LBT/LUCIFER OBSERVATIONS OF THE $z \sim 2$ LENSED GALAXY J0900+2234*

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ABSTRACT

We present rest-frame optical images and spectra of the gravitationally lensed, star-forming galaxy J0900+2234 (z = 2.03). The observations were performed with the newly commissioned LUCIFER1 near-infrared (NIR) instrument mounted on the Large Binocular Telescope. We fitted lens models to the rest-frame optical images and found that the galaxy has an intrinsic effective radius of 7.4 ± 0.8 kpc with a lens magnification factor of about 5 for A and B components. We also discovered a new arc belonging to another lensed high-z source galaxy, which makes this lens system a potential double Einstein ring system. Using the high signal-to-noise ratio rest-frame spectra covered by the H$\alpha$ and H$\beta$ emission lines and the half-light radius, we found that the dynamical mass of the lensed galaxy is $\sim 10^{10} M_\odot$. The gas mass is $(5.8 \pm 0.9) \times 10^{10} M_\odot$. The gas mass is $(5.1 \pm 1.1) \times 10^{10} M_\odot$ from the H$\alpha$ flux surface density using global Kennicutt–Schmidt law, indicating a very high gas fraction of 0.79 ± 0.19 in J0900+2234.

Key words: galaxies: abundances – galaxies: evolution – galaxies: high-redshift – galaxies: ISM – gravitational lensing: strong

1. INTRODUCTION

Redshifts between 1 < $z$ < 3 mark the time of peak cosmic star formation (Madau et al. 1998) and quasar activity (Fan et al. 2001). The current Hubble sequence was being built up, and a large fraction of present-day stars were formed (Dickinson et al. 2003). Observations of galaxies in this redshift range provide a direct picture of the formation and evolution of galaxies and the assembly of their central supermassive black holes.

By obtaining rest-frame optical spectra, we can perform detailed studies of the star formation history, as well as properties of the interstellar medium and stellar populations in galaxies. However, well-known diagnostic optical emission lines are shifted into the near infrared (NIR) for $z = 1–3$. Since high-z galaxies (e.g., Lyman break galaxies or LBGs) are faint, it is difficult to obtain high signal-to-noise ratio (S/N) NIR spectra with current facilities, especially for weak emission and absorption lines. Therefore, many previous NIR spectroscopic studies have focused on the strong [O iii] or H$\alpha$ emission lines (e.g., Pettini et al. 2001; Erb et al. 2003, 2006b, 2006c), from which only limited inferences can be drawn.

One method of addressing this problem is to observe high-z star-forming galaxies which have been gravitationally lensed by foreground massive galaxies or clusters. Lensing can boost the observed flux of high-redshift galaxies by several tens or more, so that high-S/N spectroscopy in the NIR becomes feasible. One of the first lensed galaxies to be studied in this way was the serendipitously discovered MS1513—cB58 at $z = 2.73$ (Yee et al. 1996; Bechtold et al. 1997; Teplitz et al. 2000). Subsequently, several groups began systematic searches for strongly lensed high-redshift galaxies toward clusters of galaxies (Sand et al. 2005; Richard et al. 2008) and red galaxies in the Sloan Digital Sky Survey (SDSS; York et al. 2000) images (e.g., Belokurov et al. 2009; Kubo et al. 2009). These searches are finding lensed star-forming galaxies at redshifts $z > 2$ (e.g., Allam et al. 2007; Lin et al. 2009; Diehl et al. 2009; Koester et al. 2010) which can then be followed-up in the NIR, or rest-frame optical and UV (e.g., Smail et al. 2007; Hainline et al. 2009; Finkelstein et al. 2009; Quider et al. 2009, 2010; Pettini et al. 2010).
The object of this paper is the lensed system J0900+2234 (\(z = 2.03\); Diehl et al. 2009), which was discovered in SDSS images, and then confirmed with follow-up deep optical \(g, r, i\) imaging and spectroscopy. The lens galaxy is at \(z = 0.49\) based on SDSS spectroscopy. In this paper, we report \(J, H,\) and \(K_s\) imaging and \(H + K\) spectroscopy of J0900+2234 with the newly commissioned LUCIFER instrument (Mandel et al. 2008; Ageorges et al. 2010) at the Large Binocular Telescope (LBT; Hill et al. 2008). We detected the nebular emission lines \(\text{H}\beta, [\text{O} \\text{iii}]\lambda 4959,5007, \text{H} \alpha, [\text{N} \text{ii}]\lambda 6583,\) and \([\text{S} \text{ii}]\lambda 6717,6732\) with simultaneous \(H + K\) band spectral coverage from 1.40 to 2.20 \(\mu\text{m}\). The wide simultaneous wavelength range coverage not only improves observation efficiency, but also helps to reduce the measurement uncertainties of the line ratios (e.g., \(\text{H}\alpha/\text{H}\beta\)) resulting from the flux calibration and slit loss variation between different exposures.

