NATURE OF THE STRONGLY LENSED SUBMILLIMETER GALAXY SMM J14011+0252¹

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ABSTRACT

We have carried out near-infrared JHK spectroscopy of the gravitationally lensed submillimeter galaxy SMM J14011+0252 at z = 2.565, using the OH-airglow suppressor and the Cooled Infrared Camera and Spectrograph for OHS on the Subaru Telescope. This object consists of two optical components, J1 and J2, which are lensed by the cluster Abell 1835. J1 suffers additional strong lensing by a foreground galaxy at z = 0.25 in the cluster. The rest-frame optical Hα, Hβ, and [O ii] λ3727 lines are detected in both J1 and J2, and [N ii] λ6583, 6583 lines are also detected in J1. A diagnosis of emission-line ratios shows that the excitation source of J1 is stellar in origin, consistent with previous X-ray observations. The continua of J1 and J2 show breaks at rest-frame 4000 Å, indicating a relatively young age. Combined with optical photometry, we have carried out model-spectrum fitting of J2 and find that it is a very young (∼50 Myr) galaxy of rather small mass (∼10⁸ M☉) that suffers some amount of dust extinction. A new gravitational lensing model is constructed to assess both the magnification factor and contamination from the lensing galaxy of the component J1, using a Hubble Space Telescope F702W image. We have found that J1 suffers strong lensing with magnification of ∼30, and its stellar mass is estimated to be ∼10⁸ M☉. These results suggest that SMM J14011+0252 is a major merger system at high redshift that undergoes intense star formation but is not a formation site of a giant elliptical galaxy. Still having plenty of gas, it will transform most of the gas into stars and will evolve into a galaxy of 10¹¹ M☉. Therefore, this system is possibly an ancestor of a present-day, less massive galaxy such as a mid-sized elliptical galaxy or a spiral galaxy.

Key words: galaxies: formation — galaxies: individual (SMM J14011+0250) — galaxies: starburst — gravitational lensing

1. INTRODUCTION

Since the discovery of a large population of Lyman break galaxies (LBGs; Steidel et al. 2003), the question of whether we are seeing the majority of the high-z stellar population or whether more stars are hidden in dusty star-forming galaxies has been raised. It is expected that massive galaxy formation at high z may cause rapid chemical evolution and dust enrichment, leading to a dusty phase like ultraluminous infrared galaxies (ULIRGs), which emit most of their energy in the far-IR. Such objects are supposed to suffer from severe dust extinction, are unable to be picked up as LBGs (defined by a spectral break in the rest-frame UV), and can only be detected at far-infrared to submillimeter wavelengths.

Deep submillimeter surveys by the Submillimetre Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope have revealed a large population of dusty galaxies at high z whose far-IR luminosity exceeds 10¹² L☉, satisfying the criterion of ULIRGs (see Blain et al. 2002 and references therein). Their optical to near-IR (NIR) color is often red, and some of them display no optical/NIR counterpart even when observed with 8–10 m telescopes (Ivison et al. 2002; Fox et al. 2002; Frayer et al. 2004). X-ray observations reveal that some of them contain type 2 active galactic nuclei (AGNs), but their contribution to the total luminosity is not clear (Alexander et al. 2003). Submillimeter-to-radio flux ratios indicate that these objects lie at z > 1 (Lilly et al. 1999; Gear et al. 2000; Hall et al. 2001; Smail et al. 2002; Ivison et al. 2002; Fox et al. 2002), and spectroscopic follow-ups of radio-selected sources reveal their median redshift to be around 2.4 (Chapman et al. 2003). These objects are therefore thought to be an important population for probing the star formation history of the universe. Because of their red color and faintness, spectroscopic observations are time consuming, so there is only a small sample of spectroscopically observed objects in the NIR (Ivison et al. 2000, hereafter I00; Frayer et al. 2003; Smail et al. 2003a, 2003b; Tezca et al. 2004; Simpson et al. 2004). However, spectroscopy in the NIR is important because it covers rest-frame optical wavelengths, which provide us with important information about the physical status, ionizing photons, and stellar population of these galaxies. We therefore carried out low-resolution NIR spectroscopic observations of SMM J14011+0252, one of the brightest submillimeter galaxies at high z.

