a typical Sc galaxy in Kennicutt's sample. The size of the emitting region, $r \lesssim 15$ kpc, is compatible with a wide range of possible star formation scenarios seen at the current epoch, including starburst galaxies, normal late-type spirals, and giant extragalactic H II regions, as well as gas-rich dwarf irregulars.

The rest-frame UV continuum emission from the galaxy, however, is ∼500 times brighter than NGC 2903, a luminous Sc galaxy, would appear at $z = 2.3$, assuming no evolution (Coleman, Wu, & Weedman 1980). We conclude that either the object represents an ultraluminous phase of normal galaxies familiar to us at the current epoch, a true primeval galaxy, or it is an unusual object, such as an AGN, occupying the bright end of the emission-line galaxy luminosity function. Deep broad-band imaging of the PHL 957 field may reveal additional, fainter objects associated with the emitter and the absorbing cloud.

The companion galaxy would have been easily seen in recent "blank sky" searches for randomly distributed Lyα emitters that covered sky areas many times our field of view (e.g., Lowenthal et al. 1990; Pritchet & Hartwick 1987). Using these as control fields, we interpret the fact that it was discovered in association with a previously known absorption system as evidence for spatial correlation of the damped Lyα clouds with galaxies (and indirectly with themselves). This in turn encourages an identification of the damped Lyα clouds with nearby galaxies, which are known to correlate strongly on scales of a few hundred kpc. The spatial correlation further supports the hypothesis that the damped clouds are a different class of object from the low column density Lyα forest clouds (Lanzetta et al. 1991), which exhibit weak or no detectable clustering in velocity space, although they may be closely related to other metal-line systems, such as Mg II and C IV absorbers, which are known to cluster in redshift and with other objects at the same redshift (Sargent, Steidel & Boksenberg 1988; Steidel 1990; Yanny, York, & Williams 1990).

The 3 σ upper limit on emission from the damped system itself, ∼25 times below the level of Lyα flux from the companion galaxy, suggests a low level of star formation. Following Charlot & Fall (1991) and adopting a dust-to-gas ratio $k = 0.024$, 3% the Galactic value of 0.79, a velocity dispersion within the cloud of 10 km s^{-1}, a reddening curve similar to that in the SMC, and assuming any star-forming regions to be distributed in a plane embedded in the cloud, we estimate the attenuation of Lyα photons by dust in the damped cloud to be ∼90%; this would agree with the *IUE* observations by Hartmann et al. (1988) of nearby metal-poor star-forming regions. We then derive an upper limit on star formation in the damped cloud of $\mathrm{SFR} \lesssim 2\text{–}4h^{-2}\ M_\odot\ \mathrm{yr}^{-1}$ for $q_0 = 0.5$ and 0.1, respectively; in the absence of attenuation by dust, these limits would be a factor of 10 lower. This result is in contrast to the detection of strong Hβ and [O II] λ3727 emission from another damped cloud (toward Q1215+333) at a level implying a $\mathrm{SFR} \sim 100\ M_\odot\ \mathrm{yr}^{-1}$ (Elston et al. 1991); clearly more observations are needed to determine which of these two scenarios is more common.

The significant difference between the object probed by the QSO line of sight and the emission-line region may be due to several effects. Certainly, the damped cloud is enriched to some small degree, as inferred from the presence of heavy element absorption lines, presumably due to star formation. From the lack of observed strong Lyα emission, we conclude that star formation in the damped cloud is either episodic, occurs in a strong burst that quickly decays to a much lower level, or quickly self-enriches with dust to cloak UV radiation. The last possibility seems strongly constrained by the low levels of dust and heavy elements measured in the PHL 957 system.

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