This paper is organized as follows: in Section 2, we describe the observations and reduction of the LUCIFER data. In Section 3, we describe the photometry, reconstruction of the source with lens modeling and line flux measurements. In Section 4, we construct a simple lensing model using the J0900+2234 NIR imaging. In Section 5, we report the detailed physical properties of J0900+2234 and discuss the systematic uncertainties of the physical property measurements. In Section 6, our main results are summarized. Throughout this paper, we use a cosmology with \(H_0 = 70\) \(\text{km s}^{-1}\) Mpc\(^{-1}\), \(\Omega_M = 0.3\), and \(\Omega_\Lambda = 0.7\). The magnitudes are all AB magnitudes.

2. OBSERVATIONS AND DATA REDUCTION

2.1. LUCIFER

LUCIFER1 was built by a collaboration of five German institutes. It is the first of a pair of NIR imagers/spectrographs for the LBT. It is mounted on the bent Gregorian focus of the telescope. The instrument has been in regular science operation since mid 2009 December. It is the first of a pair of NIR imagers/spectrographs for the LBT. It is mounted on the bent Gregorian focus of the telescope. The instrument has been in regular science operation since mid 2009 December.

2.2. LUCIFER Imaging And Spectroscopy

J0900+2234 was observed with LUCIFER1 on the LBT on 2010 January 6 in imaging mode and on 2010 February 13 in long-slit spectroscopy mode (Table 1). In the imaging mode, the N3.75 camera was used; the 18.5 \(\mu\text{m}\) pixels correspond to 0.′12 on the sky, for a 4.0 × 4.0 field of view. The seeing was 0.′7 with thin clouds. For each filter (\(J, H,\) and \(K_s\)), we obtained 10 randomly dithered exposures of 60 s each. For the spectroscopic observations, we used a 5′-0.6 and the conditions were photometric. The spectra were taken with an N1.8 camera, yielding a plate scale of 0.′25 per pixel. An order separation filter and a 200 1/mm \(H + K\) grating were used to cover the wavelength range from 1.40 to 2.20 \(\mu\text{m}\), simultaneously. A 1′0 by 3.9 slit was used, resulting in a spectral resolution of 16 \(\AA\). The total exposure time was 24 × 300 s with the telescope nodded ~7″ along the slit between each exposure. The instrument was rotated to P.A. = 86.57 in order to place the two brightest lensed components in the slit. Dark exposures and internal quartz lamp flats were obtained in the afternoon, and an Ar lamp was observed for wavelength calibration during the night.

2.3. Data Reduction

2.3.1. Imaging Reduction

The imaging data were reduced using standard IDL routines. The dark frames were median combined to create a master dark frame. A super-sky flat was constructed from combining the science frames after dark subtraction. The science images were dark subtracted, and then divided by the super-sky flat to correct for the detector response. The science images were registered to the SDSS–DR6 catalog using SCAMP (Bertin 2006) for astrometric calibration; the residuals were less than 0.′1 rms. Finally, the sky background was subtracted from the science frames which were then co-added using SWarp (Bertin et al. 2002). Photometric zero points were determined from Two Micron All Sky Survey stars in the field of view.

The fully reduced \(J, H,\) and \(K_s\)-band images are shown in Figure 1. In addition to the lensed galaxy (components A, B, C, and D in Figure 1) found by Diehl et al. (2009), we discovered another component, A1. The color of A1 suggests that it is also a high-redshift galaxy imaged by the foreground red galaxy, but not the same galaxy appearing in images as A, B, C, or D (see details in Section 3.1).

2.3.2. Spectroscopy Reduction

To reduce the LUCIFER spectra, we modified an IDL long-slit reduction package written by G. D. Becker for NIRSPEC (Becker et al. 2009). In this package, the following sky background subtraction procedure was used. First, four types of calibration files were created: a median-combined normalized internal flat field to correct the pixel-to-pixel variations in QE, a median-combined dark image, and two transformation maps created by tracing bright standard stars and bright sky lines. These two transformation maps were used to transform the NIR detector \((x, y)\) coordinates to the slit position and wavelength coordinates. Next, the dark image was subtracted from the science frames which were then divided by the flat field. The background in each science frame was subtracted using a fit to the science frames obtained before and after it in two dimensions, based on the transformation maps. A second-order polynomial function and a b-spline function were used to fit the sky background residual along the slit direction and the dispersion direction, respectively. After the sky background subtraction, the \(x\) and \(y\) direction distortions of the science frames were corrected based on the transformation maps created in the first step. The one-dimensional spectra were extracted from individual two-dimensional spectrum frames and combined to give the averaged spectrum shown in Figure 2. The wavelength calibration was derived from observations of Ar lamps and applied to the averaged spectrum. The spectrum was corrected for