SMM J14011+0252 was discovered behind the cluster Abell 1835 (z = 0.25) as a weakly lensed object (Smail et al. 1998; Barger et al. 1999; Frayer et al. 1999). Its intrinsic far-IR luminosity of 7 × 10¹² L☉ indicates that this is an ULIRG, and the inferred star formation rate (SFR) is a few times 10¹⁰ M☉ yr⁻¹ (100). It consists of two optical/NIR components, J1 and J2. They both lie at the same redshift of z = 2.56, and their separation is 2.1′. Both are red in the rest-frame optical (R – K = 3.8 for J1 and 3.2 for J2), and J1 is also red in the rest-frame UV (U – R = 2.1), whereas J2 is bluer (U – R = 1.1). Both show only weak Lyα emission (I00). No other emission line is detected in the rest-frame UV, but strong Hα + [N ii] λ6548, 2002; Frayer et al. 2004). X-ray observations reveal that some of them contain type 2 active galactic nuclei (AGNs), but their contribution to the total luminosity is not clear (Alexander et al. 2003). Submillimeter-to-radio flux ratios indicate that these objects lie at z > 1 (Lilly et al. 1999; Gear et al. 2000; Hall et al. 2001; Smail et al. 2002; Ivison et al. 2002; Fox et al. 2002), and spectroscopic follow-ups of radio-selected sources reveal their median redshift to be around 2.4 (Chapman et al. 2003). These objects are therefore thought to be an important population for probing the star formation history of the universe. Because of their red color and faintness, spectroscopic observations are time consuming, so there is only a small sample of spectroscopically observed objects in the NIR (Ivison et al. 2000, hereafter I00; Frayer et al. 2003; Smail et al. 2003a, 2003b; Tezca et al. 2004; Simpson et al. 2004). However, spectroscopy in the NIR is important because it covers rest-frame optical wavelengths, which provide us with important information about the physical status, ionizing photons, and stellar population of these galaxies. We therefore carried out low-resolution NIR spectroscopic observations of SMM J14011+0252, one of the brightest submillimeter galaxies at high z.
6583 lines exist in the NIR spectra (Ivison et al. 2001). A Hubble Space Telescope (HST) F702W image reveals a more complex structure for J1, consisting of several bright knots surrounded by an extended diffuse component with an extremely red object (ERO) component (J1n) elongated toward the north (Ivison et al. 2001). Integral field spectroscopy in the JHK bands shows an extended Hα emission cloud toward J1n (Tecza et al. 2004). A continuum break at rest-frame 4000 Å is found in J1, which indicates recent (~200 Myr) massive star formation activities.

Radio observations detect CO(3–2) (Frayer et al. 1999; Ivison et al. 2001; Downes & Solomon 2003) and CO(7–6) (Downes & Solomon 2003) lines at z = 2.565, which imply strong star formation activity. The detection of CO(7–6) indicates that the temperature of the gas cloud is 30–40 K, and its density is $n_{H_2} \sim 2000$ cm$^{-3}$ (Downes & Solomon 2003). The CO emission is extended over 2.7 × $<0.5^\prime$ and centered at J1 (Downes & Solomon 2003). A deep X-ray observation by Chandra shows no sign of X-ray emission (Fabian et al. 2000), suggesting that this object does not harbor a luminous AGN.

In addition to the above, a detailed reanalysis of the optical spectrum reveals several absorption features at $z = 0.25$, including Ca $\Pi$ H and K (I. Small 2003, private communication; Downes & Solomon 2003). This suggests that the main component of J1 is a foreground evolved galaxy, possibly an elliptical galaxy in Abell 1835, and that the other knots of J1 are strongly lensed images of the submillimeter galaxy at $z = 2.565$. Downes & Solomon (2003) estimated the magnification factor to be ~25 from their CO observations.

Here, we report results of low-resolution NIR JHK spectroscopy of J1 and J2, using OH-airglow suppressor (OHS; Iwamuro et al. 2001) and the Cooled Infrared Camera and Spectrograph for OHS (CISCO; Motohara et al. 2002) installed at the 8.2 m Subaru Telescope (Iye et al. 2004). Thanks to the high sensitivity of the OH-airglow suppression technique combined with the 8 m aperture, high signal-to-noise ratio (S/N) continuum spectra from rest-frame 3000 to 6500 Å with several strong emission lines are obtained.

We describe our observations and data reductions in § 2, display results in § 3, construct a new gravitational lensing model and discuss its implications for the nature of this object in § 4, and summarize our results in § 5. The values $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_{\Lambda} = 0.73$ are assumed throughout this paper.

2. OBSERVATIONS AND DATA REDUCTIONS

2.1. K-Band Imaging and Spectroscopy

Our K'-band imaging and K-band spectroscopy were carried out on 2002 February 28, with CISCO mounted at the IR Nasmyth focus of the Subaru Telescope. The optical Nasmyth secondary mirror was used, and the pixel scale was 0.011 pixel$^{-1}$.

The K'-band images were taken with a single exposure time of 20 s, and the telescope was nodded after every three frames by 10$^\prime$. The K'-band images with a 0.765 slit, providing wavelength resolution of 400 at 2.15 μm. The position angle of the slit was set at $-69^\prime$ to place both J1 and J2 on the slit. A total of 12 frames were acquired for each exposure. The exposure time of 240 s. Then, the A0 star SAO 120250 was observed for correction of the atmospheric and instrumental transmission curves.

