A GRAVITATIONAL LENS MODEL FOR THE Lyα EMITTER LAE 221724+001716 AT z = 3.1 IN THE SSA 22 FIELD†1

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ABSTRACT

During our Lyman continuum imaging survey, we found that the spectroscopically confirmed Lyα emitter LAE 221724+001716 at z = 3.10 in the SSA 22 field shows strong Lyman continuum emission (λrest ≈ 900 Å) that escapes from this galaxy. However, another recent spectroscopic survey revealed that the supposed Lyman continuum emission could arise from a foreground galaxy at z = 1.76 if the emission line newly detected from the galaxy at λobs ≈ 3360 Å is Lyα. If this is the case, as the angular separation between these two galaxies is very small (∼0.′6), LAE 221724+001716 at z = 3.10 could be amplified by the gravitational lensing caused by this intervening galaxy. Here we present a possible gravitational lens model for the system of LAE 221724+001716. First, we estimate the stellar mass of the intervening galaxy as M∗ = 3.5 × 10⁴ M⊙ from its UV luminosity and 10⁻³ M⊙ through the spectral energy distribution fitting. Then, we find that the gravitational magnification factor ranges from 1.01 to 1.16 using the so-called singular isothermal sphere model for strong lensing. While LAE 221724+001716 is the first system of an LAE–LAE lensing reported so far, the estimated magnification factor is not so significant because the stellar mass of the intervening galaxy is small.

Key words: cosmology; observations – galaxies: high-redshift – gravitational lensing: strong

Online-only material: color figure

1. INTRODUCTION

Toward resolving the cosmic reionization sources, observations directly detecting the Lyman continuum (λrest < 912 Å, hereafter LyC) from galaxies at z > 3 have proceeded in the last decade (Steidel et al. 2001; Giallongo et al. 2002; Fernández-Soto et al. 2003; Inoue et al. 2005; Shapley et al. 2006; Iwata et al. 2009; Vanzella et al. 2010a; Boutsia et al. 2011; Nestor et al. 2011, 2013). Iwata et al. (2009) and Nestor et al. (2011, 2013) reported the largest number of individual detections of the LyC from galaxies in the SSA 22 field where a massive protocluster of galaxies at z = 3.10 was found (Steidel et al. 1998; Hayashino et al. 2004). Extremely strong LyC detected from some sample galaxies suggested that they contain a primordial stellar population such as metal-free stars with mass fraction of 1%–10% (Inoue et al. 2011). However, Vanzella et al. (2010b) raised the possibility that the supposed LyC detected from the galaxies comes from a foreground galaxy closely aligned along the line of sight toward the background z ∼ 3 galaxies. The LyC observers discussed this possibility in their papers and concluded that it was unlikely that all the detections were foreground contamination, although some of them were so (Iwata et al. 2009; Nestor et al. 2011, 2013). Indeed, Nestor et al. (2013) found an example of such a contamination: a foreground galaxy very closely aligned (≪1″) located in the front of a LyC emitter (LAE) with the possible LyC detection reported (Iwata et al. 2009; Inoue et al. 2011; Nestor et al. 2011). Hereafter, we call this galaxy LAE 221724+001716. Because of the small angular separation between the foreground and background galaxies, LAE 221724+001716 may be a strong gravitational lensing system. Gravitational lensing is now recognized as a powerful tool for observational cosmology and galaxy formation and evolution studies (e.g., Kneib & Natarajan 2011; see also Coe et al. 2013 and references therein). The strong lensing enables us to search faint high-redshift galaxies behind galaxy clusters and investigate physical properties of galaxies with higher signal-to-noise ratio by brightening and magnifying effect. If LAE 221724+001716 is a strongly magnified z ∼ 3 LAE, the intrinsic luminosity should be very faint, whereas its apparent luminosity is brightest among general LAEs. In this case, this object provides us with an opportunity to investigate the nature of a faint LAE in detail. Therefore, we try to construct a simple lensing model and estimate the magnification factor of this possible lensing system.

Throughout this paper, magnitudes are given in the AB system. We adopt a flat universe with ΩM = 0.3, ΩΛ = 0.7, and H₀ = 70 km s⁻¹ Mpc⁻¹.

