Discovery of an Extremely Luminous Dust-obscured Galaxy Observed with SDSS, WISE, JCMT, and SMA

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Abstract

We present the discovery of an extremely luminous dust-obscured galaxy (DOG) at $z_{\text{spec}} = 3.703$, WISE J101326.25+611220.1. This DOG is selected as a candidate of extremely luminous infrared (IR) galaxies based on the photometry from the Sloan Digital Sky Survey and Wide-field Infrared Survey Explorer. In order to derive its accurate IR luminosity, we perform follow-up observations at 450 and 850 $\mu$m using the Submillimetre Common User Bolometer Array 2 on the James Clerk Maxwell Telescope, and at 870 and 1300 $\mu$m using the Submillimetre Array, which enable us to pin down its IR Spectral Energy Distribution (SED). We perform SED fitting using 14 photometric data (0.4–1300 $\mu$m) and estimate its IR luminosity, $L_{\text{IR}}$ (8–1000 $\mu$m), to be $2.2^{+1.5}_{-1.0} \times 10^{12} L_\odot$, making it one of the most luminous IR galaxies in the universe. The energy contribution from an active galactic nucleus (AGN) to the IR luminosity is $94^{+5}_{-9}\%$, which indicates that it is an AGN-dominated DOG. On the other hand, its stellar mass ($M_\star$) and star formation rate (SFR) are $\log(M_\star/M_\odot) = 11.2^{+0.2}_{-0.6}$ and $\log(\text{SFR}/M_\odot \text{ yr}^{-1}) = 3.1^{+0.2}_{-0.1}$, respectively, which means that this DOG can be considered a starburst galaxy in the $M_\star$–SFR plane. This extremely luminous DOG shows significant AGN and star-forming activity that provides us with an important laboratory to probe the maximum phase of the coevolution of galaxies and supermassive black holes.

Key words: galaxies: active – infrared: galaxies – methods: observational

1. Introduction

Galaxies with infrared (IR) luminosity, $L_{\text{IR}}$ (8–1000 $\mu$m), exceeding $10^{12} L_\odot$ shed important light on how galaxies form and evolve throughout the history of the universe. Their IR luminosity is generated by significant star formation (SF) and/or active galactic nucleus (AGN) activity behind a large amount of dust. The strong ultraviolet (UV) and optical radiation due to the SF/AGN activity is absorbed by the surrounding dust, which then re-emits the enormous energy at the IR wavelength. Thanks to the advent of IR satellites such as Infrared Astronomical Satellite (IRAS: Neugebauer et al. 1984), Spitzer Space Telescope (Werner et al. 2004), AKARI (Murakami et al. 2007), Wide-field Infrared Survey Explorer (WISE: Wright et al. 2010), and Herschel Space Observatory (Pilbratt et al. 2010), extreme galaxies with $L_{\text{IR}} > 10^{13} L_\odot$ and $10^{14} L_\odot$ (hyper-luminous IR galaxies (HyLIRGs) and extremely luminous infrared galaxies (ELIRGs), respectively), have been discovered (e.g., Rowan-Robinson 2000; Tsai et al. 2015). Recently, a galaxy (WISE J224612.07-714401.2, hereafter WISE2246) with $L_{\text{IR}} = 2.2 \times 10^{14} L_\odot$ was discovered (Tsai et al. 2015) and found to be one of the most luminous galaxies with multibandwidth data in the universe. Its extreme IR luminosity could indicate that it corresponds to the peak of AGN and/or SF activity, providing the laboratory for understanding the galaxy formation and evolution and connection to their supermassive black holes (SMBHs) under an extreme condition (Hopkins et al. 2008; Ricci et al. 2017b). However, the volume densities of HyLIRGs/ELIRGs are extremely low, and thus wide and deep surveys are required to detect these spatially rare populations.

For discovering extremely luminous IR objects and investigating their physical properties, Toba & Nagao (2016) have performed a systematic HyLIRGs/ELIRGs survey with the Sloan Digital Sky Survey (SDSS) Data Release 12 (DR12: York et al. 2000; Alam et al. 2015) and the ALLWISE catalogs (Cutri et al. 2014). They first selected 67 objects with $i-[22] > 7.0$, where $i$ and [22] are $i$-band and 22 $\mu$m AB magnitude, respectively. This color selection is used for IR-bright dust-obscured galaxies (DOG; e.g., Toba et al. 2015, 2017a, 2017d). They also have spectroscopic redshifts obtained from the SDSS. They then performed Spectral Energy Distribution (SED) fitting for 67 DOGs and estimated their IR luminosities. Consequently, they successfully discovered 24 HyLIRGs and a candidate of an ELIRG, WISE J101326.25+611220.1 (hereafter, WISE1013). Its spectroscopic redshift

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9 Based on the optical multi-color selection, BR 1202–0725 with $L_{\text{FR}}$ (1–200 $\mu$m) = $3.7 \times 10^{14} L_\odot$ at $z = 4.69$ is also known as one of the most luminous galaxies with multibandwidth data (Leipski et al. 2010).