2.2. H-Band Imaging and JH-Band Spectroscopy

Our H-band imaging and JH-band spectroscopy were carried out on 2002 March 1 and 2 and May 18, with OHS and CISCO mounted at the IR Nasmyth focus of the Subaru Telescope. The optical Nasmyth secondary mirror was used, and the pixel scale was 0.0111 pixel$^{-1}$.

The H-band images were taken with OHS in the imaging mode (see Iwamuro et al. 2001) before the spectroscopic observations. The single exposure time was 50 s, and the telescope was nodded after every three frames by 10$^\prime$ in the direction of the dark lane of OHS, which is the region in which the OH airglow is suppressed. A total of six frames were acquired each day. For flux calibration, FS 135 was observed after the observations on March 1 and 2, and FS 141 on May 18. The seeing size was 0.7–0.8.

The JH-band spectra were acquired using a 0.95 slit, providing resolution of 210 at 1.65 μm. The single exposure time was 1000 s, and the telescope was nodded after each exposure by 10$^\prime$ along the slit. The position angle of the slit was again set at $-69^\prime$ on March 1 and 2 to observe J1 and J2 simultaneously. On May 18, the position angle was set at $24^\prime$ to observe J1 and J1n. The total exposure time was 6000 s on March 1, 4000 s on March 2, and 8000 s on May 18. The F0 star SAO 120154, A0 star SAO 120250, and F5 star SAO 120186 were observed after the target on March 1, 2, and May 18, respectively, to correct for the atmospheric and instrumental transmission curves. The log of the spectroscopic observations is summarized in Table 1.

2.3. Data Reductions

The imaging data are reduced in a standard procedure of flat fielding, sky subtraction, bad-pixel correction, residual sky subtraction, and shift-and-add. Photometry is performed in an aperture of the same size as the slit width and length used in the JH-band spectroscopy. The position angle of the aperture is set at $-69^\prime$. The measured flux is summarized in Table 2. The spectroscopic data are reduced in a standard procedure of flat fielding, sky subtraction, bad-pixel correction, and residual sky subtraction. They are then corrected for the atmospheric and instrumental transmission curves and are co-added to create final frames. Spatial widths of the aperture to extract one-dimensional spectra are 2′′ for J1 and 1′′ for J2. In the K-band, we use a 0.765 slit, providing wavelength resolution of 400 at 2.15 μm. The position angle of the slit was set at $-69^\prime$ to place both J1 and J2 on the slit. A total of 12 frames were acquired for each exposure. The exposure time of 240 s. Then, the A0 star SAO 120250 was observed for correction of the atmospheric and instrumental transmission curves.

| Target | Date       | Band | $t_{\exp}$ (s) | P.A. (deg) |
|--------|------------|------|---------------|------------|
| J1/J2  | 2002 Feb 28| K    | 4800          | -69        |
| J1/J2  | 2002 Mar 1 | JH   | 6000          | -69        |
| J1/J2  | 2002 Mar 1 | JH   | 4000          | -69        |
| J1/J1n | 2002 May 18| JH   | 8000          | 24         |

| Component | Aperture (arcsec) | $F_{\lambda, K}$ \(10^{-18}\) W m$^{-2}$ μm$^{-1}$ | $F_{\lambda, H}$ \(10^{-18}\) W m$^{-2}$ μm$^{-1}$ |
|-----------|------------------|---------------------------------|---------------------------------|
| J1        | 0.95 x 2.2       | 9.2 ± 0.5                       | 12.2 ± 0.7                     |
| J2        | 0.95 x 1.7       | 2.4 ± 0.4                       | 3.8 ± 0.5                      |
wavelength calibration is carried out using the airglow lines in the raw frames. In the $JH$ band, because almost all the airglow lines are significantly eliminated by OHS, wavelength calibration is done using a pixel-wavelength relation obtained by previous observations of CISCO without OHS, for which the airglow lines are available. The systematic error of this pixel-wavelength relation is estimated to be less than 0.5 pixels (<3 Å). The flux of the spectra is calibrated by the photometry of the $H$- and $K'$-band imaging in Table 2.

2.4. HST WFPC2 Imaging

We also obtained archived HST WFPC2 F702W data of the Abell 1835 field (P.I.: J.-P. Kneib; Proposal ID: 8249) to investigate morphology and optical magnitude. All the frames with 2500 s exposure each are combined into a single frame after cosmic-ray rejection. The total exposure time is 7500 s.