2. LAE 221724+001716

LAE 221724+001716 is an LAE found in the SSA 22 field. Its strong Lyα emission line at z = 3.10 was confirmed by spectroscopy (Matsuda et al. 2006; Iwata et al. 2009; Inoue et al. 2011; Nestor et al. 2013). Its NB497 (central wavelength λc = 4977 Å, full width at half-maximum Δλ = 77 Å) magnitude, NB497 = 23.78, is one of the brightest among the LAE candidates in the SSA 22 field (Yamada et al. 2012). This object is also classified as a Lyα blob (LAB; No. 35) in Matsuda et al. (2004) because of its spatially extended Lyα emission, but this spatial extent is caused by the connection...
of the emission line from an eastern close companion object (the separation between them is ∼3′′). In fact, around this LAE, there are four objects within 4′′: eastern, north, northwestern, and western objects as seen in the Hubble Space Telescope (HST)/Advanced Camera for Surveys (ACS) I-band image (see Iwata et al. 2009; Nestor et al. 2011, 2013).

The shape of the central object in the HST/ACS image appears to be peculiar: a “maga-tama” (ancient Japanese amulet made of stone) like shape. If we look closely at this object, it seems to be composed of two parts: a northern “head” and southern “tail.” Iwata et al. (2009) detected this object in their NB359 (λc = 3590 Å, Δλ = 150 Å) image tracing the LyC at z = 3.10 and Inoue et al. (2011) named this object “I11-a.” Nestor et al. (2011) confirmed this detection by their NB3640 (λc = 3630 Å, Δλ = 100 Å) imaging and named it “LAE003.” There is a slight spatial offset between the NB359/NB497 (supposed LyC from LAE 221724+001716 at z = 3.10) and NB497/NB4980 (λc = 4985 Å, Δλ = 80 Å) (Lyα) positions: 0′′.4–0′′.6. From this small offset, Inoue et al. (2011) suggested the very small possibility that NB359/NB497 flux comes from a foreground object. However, Nestor et al. (2013) found an emission line around 3360 Å in the new deep spectrum of this object, strongly suggesting the presence of a foreground galaxy very closely aligned toward the z = 3.10 LAE. If this emission line is Lyα, the foreground galaxy lies at z = 1.76. Nestor et al. (2013) also noted that the southern tail is a foreground galaxy because of a small spatial offset of the 3360 Å and 4980 Å lines (Lyα at z = 3.10). The geometrical configurations of this system are shown in Figure 1.

The angular separation between LAE 221724+001716 detected in NB497/NB4980 bands and the foreground galaxy detected in the NB359/NB3640 bands is estimated as 0′′.38 (Inoue et al. 2011) and 0′′.6 (Nestor et al. 2011). While these two values are basically consistent within their observed errors, ≈0′′.2, we adopt the observed offset reported by Nestor et al. (2011), 0′′.6, as the fiducial angular separation between the two objects. This is because the luminosity-weighted central position of an extended source depends on the depth of the image and the NB3640 and NB4980 images of Nestor et al. (2011) are significantly deeper (∼0.57–1.2 mag) than the NB359 and NB497 images of Inoue et al. (2011). We also present the results in the case of the angular separation reported by Inoue et al. (2011) for reference in Section 4.

Before moving to the next section, we here summarize the photometry of this object. We measured its flux densities in 11 bands from optical to near-infrared. The details of the observations with the Subaru telescope and the data reductions are described in Hayashino et al. (2004) for B, V, R, i′, z′, J, H, and K, and Nakahiro et al. (2009) for NB359. The u∗ image was taken with the Canada–France–Hawaii Telescope (CFHT)/MegaCam and described in Kousai (2011). The spatial positions of this object in NB359 and NB497 are slightly (∼0′′.5) offset from it in R as mentioned above. Nevertheless, we simply apply aperture photometry at the R position with 1″ diameter. Table 1 shows the results. As an estimate of the total flux density, we adopt MAG_AUTO by SExtractor (Bertin & Arnouts 1996). Then, we find the aperture correction factor of 2.43 (i.e., −0.96 mag) in R. We apply it even for other bands when estimating the total flux densities in the following.