| Date (UT) | Mode   | Camera | Filter | Slit P.A. (deg) | Exp. Time (s) |
|-----------|--------|--------|--------|----------------|--------------|
| 2010 Jan 6| Imaging| N3.15  | J      | ...            | 10 × 60      |
|           |        |        |        | \(H\)         | 10 × 60      |
|           |        |        |        | \(K_s\)       | 10 × 60      |
| 2010 Feb 13| Spectroscopy | N1.8   | \(H + K\) | 86.57 | 24 × 300 |

Table 1

LUCIFER Observation Log of J0900+2234
telluric features with the spectrum of an AV star observed at the same average air mass as the science exposures. Finally, we derived the flux calibration by normalizing the spectrum to the $H$-band magnitude.

3. MEASUREMENTS

3.1. NIR Photometry: Discovery of a New Lensed Galaxy

The GALFIT program (Peng et al. 2002, 2010) was used to model the central lensing galaxies and lensed components. We fitted each of the two central massive galaxies with de Vaucouleurs models, and fitted the three lensed knots and two arcs with exponential disk models. The initial input parameters—namely, position, total magnitude, axis ratio, and position angle for each component—were determined using SExtractor (Bertin & Arnouts 1996). We used the $K_s$-band co-added image to fit the profile parameters (Figure 3 and Table 2), and fixed these parameters when fitting the $J$- and $H$-band images to obtain the magnitude of each component (Table 3). The values of best-fit reduced $\chi^2$ for $J$, $H$, and $K_s$ bands were 1.064, 1.094, and 1.088, respectively.

The NIR colors of the A and B components are similar, with $J - H \sim 0.1$ and $H - K_s \sim 0.0$, while the colors of the C and D components appear to be different from those of the A and B components. For the D component, the reason for this discrepancy may be that the exponential disk profile is not a
good fit to the observed arc structure. For the C component, the follow-up spectroscopy was performed with an MMT/Blue Channel spectrograph, which shows that the C component is not part of this lens system. Current data are not yet extensive enough to uncover other components of the weak A1 component. If confirmed by spectroscopy and deeper imaging, this newly discovered arc would make J0900+2234 a rare example of a double Einstein ring system.

3.2. Emission-line Measurements

We used the IDL MPFIT\(^9\) package to fit the emission lines. The results are listed in Table 4. The Hβ, [O iii]λ4959 and [O iii]λ5007 were fit as Gaussian functions individually. The positions of Hα and [N ii]λ6583 as well as [S ii]λλ6717, 6732 are close to each other, so they were fit by two Gaussian functions together to deblend these two lines. The observed line wavelength, line flux, and full width at half maximum (FWHM) were derived from the Gaussian fitting (Table 4). Monte Carlo (MC) simulation was used to estimate the uncertainties of line flux and FWHM. One thousand artificial spectra were generated by perturbing the flux of each data point from the true spectrum by a random amount proportional to the 1σ flux error. We then measured the line flux of each fake spectrum, leaving all the parameters free for both the single lines and deblended line pairs. The standard deviations of the distributions of the line flux and the FWHM were adopted as the uncertainty of measurements of the line flux and the FWHM (Table 4). The emission-line redshifts of A and B knots are 2.0321 ± 0.0009 and 2.0318 ± 0.0005, respectively, and are consistent with each other within Δz/(1 + z) = 0.0001. These results also agree with the mean redshift from the optical spectra, z = 2.0325 ± 0.0003 (Diehl et al. 2009).

4. LENSED MODEL

The lens modeling is performed using LENSFIT (Peng et al. 2006). Briefly, LENSFIT is patterned after and works like GALFIT (Peng et al. 2002, 2010). LENSFIT is designed to specifically deal with situations where the image geometry is crowded: it allows one to simultaneously decompose foreground and background galaxy light profiles and determine the lens deflection model. The number of light profile and singular isothermal ellipsoid (SIE) deflection models is unrestricted, and the optimization process is done using the Levenberg–Marquardt algorithm in Numerical Recipes (Press et al. 1992).

In J0900+2234, the deflection model is potentially quite complicated because the system is embedded in a compact cluster environment. There are at least two primary deflectors, and potentially five in all, just within the Einstein ring of the system which has a radius of roughly 7.7 arcsec. Due to the low S/N of the source detection, it is difficult to determine an accurate lens model. However, it is clear from visual inspection that a single SIE deflector probably would not suffice because the geometric center of the lensed arcs falls in the gap between the two primary deflectors. Therefore, the simplest lens deflection

\(^9\) http://cow.physics.wisc.edu/~craigm/idl/idl.html
model we adopt is that of two SIEs held to the position of the light profile of the two primary lensing galaxies. We also hold the SIE axis ratios fixed to the light profile models of the lenses, but allow the Einstein ring radii and position angle parameters to be free in the fit. We simultaneously optimize the light profiles of all the foreground sources and the background galaxy light profiles, in all 14 objects in the J-band image.