3. RESULTS

The final $JHK$ spectra of J1 and J2 extracted from the February and March data are shown in Figure 1. Although the wavelength resolution is lower ($\lambda/\Delta\lambda = 200–400$) than that of Tecza et al. (2004; $\lambda/\Delta\lambda \sim 1500$), the quality of the continuum spectra is greater in the $JH$ band because of the high sensitivity of OHS. In J1, we detect strong H$\alpha$ + [N ii] $\lambda\lambda6548,6583$ and relatively faint [O ii] $\lambda3727$ and H$\beta$. No [O ii] $\lambda\lambda4959,5007$ is found. In J2, H$\alpha$, H$\beta$, and [O ii] are detected, but all the lines are weaker than those in J1. No line is resolved with the low resolution of OHS/CISCO, which is 750 km s$^{-1}$ in the $K$ band and 1400 km s$^{-1}$ in the $H$ band. The $JH$-band spectrum of J1 taken in May is identical to that taken in March, with weak H$\beta$ and [O ii] without [O iii] lines. J1n is not detected.

We next carry out line fitting with Gaussian profiles to estimate their redshifts, fluxes, and equivalent widths. We also deblend H$\alpha$ and [N ii], which are merged because of the low resolution, assuming [N ii] $\lambda6583$/[N ii] $\lambda6548 = 3.0$. Because the S/N of the spectrum is low, line widths are fixed to the resolving power determined by the slit width. Results are given in Table 3, and fitted profiles of J1 are shown in Figure 2. We also estimate an 1 $\sigma$ upper limit of the line flux of [O iii] $\lambda5007$ in J1 to be $2.0 \times 10^{-20}$ W m$^{-2}$. The lines of J2 are weaker, and the S/N is quite low. However, because the redshifts of all the lines match within 1 $\sigma$ errors, we conclude that these detections are real.

4. DISCUSSION

4.1. Emission-Line Cloud of J1

A diagram of H$\alpha$/[N ii] $\lambda6583$ and [O iii] $\lambda5007$/H$\beta$ is shown in Figure 3. The line ratios indicate that the emission-line cloud of J1 is ionized/excited by massive stars and not by a strong active galactic nucleus (AGN), which is consistent with the X-ray observations showing no sign of a luminous AGN unless it is Compton thick (Fabian et al. 2000).

The Balmer decrement is measured to be H$\alpha$/H$\beta = 4.0 \pm 2.2$. If we assume the intrinsic line ratio of a star-forming region to be 2.9 (Case B, $T = 10^4$ K; Osterbrock 1989) and adopt the SMC extinction curve (Pei 1992), the dust extinction is estimated to be $E(B-V) = 0.36\pm0.16$. Because of the large errors in the line fluxes, this value is quite insecure. Nevertheless, this indicates that the H$\beta$ region suffers extinction of $A_V \sim 1$.

A lower limit of the metallicity can be assessed by the O3N2 or R$_{23}$ estimators. The metallicity derived from O3N2 is $12 + \log (O/H) > 8.7$ (Pettini & Pagel 2004), whereas that from $R_{23}$ is $12 + \log (O/H) > 8.9$ (Kobulnicky et al. 1999). These

| TABLE 3 |

| LINE | $\lambda_{rest}$ (Å) | LINE FLUX $(10^{-19}$ W m$^{-2}$) | CONTINUUM FLUX $(10^{-18}$ W m$^{-2}$ μm$^{-1}$) | EW$_{rest}$ (Å) | $z$ |
|------|---------------------|-------------------------------|---------------------------------|----------------|----|
| J1   |                     |                               |                                 |                |    |
| H$\alpha$ | 6563               | $1.3 \pm 0.4$               | $8.9 \pm 1.8$               | 42             | 2.565 ± 0.001 |
| [N ii] | 6583               | $0.62 \pm 0.39$            | $8.9 \pm 1.8$               | 20             | 2.565 ± 0.001 |
| H$\beta$ | 4861               | $0.33 \pm 0.12$            | $10.9 \pm 0.5$              | 8.5            | 2.562 ± 0.002 |
| [O ii] | 3727               | $0.41 \pm 0.13$            | $14.0 \pm 0.6$              | 8.1            | 2.563 ± 0.003 |
| J2   |                     |                               |                                 |                |    |
| H$\alpha$ | 6563               | $0.48 \pm 0.34$            | $1.9 \pm 1.1$               | 72             | 2.562 ± 0.003 |
| [N ii] | 6583               | $0.27 \pm 0.33$            | $1.9 \pm 1.1$               | 40             | 2.562 ± 0.003 |
| H$\beta$ | 4861               | $0.11 \pm 0.09$            | $3.5 \pm 0.4$               | 9.0            | 2.561 ± 0.005 |
| [O ii] | 3727               | $0.26 \pm 0.09$            | $3.6 \pm 0.4$               | 20             | 2.564 ± 0.003 |
results are consistent with those of Tecza et al. (2004), suggesting that this system is well polluted by metals supplied from the starburst activities.