3. GRAVITATIONAL LENS MODEL FOR LAE 221724+001716

We construct a gravitational lens model for LAE 221724+001716. We use the so-called Singular Isothermal

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**Figure 1.** Schematic view of the relative positions of LAE 221724+001716 and the lensing galaxy. The light blue ellipse labeled “I” shows the image of LAE 221724+001716 at z = 3.10 and the yellow ellipse labeled “L” shows the foreground lensing galaxy at z = 1.76. The orange area shows the NB497/NB4980 emission that is dominated by the Lyα emission from LAE 221724+001716 and the green area shows the NB359/NB3640 emission that is dominated by the rest-frame UV stellar continuum emission from the foreground galaxy. The angular separation θ is defined as the angle between the luminosity-weighted central positions of the NB3640 and NB4980 images (= 0′′.6; Nestor et al. 2011) or NB359 and NB497 images (= 0′′.38; Inoue et al. 2011). For reference, the thumbnail images for NB359, NB497, and ACS/F814W are shown in the bottom column. North is up and east is left. The field of view is 5′′ × 5′′. (A color version of this figure is available in the online journal.)
Sphere (SIS) lens model (e.g., Binney & Merrifield 1998) for LAE 221724+001716. This lens model is appropriate for describing the actual density distribution of the dark matter halo of a galaxy. Moreover, this SIS lens model has only one parameter, that is, the velocity dispersion for the foreground galaxy, $\sigma$. Thus, it is also convenient to estimate the gravitational magnification factor as

$$M_+ = \frac{\theta}{\theta - \theta_E},$$

where $\theta$ is the angular separation between the source and the lensed image, $\theta = 0.6$ (Nestor et al. 2011). The Einstein angle, $\theta_E$, is defined as

$$\theta_E = \frac{4\pi\sigma^2}{c^2} \frac{D_{LS}}{D_{OS}},$$

where $\sigma$ is the velocity dispersion of dark matter halo hosting the lensing galaxy, $D_{LS}$ is the angular diameter distance between the foreground galaxy and LAE 221724+001716, and $D_{OS}$ is that between the observer and LAE 221724+001716; see Figure 2.

In order to estimate $\sigma$, we use the stellar-mass Tully–Fisher relation (Pizagno et al. 2005; Swinbank et al. 2012),

$$V_{2.2} = 155.6 \left( \frac{\Delta TF}{2.32} \frac{M_*}{10^{10} M_\sun} \right)^{1/3},$$

where $V_{2.2}$ is the rotation velocity at 2.2 times the disk scale length and $\Delta TF$ is the evolution factor of the zero point of the Tully–Fisher relation from $z \sim 0$ to $z \sim 2$ defined by $M_*(z \sim 0)/M_*(z \sim 2)$ (see Figure 6 of Swinbank et al. 2012 in detail). We also note that this relation is valid for the Chabrier initial mass function (IMF) with $0.1–100 M_\sun$.

Now we estimate the stellar mass of the lensing galaxy ($M_{\star,L}$), which is used as an input to Equation (3), using the following two independent methods: (1) the UV luminosity–stellar mass relation (Sawicki 2012), and (2) the spectral energy distribution (SED) fitting method. First, we use the Sawicki relation,

$$\log_{10} \left( \frac{M_\star}{M_\sun} \right) = 0.68 - 0.46M_{UV},$$

where $M_{UV}$ is the absolute UV magnitude at the rest-frame wavelength of 1700 Å. This relation is empirically obtained from the UV-selected galaxies adopting the Salpeter IMF with $0.1–100 M_\sun$. The stellar mass obtained with the Salpeter IMF is larger than that with the Chabrier IMF by a factor of 1.8. The observed total AB magnitude of $NB3640 = 24.74$ by Nestor et al. (2011) gives $M_{UV} = -19.78$. While this corresponds to the magnitude at $\lambda_{rest} = 1315$ Å, it can be regarded as the magnitude at $\lambda_{rest} = 1700$ Å under the assumption that the lensing galaxy has a flat continuum. This assumption is reasonable since the lensing galaxy is an LAE and such a flat continuum is expected for the galaxies that are young and have a small amount of dust like LAE. From the Sawicki relation, we obtain $M_{\star,L} = 3.5 \times 10^5 M_\sun$ for the Chabrier IMF. We adopt this value in later discussion.