With the limitation of our lens model and the data S/N in mind, we infer that the size of the background source is 0.8–1.0 arcsec which corresponds to a physical size of 6.6–8.2 kpc, in deprojected angular size, and it has a luminosity of 21.7 to 21.8 mag (AB) in the J band, given a magnification of the A and B components together of 4.6–5.0. For the further analysis, we use an effective radius of 7.4 kpc and an A and B component magnification of 4.8. The Sersic index is quite high, from $n = 3.5$ to $n = 4$. The major uncertainty of the lens fitting is caused by the influence of the bright foreground source C, which is right on the Einstein ring and the source elsewhere has quite low S/N.

5. PHYSICAL PROPERTIES

With LUCIFER, we obtained $H + K$ (1.40–2.20 μm) spectra of the A and B components of the lensed galaxy J0900+2234 (Figure 2). The Hβ, [O iii]λλ4959,5007, Hα, [N ii]λ6583, and [S ii]λλ6717,6732 lines were detected. In this section, we discuss the physical properties which can be derived from these observations.

5.1. Emission-line Diagnostics

First, it is important to examine the observed values of well-known empirical line ratio diagnostics to determine whether the emission is from an H II region, active galaxy, or shocked gas. The line ratios of the A and B components on the diagram of Baldwin et al. (1981) (BPT diagram) are shown in Figure 5. The weak N II emission rules out the possibility that the emission is from the activity of a central active galactic nucleus (AGN). The location of the A and B components on the BPT diagram are similar to other high-z star-forming galaxies (e.g., Liu et al. 2008; Hainline et al. 2009). They have relatively higher [O iii]λ5007/Hβ values and lower [N ii]λ6584/Hα values compared to the local star-forming galaxies from the SDSS (Figure 5). This offset could be the result of relatively intensive star formation activity and high electron density in these high-redshift galaxies, compared to the local sample. Overall, we conclude that the line emission is from gas that is photoionized by a hot stellar continuum, that is, the emission is from star formation regions.

5.2. Reddening and Extinction

We estimated the extinction of the lensed galaxy by two methods: (1) a fit to the stellar continuum as measured by broadband photometry and (2) Balmer decrement. These two methods represent the dust extinction to the stellar continuum $E_s(B – V)$ and the dust extinction to the nebular gas in the H II region ($E_s(B – V)$), respectively. One expects these two estimates to differ, and indeed some previous studies have observed that there is more extinction toward the ionized gas than the stellar continuum in local star-forming galaxies (Calzetti et al. 2000) and high-redshift galaxies (e.g., Förster Schreiber et al. 2009). In contrast, Erb et al. (2006b) did not find any extinction difference between ionized gas and the stellar continuum in star-forming galaxies at a redshift of $z \sim 2$. For lensed galaxies, the reddening derived from individual images often differs because of reddening by different amounts of foreground dust, since the images traverse different sight lines through the lensing galaxies.

With optical photometry alone, one can measure only the UV continuum shape in high-redshift galaxies, making it difficult to distinguish between reddening by dust and age of the stellar population. By adding the NIR photometry, we can measure the Balmer break (3600–3700 Å) which is sensitive to the age of the stellar population, and the 4000 Å break strength only weakly depends on metallicity. By combining our NIR photometry with the optical, we can fit stellar population models and simultaneously determine the age of the galaxy and average extinction.

Here, we used the $J$, $H$, and $Ks$-band (rest-frame optical bands) magnitudes combined with the $g$, $r$, and $i$-band (rest-frame UV bands) magnitudes (3σ from Diehl et al., 2009) to estimate the $E_s(B – V)$ and the age of the galaxy. The Bruzual & Charlot (2003, BC03) standard simple stellar population model was used to build the spectral templates of star-forming galaxies. We adopted a constant star formation rate (SFR) with the Chabrier initial mass function (IMF; Chabrier 2003), and solar metallicity, to generate a series of spectra with different ages and reddening. Figure 4 shows the best-fit spectra with the photometry data of the A and B components. From the fitting, we found that the ages of the components A and B were consistent with each other, and equal to 180 Myr, with the values of $E_s(B – V)$ equal to 0.07 and 0.20 for the components A and B, respectively. Based on the metallicity found in Section 5.4, we also generated the spectra with 0.25 solar metallicity to fit the broadband photometry data, and found similar results.