4.2. Gravitational Lensing Model

The HST F702W image is shown in Figure 4. It can be seen that J1 consists of many subcomponents. We name them J1a, J1b, J1c, and J1d, as labeled in the figure.

Recently, I. Smail (2003, private communication) found Ca ii H and K and other absorption lines at \( z = 0.25 \) in the optical spectrum of J1, which suggests J1 to be contaminated and strongly lensed by a foreground galaxy. In addition, as seen in the H \( \alpha \) image (Fig. 1 of Tecza et al. 2004), the line brightness becomes weak at the position of J1c, and a “hole” is seen there. These results indicate that J1c is a member of Abell 1835 at \( z = 0.25 \) and causes a strong lensing effect on J1 at \( z = 2.565 \).

Downes & Solomon (2003) claimed that the estimated brightness temperature of CO(3–2) is much smaller than that expected from the CO line ratio and argued that this is due to the gravitational lensing effect. They roughly estimate the magnification factor to be \( \lambda C24 \) \( \lambda C25 \). They also constructed a simple gravitational lensing model using the HST F702W image, assuming that J1a, J1b, J1n, and J2 are all the lensed image of a single object. However, this model failed to reproduce the position of the observed components. In addition, it is known that the redshifts of J1 and J2 differ slightly (Ivison et al. 2000; Tecza et al. 2004), and they are thought to be different objects. We therefore propose a new gravitational lensing model, assuming that J1a, J1b, and J1d are lensed images of a single object by J1c and Abell 1835. Hereafter, we refer to the lensing galaxy at \( z = 0.25 \) as “J1c” and distinguish it from the lensed galaxy J1 at \( z = 2.565 \).

4.2.1. Lensing Model by GRAVLENS

We use the gravitational lensing software GRAVLENS (Keeton 2001). The model potential consists of two components, J1c and Abell 1835; both lie at \( z = 0.25 \). The potential of J1c is assumed to be an isothermal ellipsoid with core radius \( b = 0 \), whereas that of Abell 1835 is a Navarro-Frenk-White model with parameters taken from Schmidt et al. (2001).
Fig. 4.—The HST F702W image of SMM J14011+0252. The dotted line indicates the slit position of the OHS/CISCO spectroscopy.

then carry out fitting calculations of the positions and aperture fluxes of J1a, J1b, and J1d by varying the velocity dispersion \( \sigma \), the ellipticity \( e \), and the position angle of the ellipticity \( \theta_\varepsilon \) of J1c. All of the parameters of the lensing model are shown in Table 4. The uncertainty of each parameter is evaluated as follows: We start at the best-fit model and vary a single parameter at a time. For the varied model, \( \chi^2 \) fitting is carried out by varying the position of the source to find the best-fit position. The average displacement between the positions of the best-fit spots and the original spots in the image plane is then calculated, and the error for the parameter is defined to be the value at which the average displacement becomes less than 0.‘1.

Using this model, we also reconstruct the lensed image of J1n, J2, and the extended H\( \alpha \) cloud found by Tecza et al. (2004). Positions and magnification factors of these components are listed in Table 5.

Figure 5 shows the image and source planes of the model. The solid contours show the profile of J1 at \( z = 2.565 \), with an intrinsic diameter of 0.‘1 (0.8 kpc). It can be seen that J1a and J1b in the model image are elongated, whereas in the HST F702W image, they are not. This suggests that the intrinsic size of J1 is smaller than 0.‘1 (0.8 kpc) and that what we are seeing is a kind of a circumnuclear starburst disk like that in a nearby ULIRG. The total magnification factor of J1 is found to be 34.\( ^{+9}_{-5} \). However, we should keep in mind that this magnification factor is that of a point source. If the source is assumed to be extended by 0.‘1, the total magnification factor becomes 26.\( ^{+14}_{-8} \).

Model contours of J1n, J2, and the H\( \alpha \) cloud are plotted with dotted lines. The extended H\( \alpha \) emission line report\ed in Tecza et al. (2004) is well reproduced by a cloud with an intrinsic size of 0.‘2 × 0.‘4 (1.6 kpc × 3.3 kpc) located at 0.‘1 (0.8 kpc) west of J1. Its total magnification factor estimated from our model is 23.\( ^{+4}_{-3} \), assuming that the H\( \alpha \) emission-line region is extended by 0.‘3. This value matches that from the CO emission, which is estimated to be \( \sim 25 \) (Downes & Solomon 2003).

J1e, a counter image of J1 with half the flux of J1d, as well as H\( \alpha \)-d, should appear on the west side of J1c. However, both are not detected in either the HST F702W or H\( \alpha \) images. There are several explanations for this: (1) they are absorbed by dust in the line of sight, presumably in J1c; (2) the real potential of J1c deviates from the model and the flux of J1e and H\( \alpha \)-d are depressed; and (3) J1a, J1b, and J1d are not a multiple image of a single source but different components of a merging source structure. In the last case, the mass of J1c should be much smaller to avoid the multiple lensing. However, because the optical properties of J1c match our model well, as discussed in § 4.2.2, it is unlikely that the mass of J1c is much smaller than our model. We therefore assume that J1e and H\( \alpha \)-d are depressed either by dust or by the shape of the real potential.