Next, we use the SED fitting method. Here we use the Bruzual & Charlot (2003) model together with the following parameters: (1) Chabrier IMF with $0.1–100 M_\sun$, (2) metallicity $Z = 0.004 (= 0.2 Z_\sun)$, (3) constant star formation history, and (4) the extinction curve by Calzetti et al. (2000) with $E(B-V) = 0.2$ with an interval of 0.05. In our analysis, we use the total flux densities in optical and near-infrared wavelengths described in Section 2. The total flux densities are a combination of those
from LAE 221724+001716 at $z = 3.10$ and the foreground galaxy at $z = 1.76$. However, the total flux density of $NB359$ is considered to be dominated by the flux from the foreground galaxy if the escape fraction of the LyC photons from LAE 221724+001716 is not significant. Hence, in the course of the SED fitting to determine a robust upper limit and possible lower limit of $M_{\ast,L}$, we use the total flux density of $NB359$ with its photometric error and regard those of the other bands as upper limits because they are contaminated by the flux from LAE 221724+001716. The resultant upper and lower limits of $M_{\ast,L}$ are $2.4 \times 10^{9} M_{\odot}$ and $3.0 \times 10^{9} M_{\odot}$, respectively. The upper limit of $M_{\ast,L}$ is smaller than that estimated from the Sawicki relation above (i.e., $M_{\ast,L} = 3.5 \times 10^{9} M_{\odot}$) by a factor of $\sim 1.5$. However, this difference is not surprising because the lensing galaxy is young, $\sim 100$ Myr, and Sawicki (2012) has found that the stellar masses of such young galaxies are typically much smaller than those estimated from Equation (4) at a fixed $M_{UV}$ (see Figure 6 of Sawicki 2012).

In summary, (1) the Sawicki relation gives $\sigma = V_{2,2} = 105 \text{ km} \text{ s}^{-1}$. On the other hand, (2) the SED fitting method gives $\sigma \simeq 22–93 \text{ km} \text{ s}^{-1}$ for $M_{\ast,L} \sim 3.0 \times 10^{9}–2.4 \times 10^{9} M_{\odot}$. Based on these results, we estimate the gravitational magnification factor, $M_{\ast}$. In Figure 3, we show our results for the separation between the LAE and the foreground galaxy, $0.6$. We obtain $M_{\ast} \simeq 1.16$ and $\simeq 1.01–1.12$ in the cases (1) and (2), respectively. We note that the estimated magnification factors are fairly small although the angular separation between the lensing galaxy and the source galaxy is very small ($\approx 0.6$). This is due to the low mass of the lensing galaxy at $z \sim 1.8$, $\sim 10^{9} M_{\odot}$.

4. DISCUSSION

In this paper, we have investigated possible models for gravitational lensing for LAE 221724+001716 at $z = 3.10$. The intervening galaxy is located at $z = 1.76$ with a very small angular separation of $0.6$ from the line of sight toward LAE 221724+001716. This small separation suggests that LAE 221724+001716 could be amplified by gravitational lensing. If this is the case, LAE 221724+001716 is the first system of an LAE–LAE lensing. However, our analysis has shown that the magnification factor is only 1.16 at most. This result does not change significantly even if we adopt the smaller angular separation reported by Inoue et al. (2011), $\theta = 0.38$; in this case, $M_{\ast} \simeq 1.27$ and $1.01–1.20$ for $\sigma = 105 \text{ km} \text{ s}^{-1}$ and $\sigma = 22–93 \text{ km} \text{ s}^{-1}$ inferred from the Sawicki relation and the SED fitting, respectively (see Figure 3).