With this fit to the stellar population, we derived the intrinsic stellar mass of the source galaxy to be $1.9 \times 10^{10} M_\odot$ after correcting for lensing magnification, which is smaller than the mean stellar mass of $3.6 \times 10^{10} M_\odot$ found in a $z \sim 2$ UV-selected galaxy sample (Erb et al. 2006c). Using $Ks$-band magnitude to approach the rest-frame $R$-band magnitude, we found that the $M/L_R$ in J0900+2234 is 0.13. Shapley et al. (2005) found that the mean of $M/L_R$ is 0.29 with a large scatter from 0.02 to 1.4 (where the values were divided by 1.8 to convert the Salpeter IMF to Chabrier IMF) in $z \sim 2$ UV-selected star-forming galaxies. Considering the high scatter, $M/L_R$ in J0900+2234 agrees with that in other $z \sim 2$ star-forming galaxies.
**5.4. Oxygen Abundance**

Emission lines from H ii regions can be used to measure metallicity. The oxygen abundance was calculated using the following indicators: the N2 index \((N2 \equiv \log(F_{NII}/F_{Hα}))\) and the O3N2 index \((O3N2 \equiv \log(F_{OIII}/F_{Hβ})/F_{NII}))\), which have been well calibrated using nearby extragalactic H ii regions to measure O/H (Pettini & Pagel 2004). The advantage of using the N2 and O3N2 indices as metal abundance estimators is that Hα and the [N ii] and [O iii] lines are close in wavelengths, making these two estimators relatively insensitive to extinction.

The N2 index is sensitive to the oxygen abundance (Storchi-Bergmann et al. 1994), and was further calibrated by Raimann et al. (2000) and Denicoló et al. (2002). Here, we use the best linear fit between the N2 and (O III) pairs, as well as the Hβ and [O ii] pairs, to measure O/H.

\[
12 + \log(O/H) = 8.90 + 0.57 \times N2, \tag{2}
\]

where N2 is in the range from 2.5 to 0.3, and the 1σ error of the measurements of \(\log(O/H)\) is 0.18. We find the values of \(12 + \log(O/H)\) equal to 8.12 ± 0.21 and 8.23 ± 0.19 for components A and B, respectively, which are about 0.27 ± 0.13 to 0.35 ± 0.15 solar abundance (for the Sun: \(12 + \log(O/H) = 8.69\); Asplund et al. 2009).

The O3N2 index was first introduced by Alloin et al. (1979), and was well calibrated by Pettini & Pagel (2004) using 137 extragalactic H ii regions. The relation between the metallicity \((12 + \log(O/H))\) and the O3N2 index is

\[
12 + \log(O/H) = 8.73 - 0.32 \times O3N2, \tag{3}
\]

where O3N2 is in the range from 1 to 2, and the 1σ error of the measurements of \(\log(O/H)\) is 0.14, which indicates less scattering than the N2 index. We found the values of intrinsic UV \((\sim 1700\,\text{Å})\) brightness of the J0900 + 2234 is 22.1 magnitude, so that the absolute magnitude is \(M(1700)_{\text{AB}} = -22.7\), compared to \(L^* = -20.20\) to -20.97 at \(z \sim 2\) (e.g., Oesch et al. 2010; Reddy et al. 2008; Reddy & Steidel 2009).

Thus, J0900+2234 has \(L/L^* \approx 5-10\), and is an intrinsically luminous galaxy. Galaxies with these high luminosities are very rare, and their number density is about a few \(10^{-6}\) Mpc\(^{-3}\) mag\(^{-1}\) based on the luminosity function from Reddy et al. (2008) and Reddy & Steidel (2009). The high-intrinsic UV luminosity indicates a high SFR (see details in Section 5.3) in this galaxy.

We estimated \(E_\alpha(B - V)\) of J0900+2234 using the flux ratio of the Hα and Hβ lines. Under Case B, H i recombination at a temperature \(T = 10,000\,\text{K}\) and electron density \(n \sim 10^3\,\text{cm}^{-3}\) (Zaritsky et al. 1994), the intrinsic value of Hα/Hβ is 2.86 (Osterbrock & Ferland 2006, p. 73). Using the extinction law proposed by Calzetti et al. (2000), we found that the values of \(E_\alpha(B - V)\) were 0.84 ± 0.31 and 0.59 ± 0.08 for the A and B components. For both A and B components, the values of \(E_\alpha(B - V)\) are significantly larger than those of \(E_\alpha(B - V)\) in agreement with the results of Calzetti et al. (2000) and Förster Schreiber et al. (2009). The stars and line-emitting gas are not co-spatial, and the line-emitting regions are dustier than the galaxy as a whole. Note that the low S/N of the Hβ line in knot a makes the uncertainty of the \(E_\alpha(B - V)\) for component A large. Therefore, we use the value of \(E_\alpha(B - V) = 0.59 \pm 0.08\) of knot B for further analysis.