10 The original definition of DOGs was flux density at 24 $\mu$m $> 0.3$ mJy and $R - [24] > 14$ (corresponding to $F_{24}/F_R > 982$), where $R$ and [24] represent Vega magnitudes in the $R$-band and 24 $\mu$m, respectively (Dey et al. 2008). Our DOGs selection criteria is optimized for $i$-band and 22 $\mu$m flux density (see Toba et al. 2015 for more detail.).

11 Given the best-fit SED of WISE1013 (see Figure 2), the estimated flux ratio, $F_{24}/F_R = 1005$ that satisfies the original DOG’s criteria defined by Dey et al. (2008).
Table 1

| Observed Properties of WISE1013 |
|---------------------------------|
| R.A. (SDSS) [J2000.0]           | 10:13:26.24 |
| Decl. (SDSS) [J2000.0]          | +61:12:17.96 |
| Redshift (SDSS)                 | 3.703 ± 0.003 |
| SDSS u-band [μJy]               | 1.26 ± 0.87 |
| SDSS g-band [μJy]               | 3.47 ± 0.47 |
| SDSS r-band [μJy]               | 13.70 ± 0.67 |
| SDSS z-band [μJy]               | 13.58 ± 0.95 |
| SCUBA-2 870 μm [mJy]            | 21.09 ± 4.03 |
| WISE 3.4 μm [mJy]               | 0.05 ± 0.01 |
| WISE 4.6 μm [mJy]               | 0.13 ± 0.01 |
| WISE 12 μm [mJy]                | 3.30 ± 0.16 |
| WISE 22 μm [mJy]                | 10.70 ± 0.98 |
| AKARI 90 μm [mJy]               | <0.33b |
| SCUBA-2 450 μm [mJy]            | 46.00 ± 8.05c |
| SCUBA-2 850 μm [mJy]            | 13.35 ± 0.67 |
| SMA 870 μm [mJy]                | 13.60 ± 2.72 |
| SMA 1.3 mm [mJy]                | 6.49 ± 1.30 |
| $L_{IR}$ (8-1000 μm) [L$_{⊙}$] | 2.2 ± 1.0 × 10$^{14}$ |
| $L_{IR}$ (8-1000 μm) [L$_{⊙}$] | 2.0 ± 1.0 × 10$^{14}$ |
| $L_{IR}$ (8-1000 μm) [L$_{⊙}$] | 1.2 ± 0.6 × 10$^{13}$ |
| log $M_*$ [M$_{⊙}$]             | 9.0 ± 0.6 |
| logSFR (M$_{⊙}$ yr$^{-1}$)      | 3.1 ± 0.1 |

Notes.

* Used for upper limit (see Section 3.2).

b 3σ upper limit.

c Includes both systematic error and rms noise.

is $z_{spec} = 3.703$ and the estimated IR luminosity is $L_{IR} = 1.1 \times 10^{15}$ L$_{⊙}$ (see the lower right panel of Figure 6, and the bottom panel of Figure 8 in Toba & Nagao 2016). However, since they did not have deep rest-frame mid-IR (MIR) and far-IR (FIR) photometry, the derived IR luminosity has a large uncertainty. In order to determine the accurate IR luminosity of this candidate of an “extremely luminous DOG,” FIR and submillimeter data are strongly required.

In this paper, we present follow-up observations of the candidate of an extremely luminous DOG, WISE1013, at 450 and 850 μm using the Submillimetre Common User Bolometer Array 2 (SCUBA-2: Holland et al. 2013) on the James Clerk Maxwell Telescope (JCMT), and at 870 and 1300 μm using the Submillimeter Array (SMA: Ho et al. 2004). Since these observing wavelengths correspond to rest-frame FIR for this object, these observations are critical to constrain the IR-SED. Throughout this paper, the adopted cosmology is a flat universe with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $Ω_M = 0.3$, and $Ω_Λ = 0.7$. Unless otherwise noted, all magnitudes refer to the AB system.