4.2.2. Properties of the Lensing Galaxy

To check the feasibility of the gravitational lensing model, we next assess the optical properties of the lensing galaxy J1c and compare them with the model.

The profile of J1c in the HST F702W image is fitted with the Sérsic (1968) profile

\[
I(r) = I_e \exp \left\{ -b_n \left( \frac{r}{r_e} \right)^{1/n} - 1 \right\},
\]

where \( b_n = 1.9992n - 0.3271 \) (Graham 2001). Fitted parameters are \( n = 2.1 \) and \( r_e = 0.‘55 \), and the flux within \( r_e \) is estimated

| Source Name | Positiona (arcsec) | Image Name | Magnification | Positionb (arcsec) |
|-------------|-------------------|------------|---------------|-------------------|
| J1.......... | (24.71, 10.64)    | J1a        | 11            | (−0.59, −0.18)    |
| J1b        | 13                | J1d        | 6.3           | (−0.23, 1.10)     |
| J1c        | 3.1               | (J1c)      | 0(46, −0.21)  |
| J1n......... | (24.38, 11.10)    | J1n        | 4.4           | (−1.00, 2.25)     |
| J2......... | (25.79, 10.93)    | J2         | 5.7           | (1.89, 0.80)      |
| H\( \alpha \)..... | (24.62, 10.57)   | H\( \alpha \)-a | 12       | (−0.78, 0.28)     |
|             |                   | H\( \alpha \)-b | 10        | (−0.44, −0.73)    |
|             |                   | H\( \alpha \)-c | 9.5       | (−0.51, 0.90)     |
|             |                   | (H\( \alpha \)-d) | 2.0     | (0.36, −0.06)     |

Note.—The position of each component is shown in Figure 5. The parenthesized images are those not detected. Note that these magnification factors are calculated assuming that a lensed image is a point source. If the image is extended, the magnification factor becomes smaller (see text).

\( ^a \) Position on the source plane in arcseconds, relative to J1c.

\( ^b \) Position on the image plane in arcseconds, relative to J1c.

### TABLE 4

| Parameter | Value |
|-----------|-------|
| \( \sigma \) | 123\( ^{+10}_{-14} \) km s\(^{-1} \) |
| \( e \) | 0.67\( ^{+0.09}_{-0.10} \) |
| \( \theta_\varepsilon \) | 53\( ^{+6}_{-5} \) deg |
| \( b_n \) | 0(9)\( ^{+0.07}_{-0.18} \) arcsec |

Abell 1835

| Parameter | Value |
|-----------|-------|
| \( r_s \) | 0.64\( ^{+0.05}_{-0.10} \) Mpc |
| \( r_g \) | 0.189\( ^{+0.005}_{-0.015} \) |
| \( dx \) | 44\( ^{+1}_{-5} \) arcsec |
| \( dy \) | 20\( ^{+5}_{-4} \) arcsec |

### TABLE 5

| Source Name | Positiona (arcsec) | Image Name | Magnification | Positionb (arcsec) |
|-------------|-------------------|------------|---------------|-------------------|
| J1.......... | (24.71, 10.64)    | J1a        | 11            | (−0.59, −0.18)    |
| J1b        | 13                | J1d        | 6.3           | (−0.23, 1.10)     |
| J1c        | 3.1               | (J1c)      | 0(46, −0.21)  |
| J1n......... | (24.38, 11.10)    | J1n        | 4.4           | (−1.00, 2.25)     |
| J2......... | (25.79, 10.93)    | J2         | 5.7           | (1.89, 0.80)      |
| H\( \alpha \)..... | (24.62, 10.57)   | H\( \alpha \)-a | 12       | (−0.78, 0.28)     |
|             |                   | H\( \alpha \)-b | 10        | (−0.44, −0.73)    |
|             |                   | H\( \alpha \)-c | 9.5       | (−0.51, 0.90)     |
|             |                   | (H\( \alpha \)-d) | 2.0     | (0.36, −0.06)     |
to be 3.1 μJy. Using spectra of the 2–5 Gyr instantaneous-burst model calculated by PEGASE (Fioc & Rocca-Volmerange 1997), the stellar mass is then estimated to be $1.5-3.8 \times 10^9 M_\odot$.