**5.3. Star Formation Rate**

We estimated the SFR in J0900 + 2234 using the luminosity of Hα \((L_{\text{Hα}}\); Kennicutt et al. 1998). The relation between the SFR and \(L_{\text{Hα}}\) is

\[
\text{SFR}(M_\odot\,\text{yr}^{-1}) = 7.9 \times 10^{-42} \frac{L_{\text{Hα}}}{\text{erg s}^{-1}} \tag{1}
\]

The Hα fluxes of the A and B components are 37.01 ± 0.79 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} and 84.64 ± 3.21 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2}. We used \(E_\alpha(B - V) = 0.59 \pm 0.08\) to correct the fluxes for extinction and found the extinction-corrected fluxes to be \((225.5 \pm 55.5) \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2}\) and \((516.0 \pm 128.0) \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2}\). The extinction-corrected luminosities are, therefore, \((15.4 \pm 3.8) \times 10^{43} \text{erg s}^{-1}\) and \((6.75 \pm 1.66) \times 10^{43} \text{erg s}^{-1}\). The lensed SFRs of components A and B are 533 ± 131 M_\odot yr\(^{-1}\) and 1220 ± 303 M_\odot yr\(^{-1}\). We added the SFRs of the components A and B together, corrected for the magnification, and found that the intrinsic SFR of the lensed galaxy was 365 ± 69 M_\odot yr\(^{-1}\). Note that if we use the Chabrier IMF, the SFR derived from the \(L_{\text{Hα}}\) will be 203 ± 38 M_\odot yr\(^{-1}\). We also estimated the SFR from the UV luminosity (Kennicutt et al. 1998) which is derived from the average of g and r-band flux. We found that the SFR is 276 M_\odot yr\(^{-1}\) for Shapley IMF and 153 M_\odot yr\(^{-1}\) for Chabrier IMF by correcting for the dust extinction, \(E_\alpha(B - V) = 0.07(0.20)\) for the A (B) components. The SFR based on the dust-corrected Hα emission is consistent with that from the dust-corrected UV emission. If we use \(E_\alpha(B - V) = 0.20\) to correct for the extinction of the Hα flux, the Hα-derived SFR of 110 M_\odot yr\(^{-1}\) will be significantly lower than UV-derived SFR. This supports the result that the \(E_\alpha(B - V)\) is larger than \(E_\alpha(B - V)\). The average of the SFR for \(z \sim 2\) star-forming galaxies is \(\text{SFR}_{\text{UV}} = 31\, M_\odot\, \text{yr}^{-1}\) and \(\text{SFR}_{\text{Hα}} = 29\, M_\odot\, \text{yr}^{-1}\) (Erb et al. 2006). Despite the uncertainties in interpreting the SFR measurements, we conclude that the SFR of J0900 + 2234 is an order of magnitude higher than typical star-forming galaxies at \(z \sim 2\).

![Figure 5. Hα region diagnostic diagram of log(N II/5684/Hβ) and log(O III/5007/Hβ). The open rectangles show the location of the A (left) and B (right) components. The open diamonds represent \(z \sim 1–1.5\) DEEP2 objects (Liu et al. 2008) and the open triangles represent \(z \sim 2\) lensed star-forming galaxies (Hainline et al. 2009). The gray points represent SDSS star-forming galaxies and AGNs. The dotted line and dashed line are empirical (Kauffmann et al. 2003) and theoretical (Kewley et al. 2001) separation of star-forming galaxies and AGNs.](image-url)
12 + \log(O/H) of components A and B were 8.00 ± 0.16 and 8.09 ± 0.15, which are 0.21 ± 0.08 and 0.25 ± 0.08 solar abundance.

Both the N2 and O3N2 indices indicate that J0900+2234 has a low oxygen abundance compared with other z ~ 2 star-forming galaxies. Figure 6 shows the stellar mass and metallicity relation in the local SDSS starburst galaxies and z ~ 2 star-forming galaxies (Erb et al. 2006a). The metallicity is derived from the N2 index. We averaged the value 12 + \log(O/H) of the A and B components and the stellar mass is from the broadband fitting result. Our data point is significantly lower than the mass and metallicity relation in star-forming galaxies at z ~ 2 (Erb et al. 2006a). Mannucci et al. (2010) proposed a more general fundamental relation between stellar mass, SFR, and metallicity derived with SDSS galaxies, in which the metallicity decreases with the increase of SFR. We used the relation derived in Mannucci et al. (2010) (Equation (2)) to obtain the predicted metallicity from SFR and stellar mass and found the value to be 8.45. Although our measured metallicity is ~0.27 dex lower than the predicted value, this dispersion is consistent with the results of Mannucci et al. (2010) that the distant galaxies show 0.2–0.3 dex dispersions for the fundamental metallicity relation.