This small magnification factor is due to the fact that the lensing galaxy at $z \sim 1.8$ is significantly less massive, i.e., $M_{\ast,L} \sim 10^{9} M_{\odot}$. It does not change significantly even if we adopt another SED fitting method with two galaxy components (i.e., the foreground galaxy at $z = 1.76$ and LAE 221724+001716 at $z = 3.10$) by using all of the total flux densities; the resultant stellar masses of the foreground galaxy and LAE 221724+001716 are $\sim 7 \times 10^{8} M_{\odot}$ and $1 \times 10^{9} M_{\odot}$, respectively, in the case of their SEDs being identical with each other. However, this stellar mass is not unusually small among the LAEs at $z = 3.1–6.6$. In contrast, it is similar to that of the LAEs at $z = 3.1$ undetected in the $K$ band (Ono et al. 2010). Hence, the intervening galaxy at $z \sim 1.8$ (and perhaps, the source galaxy at $z \sim 3.1$) is considered to be a typical LAE.

Regarding the dark halo mass of LAEs, Ouchi et al. (2010) found that its average inferred from a clustering analysis is roughly $10^{11+0.5} M_{\odot}$ at $z = 2.1–6.6$. They also reported that the dark halo masses of LAEs show no significant redshift evolution in this redshift range beyond the mass-estimate scattering. It is possible that the intervening galaxy at $z \sim 1.8$ with $M_{\ast,L} \sim 10^{9} M_{\odot}$ is embedded in such a small mass halo. This may imply that the lack of evolution of halo mass of LAEs reported by Ouchi et al. (2010) extends to even lower redshift, $z \sim 1.8$.

The narrowband magnitude of LAE 221724+001716 is bright among the sample of the LAEs at $z \sim 3$ in the SSA 22 field given in Yamada et al. (2012). Although this property could be attributed to the gravitational magnification, the small magnification factor obtained here implies that this LAE is indeed bright. However, a number of high-redshift galaxies and quasars could be gravitationally magnified by the strong lensing by a foreground galaxy (e.g., Faure et al. 2008; Muzzin et al. 2012; Inada et al. 2012). Therefore, it is worthwhile estimating how often such a lensing event occurs for LAEs at $z \sim 3$. Here, we estimate the possibility of an LAE at $z \sim 3$ is gravitationally magnified by a foreground galaxy with $U$-band magnitude of $\sim 25$. This is actually the case for LAE 221724+001716 studied in this paper since $NB3640 = 24.74$ and $NB359 = 24.98$ approximately correspond to $U = 25$. We evaluate the possibility to find more than one foreground galaxy within 0.6 using the $U$-band number count data obtained by the Very Large Telescope (VLT)/VIMOS (Vanzella et al. 2010b); note that the central wavelengths of both NB359 and NB3640 are similar to that of $U$ band on the VLT/VIMOS. The possibility, $P_{\text{foreground}}$, is calculated by using the following equation:

$$P_{\text{foreground}} = \pi r^2 N,$$

where $r$ is the radius from the background galaxy and $N$ is the $U$-band galaxy number count. Adopting $r = 0.6$ and $N = 57,300 \text{ deg}^{-2}$ (galaxies with $U = 24.5–25.5$), we obtain $P_{\text{foreground}} \sim 0.005$. We conclude that the possibility of finding a foreground galaxy around an LAE at $z \sim 3$ within a radius of 0.6 is very small; the probability of LAE–LAE lensing is even smaller if the LAE fraction at $z \sim 1.8$ among the entire galaxy population is small.
Nevertheless, we have found such a case. A possible reason is that the NB359 detection more preferentially selects foreground galaxies than a blind survey. If most \( z \sim 3 \) galaxies do not emit LyC at all, they are not detected in NB359. Thus, the NB359 detection is biased toward close-foreground systems (Vanzella et al. 2010b). However, the number of NB359 detections is significantly larger than that of the foreground galaxies expected, and thus some NB359 sources are real LyC emitters (Iwata et al. 2009; Inoue et al. 2011; Nestor et al. 2011, 2013). In any case, it is interesting that the LyC survey with NB359 imaging is also useful in finding the close-foreground systems discussed in this paper.