On the other hand, the projected mass within 1$ r_e$ of J1c estimated from the gravitational lensing model is $3.8 \times 10^9 M_\odot$, using the equation of Kochanek (1995), which contains both stellar mass and the dark matter halo. Considering the dark matter fraction in early-type galaxies of $\approx 0.5$ (Treu & Koopmans 2004), this is a good agreement with the value obtained above, and our gravitational lensing model seems reasonable. In addition, the size ($r_e = 0.5 \sim 2$ kpc) and the velocity dispersion ($\sigma = 123$ km s$^{-1}$) indicate that J1c is a relatively small elliptical galaxy in Abell 1835.

4.3. Spectral Energy Distributions and Model Fitting

To quantify the stellar contents of J1 and J2 together with their star formation history, we combine the optical $BRI$ photometry of I00 with the current spectra to construct spectral energy distributions (SEDs) from the optical to NIR. Because I00 use a 3$''$ aperture for the photometry, whereas our slit size is much smaller, we measured the ratio of the flux between the different aperture sizes in the $R$ band, using the $HST$ F702W image convolved to the 0.7$''$ seeing size of the $JH$-band spectroscopy. This ratio is used to correct all the fluxes of the optical bands in I00. An additional error of 0.1 mag is added to the optical data to account for the systematic uncertainties in the flux calibration of the NIR spectra. The emission lines in the NIR spectra are removed by the Gaussian fitting described in § 3. The obtained SEDs are shown in Figure 6. Continuum breaks at rest-frame 4000 Å are seen in both J1 and J2.

4.3.1. Component J2

We fit the SED of J2 by spectrum templates calculated by PEGASE (Fioc & Rocca-Volmerange 1997) to which an empirical dust extinction law of starburst galaxies by Calzetti et al. (2000) is applied. The free parameters are dust extinction E(B − V), age, and total mass. The initial mass function of Salpeter is adopted. We consider two extreme cases of star formation history: one is an instantaneous burst, and the other is a continuous burst with a duration of 1 Gyr. The results are summarized in Table 6, and the fitted spectra are shown in Figure 6b. J2 is expected to be dominated by a very young population and have formed on the order of $\sim 10^9 M_\odot$ of stars. We must keep in mind that the SED is extracted from a small aperture ($1'' \times 2''$) and what we see is only the central region of J2. The 3$''$ aperture flux in the $K$ band (100) indicates that the obtained mass may be underestimated by a factor of $\sim 3$.

4.3.2. Component J1

To assess the contamination of J1c to the SED of J1, the spectral shape of J1c is assumed to be that of a 2 Gyr instantaneous-burst model. It is scaled by the flux obtained from the $HST$ F702W image and plotted in Figure 6a as the dotted line. This model spectrum of J1c is then subtracted from the SED of J1 to obtain the intrinsic SED, which is shown as the dotted points in Figure 6a.

It can be seen that the $B$-band flux has little contamination from J1c. This agrees with the result of I00 that the peak of J1 in the $U$ band is slightly offset toward the east from that in the $R$ band, indicating that J1 at $z = 2.565$ dominates the $U$- and $B$-band fluxes.

We next estimate the total intrinsic flux of J1 in the $K$ band to be 25 μJy by subtracting the model spectrum of J1c obtained above from the $K$-band flux of I00 (3$''$ aperture). Assuming the magnification factor of J1 to be 5 as a lower limit and the shape of the SED to be same as that of J2, the upper limit of the stellar mass in J1 is estimated to be $\sim 10^9 M_\odot$. If more dust exists in this system than in J2, this upper limit of the stellar mass will become larger.

Fig. 5.—Gravitational lensing model image of (a) the image plane superposed on the $HST$ F702W image and (b) the source plane. The solid contours show the profile of J1 at $z = 2.565$ with an intrinsic diameter of 0$''$1 (0.8 kpc), whereas the dotted contours show that of J1n, J2, and the Hα emission-line cloud. Intrinsic sizes of J1n and J2 are 0$''$2 (1.6 kpc), whereas that of the Hα cloud is an ellipse of 0$''$2 × 0$''$4 (1.6 kpc × 3.3 kpc).
4.3.3. Formation Site of a Normal Galaxy?

The amount of the gas reservoir in J1 is a few times $10^9 M_\odot$, estimated from the CO observations (Downes & Solomon 2003). Therefore, if SMM J14011+0252 is a place where a massive galaxy of $\sim 10^{12} M_\odot$ is being assembled, a stellar mass of $\sim 10^{12} M_\odot$ must have already been assembled and hidden in dust. This is more than 100 times as much as the value calculated above, and an extinction of $A_V > 50$ is required throughout the galaxy. Although such an amount of extinction is broadly observed in the circumnuclear starburst disk in nearby ULIRGs (e.g., Genzel et al. 1998), their size is smaller (<0.5 kpc), and their stellar and gas masses are comparable to each other and much smaller ($\sim 10^{10} M_\odot$) than those required in SMM J14011+0252. Therefore, considering the difficulty of hiding a stellar component of $10^{12} M_\odot$ in dust, it is more probable that SMM J14011+0252 is a site of less massive ($\lesssim 10^{11} M_\odot$) galaxy formation.