5.5. Electron Density

The flux ratio of [S II]λ6717 and [S II]λ6732 was used to estimate the electron density in the H II region of J0900 + 2234. The IRAF task stdas.analysis.nebular.temden was used to compute the density. We assumed that the temperature in these regions was 10,000 K. We found that the values of \frac{F_{[\text{S II}]6717}}{F_{[\text{S II}]6732}} were 0.88 ± 0.24 and 0.84 ± 0.31 for the components A and B. The large error bar is due to the low S/N (≤5) of these [S II] lines in both apertures. The values of the ratio yielded a range of electron number density 1029−3333 cm−3 and 1166±525 cm−3, respectively, for these two components. Nonetheless, these densities are much higher than those typical of local H II regions n_e ~ 100 cm−3 (e.g., Zaritsky et al. 1994). The electron density of J0900+2234 is similar to that in the lensed galaxies, the Cosmic Horseshoe and the Clone, which is also derived from the ratio of [S II] double lines (Hainline et al. 2009). The high electron density was also found in the Cosmic Horseshoe with 5000–25,000 cm−3 derived from the ratio of C III][\lambda\lambda1906, 1908 doublet (Quider et al. 2009). The high electron density implies the compact size of the H II regions in the high-z galaxies. If these high-z H II regions follow a similar electron density–size relation to that found in the local galaxies (Kim & Koo 2001), their sizes should be less than 1 pc.

5.6. Virial Mass and Gas Mass

The width of the emission lines can be used to probe the dynamics and the total mass of the parent galaxy. By fitting the emission lines (e.g., Hα, [O III]) as Gaussian profiles, we found that the FWHMs of Hα of A and B knots were 19.0 A and 21.8 Å. These observed FWHMs were corrected by subtracting the instrument resolution (∼16 Å) in quadrature. The corrected FWHMs were converted to the 1D velocity dispersion with \sigma = FWHM/2.355 \times c/\lambda. The values of \sigma for the A and B knots were 66±5 km s−1 and 95±6 km s−1, respectively. We averaged the \sigma components of A and B to estimate the velocity dispersion of J0900+2234, which is 81 ± 4 km s−1. Our velocity dispersion is about 30% lower than that in a sample of z ~ 2 star-forming galaxies (Erb et al. 2003), where a mean velocity dispersion of ∼110 km s−1 was found.

The mass of the galaxies can be estimated by assuming a simplified case of a uniform sphere (Pettini et al. 2001)

\[ M_{\text{vir}} = \frac{5\sigma^2 r_{1/2}}{G}, \]

\[ M_{\text{vir}} = 1.2 \times 10^{10} M_{\odot} \left( \frac{\sigma}{100 \text{ km s}^{-1}} \right)^2 \frac{r_{1/2}}{\text{kpc}}, \]

where G is the gravitational constant and r_{1/2} is the half-light radius, which is 7.4 ± 0.8 kpc from the lens model. We find that the dynamical mass of J0900 + 2234 is (5.8 ± 0.9) \times 10^{10} M_{\odot}, an upper limit since the line-emitting gas may not be in virial equilibrium with the gravitational potential of the galaxy.

Using the global Kennicutt–Schmidt law (Kennicutt et al. 1998), we convert the surface gas density (Σ_{\text{gas}}) with the SFR derived from Hα:

\[ \Sigma_{\text{gas}} = 1.6 \times 10^{-27} \left( \frac{\Sigma_{\text{H} \alpha}}{\text{erg} \text{ s}^{-1} \text{ kpc}^{-2}} \right)^{0.71} M_{\odot} \text{ pc}^{-2}, \]

where \Sigma_{\text{H} \alpha} \sim L_{\text{H} \alpha}/r_e^2 is the surface density of Hα luminosity (Erb et al. 2006b; Finkelstein et al. 2009). Then the gas mass, M_{\text{gas}}, can be derived from \Sigma_{\text{H} \alpha} \times r_e^2, which is (5.1 ± 1.1) \times 10^{10} M_{\odot}. The gas fraction, f_{\text{gas}} = M_{\text{gas}}/(M_{\text{gas}} + M_{\text{stellar}}), is 0.74 ± 0.19. Erb et al. (2006a) found the gas fraction increases when the stellar mass decreases in the UV-selected star-forming galaxies at z ~ 2. The gas fraction in J0900+2234 is higher than the mean gas fraction (0.48 ± 0.19) of Erb et al.’s (2006a) galaxies in a similar stellar mass bin ((1.5 ± 0.3) \times 10^{10} M_{\odot}), but still 1σ consistent. The total baryonic mass M_{\text{gas}} + M_{\text{stellar}} is (6.9 ± 1.1) \times 10^{10} M_{\odot}, which is in the agreement with the dynamic mass.