One interesting property of the gravitational lensing in LAE 221724+001716 is that the lensing galaxy is located at \( z \sim 1.8 \). Although a number of gravitational lensing events by a galaxy have been found to date (e.g., Faure et al. 2008; Muzzin et al. 2012), the redshifts of the lensing galaxies are preferentially \( z < 1 \). One high-redshift lensing galaxy at \( z \sim 1.5–2.5 \) has been found for one of the Sloan Digital Sky Survey quasars, SDSSp J104433.04–012502.2 at \( z = 5.74 \) (Shioya et al. 2002). The detection of such gravitational lensing by a high-redshift galaxy (\( z > 1 \)) is currently rare. Since the number density of potential lensing galaxies could decrease with increasing redshift, it seems difficult to find events of gravitational lensing by such high-redshift galaxies. Relatively lower masses of high-redshift galaxies also make it difficult to detect them. However, such events will help us in investigating very high redshift galaxies (e.g., \( z > 10 \)) in future very deep and wide-field imaging surveys.

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REFERENCES

Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Binney, J., & Merrifield, M. 1998, Galactic Astronomy (Princeton Series in Astrophysics; Princeton, NJ: Princeton Univ. Press)
Boutsia, K., Grazian, A., Giallongo, E., et al. 2011, ApJ, 736, 41
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682
Coe, D., Zitrin, A., Carrasco, M., et al. 2013, ApJ, 762, 32
Faure, C., Kneib, J.-P., Covone, G., et al. 2008, ApJS, 176, 19
Fernández-Soto, A., Lanzetta, K. M., & Chen, H.-W. 2003, MNRAS, 342, 1215
Giallongo, E., Cristiani, S., D’Odorico, S., & Fontana, A. 2002, ApJL, 568, L9
Hayashino, T., Matsuda, Y., Tamura, H., et al. 2004, AJ, 128, 2073
Inada, N., Oguri, M., Shin, M.-S., et al. 2012, AJ, 143, 119
Inoue, A. K., Iwata, I., Deharveng, J.-M., Buat, V., & Burgarella, D. 2005, A&A, 435, 471
Inoue, A. K., Kousai, K., Iwata, I., et al. 2011, MNRAS, 411, 2336
Iwata, I., Inoue, A. K., Matsuda, Y., et al. 2009, ApJ, 692, 1287
Kneib, J.-P., & Natarajan, P. 2011, A&ARv, 19, 47
Kousai, K. 2011, PhD thesis, Tohoku Univ.
Matsuda, Y., Yamada, T., Hayashino, T., Yamauchi, R., & Nakamura, Y. 2006, ApJL, 640, L123
Matsuda, Y., Yamada, T., Hayashino, T., et al. 2004, AJ, 128, 569
Muzzin, A., Labbé, I., Franx, M., et al. 2012, ApJ, 761, 142
Nestor, D. B., Shapley, A. E., Kornei, K. A., Steidel, C. C., & Siana, B. 2013, ApJ, 765, 47
Nestor, D. B., Shapley, A. E., Steidel, C. C., & Siana, B. 2011, ApJ, 736, 18
Ono, Y., Ouchi, M., Shimasaku, K., et al. 2010, MNRAS, 402, 1580
Ouchi, M., Shimasaku, K., Furusawa, H., et al. 2010, ApJ, 723, 869
Pizagno, J., Prada, F., Weinberg, D. H., et al. 2005, ApJ, 633, 844
Sawicki, M. 2012, MNRAS, 421, 2187
Shapley, A. E., Steidel, C. C., Pettini, M., Adelberger, K. L., & Erb, D. K. 2006, ApJ, 651, 688
Shioya, Y., Taniguchi, Y., Murayama, T., et al. 2002, PASJ, 54, 975
Steidel, C. C., Adelberger, K. L., Dickinson, M., et al. 1998, ApJ, 492, 428
Steidel, C. C., Pettini, M., & Adelberger, K. L. 2001, ApJ, 546, 665
Swinbank, A. M., Sobral, D., Smail, I., et al. 2012, MNRAS, 426, 935
Uchimoto, Y. K., Suzuki, R., Tokoku, C., et al. 2008, PASJ, 60, 683
Vanzella, E., Giavalisco, M., Inoue, A. K., et al. 2010a, ApJ, 725, 1011
Vanzella, E., Siana, B., Cristiani, S., & Nonino, M. 2010b, MNRAS, 404, 1672
Yamada, T., Nakamura, Y., Matsuda, Y., et al. 2012, AJ, 143, 79