If we assume that the submillimeter radiation is emitted from the same region that emits CO or H$_2$ and its magnification factor is on the order of 30, the intrinsic 850 $\mu$m flux is $\sim 0.5$ mJy. This is the upper limit for the flux that most of the less massive high-$z$ galaxies such as LBGs are expected to emit (Chapman et al. 2000). Also, the luminosity in the far-IR wavelengths becomes $\sim 10^{12} L_\odot$, which is the same as that of local ULIRGs.

However, readers should keep in mind that the above discussion is based on the uncertain gravitational lensing model, which does not have redshift information for the observed components to settle their membership. The uncertainties in the model parameters are also large, and the calculated total magnification may change by a factor of 2. In addition, there is a possibility that the position of the submillimeter source is offset from that of CO or H$_2$ and it does not suffer a strong lensing effect. In such case, the total magnification is only a factor of 5, and the intrinsic luminosity in far-IR becomes an order of magnitude larger. In that case, this object may be interpreted as a massive and dusty starburst forming a larger mass ($\sim 10^{11} M_\odot$) of stars.

It is likely that the starburst in this system was triggered by an encounter of J1 and J2. If we ignore the radial distance (that is, assuming the distance between J1 and J2 is that observed in the source plane of $12^\prime = 10$ kpc) and assume the encounter to have occurred 50 Myr ago, the projected relative velocity is estimated to be 200 km s$^{-1}$. Considering the radial distance and motion of J1 and J2, this matches the typical relative velocity of 1000 km s$^{-1}$ in a cluster of galaxies.

Therefore, J1 may be a high-$z$ counterpart of the local ULIRGs such as Arp 220, and its submillimeter flux is magnified above the detection limit of SCUBA by the strong lensing effect of J1c. Its total baryon mass is $\sim 10^{10} M_\odot$, and we hypothesize that this object is a less massive forming galaxy at $z \sim 3$ that will evolve into a midsized elliptical galaxy or a spiral galaxy such as the Milky Way.

5. SUMMARY

We have conducted $JHK$ spectroscopy of components J1 and J2 of the gravitationally lensed submillimeter galaxy SMM J14011+0252 at $z = 2.565$ using OHS/CISCO at the Subaru Telescope. H$_\alpha$, H$\beta$, and [O $\alpha$] lines in both J1 and J2 are detected, and [N $\alpha$] $\lambda 6548, 6583$ lines are also detected in J1. No [O $\alpha$] lines

![Fig. 6.—Optical-to-NIR SEDs of (a) J1 and (b) J2. Our data are shown as open circles, whereas the data taken from I00 are shown as filled circles. (a) The dotted line shows the assumed model spectrum of $z = 0.25$ lensing galaxy, and the dotted points show the lens-subtracted SED. (b) The dashed and dotted lines show the result of the fitting by instantaneous-burst and 1 Gyr continuous-burst models, respectively.](image)

| Model                  | Age (Myr) | $E(B-V)$ | Stellar Mass ($M_\odot$) | Total Mass ($M_\odot$) | SFR ($M_\odot$ yr$^{-1}$) | $\chi^2$ |
|------------------------|-----------|----------|--------------------------|------------------------|---------------------------|----------|
| Instantaneous...........| 8         | 0.33     | $6.1 \times 10^7$        | $6.2 \times 10^7$      | 0.0                       | 16.85    |
| 1 Gyr continuous........| 70        | 0.40     | $1.7 \times 10^8$        | $2.4 \times 10^9$      | 4.4                       | 22.83    |

Note.—Mass and SFRs are corrected for the gravitational lensing effect with the magnification factor of 5.7.
are found. From the emission-line diagnosis, the emission-line cloud of J1 is shown to be ionized/excited by stellar UV radiation, not by an AGN. The continuum is detected in both J1 and J2, and the Balmer breaks are clearly seen. The SED of J2 is fitted by a model spectrum of a young (~50 Myr) stellar population with some dust extinction.

The new gravitational lensing model is constructed to reproduce the small knots of J1 and also reproduces the morphology of the extended Hα cloud well. This model suggests that J1 may be magnified by a factor of 30 by the elliptical galaxy in Abell 1835. In addition, using this model together with the profile fitting of the lensing galaxy, the stellar mass of J1 at z = 2.565 is estimated to be \( \lesssim 10^{13} M_\odot \). This indicates that SMM J14011+0252 is not a formation site of a present-day massive elliptical galaxy but more like a high-z version of an ULIRG and will become a present-day spiral galaxy or a midsized elliptical galaxy of \( 10^{10} – 10^{11} M_\odot \).

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