5.7. Measurement Uncertainty

The main uncertainty in the measurement of the extinction and abundance is from the uncertainties in the measurements of the weak emission lines (e.g., Hβ and S II) in the observed NIR. There are many prominent sky emission lines in the
NIR, especially in the $H$-band, which can contaminate our line measurements, especially for the weak emission lines. In the LUCIFER spectra of J0900+2234, the $H\beta$ sits near the blue cut of the $H$-band, where there are several moderate strong sky emission lines and the instrument efficiency is low, which contributes large flux errors ($S/N < 5$) and underestimates the fluxes. The higher $E_\alpha(B - V)$ value of the A (fainter) component and systematically lower metallicities estimated from O3N2 index compared to those from the N2 index may imply that the flux of $H\beta$ is underestimated.

The systematic uncertainty of SFR, associated with the absolute flux of the $H\alpha$, is mainly due to the uncertainties in the absolute calibration of the NIR spectra. We calibrated the spectra with an $AV$ star, and scaled the spectral flux to the $V$-band, where there are several moderate strong emission-line gas suffers an extinction of $(S/N < 5)$ and underestimates/overestimates the fluxes. The higher $E_\alpha(B - V)$ value of the A (fainter) component and systematically lower metallicities estimated from O3N2 index compared to those from the N2 index may imply that the flux of $H\beta$ is underestimated.

### 6. CONCLUSIONS

We present LBT/LUCIFER 1 NIR (rest-frame optical) imaging and spectroscopy of the lensed galaxy J0900+2234 ($z = 2.03$). The lensed components A and B were placed in the slit to obtain NIR spectra covering 1.40 to 2.20 $\mu$m. The detailed physical properties of the lensed star-forming galaxy were studied using the rest-frame optical spectra (Table 5). We summarize the main results as follows.

1. The new imaging was used to construct a lensing model.
2. The magnification factor for the fluxes of the lensed galaxies (A plus B) is estimated to be 4.8.
3. A new lensed arc A1 was discovered by the deep NIR $J$, $H$, and $Ks$-band images. The colors and position imply that this arc does not have the same source galaxy as the other four components discovered previously, suggesting the presence of a rare double Einstein ring. Follow-up spectroscopy shows that the C component does not have the same source galaxy as A and B.
4. We fitted the optical and NIR broadband photometry to theoretical stellar population spectral templates (BC03), and found the galaxy age to be 180 Myr, $E_\alpha(B - V) = 0.07$ ($E_\alpha(B - V) = 0.20$) for the A (B) component. The stellar mass is $1.9 \times 10^{10} M_\odot$, and the intrinsic luminosity of the galaxy is $L/L^* \approx 5$–10.
5. Using the flux ratio of $H\alpha$ and $H\beta$, we found that the emission-line gas suffers an extinction of $E_\alpha(B - V)$ of 0.84 $\pm$ 0.31 (0.59 $\pm$ 0.08) for the A (B) component, which is much higher than $E_\alpha(B - V)$. This result implies that there is more extinction toward the ionized gas than the stellar continuum.

### Table 5

| Knots | Age (Myr) | $E_\alpha(B - V)$ | $Z_{\text{N2}}$ | $Z_{\text{O3N2}}$ | $n_e$ \left(\text{cm}^{-3}\right)$ | SFR$_{\text{H}\alpha}$ \left(M_\odot \text{yr}^{-1}\right)$ | SFR$_{\text{CN}}$ \left(M_\odot \text{yr}^{-1}\right)$ | log(M$_{\text{stellar}}$) \left(M_\odot\right)$ | log(M$_{\text{gas}}$) \left(M_\odot\right)$ | log(M$_{\text{vir}}$) \left(M_\odot\right)$ |
|-------|-----------|------------------|---------------|----------------|---------------------|-----------------|-----------------|-----------------|-----------------|----------------|
| A     | 180       | 0.07             | 0.84 $\pm$ 0.31 | 0.27 $\pm$ 0.13 | 0.21 $\pm$ 0.08   | $1029^{+3333}_{-669}$ $^{+7020}_{-855}$ | 365 $\pm$ 69    | 203 $\pm$ 38    | 10.28           | 10.71           | 10.76           |
| B     | 180       | 0.20             | 0.59 $\pm$ 0.08 | 0.35 $\pm$ 0.15 | 0.26 $\pm$ 0.09   | $1166^{+855}_{-7020}$ | ...             | ...             | ...             | ...             | ...             |

### Note.

A $^*$ This value is derived from the average of the A and B components.

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