2. Data and Analysis

2.1. A candidate of ELIRGs: WISE1013

WISE1013, a candidate of ELIRGs is selected from the sample in Toba & Nagao (2016). The basic information and the measured fluxes (see Section 2.2) are summarized in Table 1. This object was reported as an extremely red quasar (ERQ) (SDSS J101326.24+611219.7) by Hamann et al. (2017). The authors selected ERQs based on the SDSS and WISE catalogs by adopting a color cut, $(r - [22])_vega > 14$, which is similar to our selection, and conducted a detailed analysis for their spectra. They reported that this object shows a broad CIV $\lambda 1549$ emission line with a blueshift of $>2500$ km s$^{-1}$. That unusual spectrum could indicate that ionized gas is outflowing from the ERQ. Such a phenomenon is often observed in red/dust-obscured AGNs (e.g., Zakamska et al. 2016; Toba et al. 2017c).

2.2. Follow-up Observations with SCUBA-2 and SMA

Imaging at 450 and 850 μm was taken simultaneously with SCUBA-2 on JCMT. The observations were conducted under the Band-1 condition ($\nu_{225}$ GHz < 0.05) on 2017 May 8 and 18, as an urgent program (S17AP002, PI: Y.Toba). We observed WISE1013 in four 30-minute scans using the compact “Daisy” scan pattern. The total on-source time is about 2 hr. During the observations, we observed the nearby radio source IRC+10216 for a pointing check. The pointing offsets are typically about 1″. All data were reduced using the Sub-Millimeter Common User Reduction Facility (Chapin et al. 2013) and the Pipeline for Combining and Analyzing Reduced Data (PICARD: Jenness et al. 2008). We adopted the standard “blank field” configuration, which is optimized for faint point sources. To obtain flux calibration, we observed six calibrators on the same nights under Band-1 weather. The averaged Flux Conversion Factors are 503 ± 88 and 519 ± 26 Jy beam$^{-1}$ pW$^{-1}$ for 450 μm and 850 μm, respectively, and are consistent with the nominal values of 491 and 537 Jy beam$^{-1}$ pW$^{-1}$ (Dempsey et al. 2013). To optimize the detection, we convolved the maps with broad Gaussian kernels (FWHM of 20″ and 30″ for 450 and 850 μm, respectively) and subtracted the convolved maps from the original maps to remove any large structure. Then, we convolved matched-filters to the maps, using Gaussian kernels matched to the instrumental point-spread functions (FWHM of 7.5″ and 14″ for 450 and 850 μm, respectively) to obtain an optimal signal-to-noise ratio. We detect the source at both wavebands.

Observations at 870 μm (345 GHz) and 1.3 mm (240 GHz) were carried out with the SMA on 2016 December 28 (2016B-A003, PI: Y.Toba). In order to observe at 345 GHz and 240 GHz simultaneously, we used the dual frequency mode of the SWARM correlator, which gave the total bandwidth of 12.6 GHz for each receiver. The data were obtained using the compact configuration. The FWHM of the primary beam is 32″ at 345 GHz and 46″ at 240 GHz. The quasar 3c273 was observed for bandpass calibration, and the quasar J1048+717 was observed for phase and amplitude calibration. Absolute flux calibration was performed using Callisto. The uncertainty of flux calibration is 20%. Data reduction was carried out using the IDL-based SMA calibration tool MIR, and imaging was done using the MIRIAD package. The total observing time on WISE1013 is about 2.3 hrs, excluding bad scans. The synthesized beam sizes are $2″.51 \times 1″.67$ at 870 μm and $3″.55 \times 2″.33$ at 1.3 mm by adopting natural weighting of the visibilities. The achieved rms noise levels are 2.1 mJy beam$^{-1}$ and 0.7 mJy beam$^{-1}$ in the 870 μm and 1.3 mm continuum maps, respectively.

The flux measurements of the SCUBA-2 and SMA data were performed using the Common Astronomy Software Applications package (CASA12, ver. 4.7.2). We performed a 2D Gaussian fit for each image and estimated the total fluxes within 10″ × 10″ apertures for the SCUBA-2 data, and

12 https://casa.nrao.edu/
4″ × 4″ apertures for the SMA data. The measured fluxes are listed in Table 1.

3. Results and Discussions

3.1. Multiwavelength Images

Figure 1 shows the multiwavelength images of WISE1013. We note that its u-band magnitude (23.50 mag) is significantly fainter than the magnitude limit (95% completeness for point source) of the SDSS (u-mag = 22.0)\(^{13}\), and we confirmed that there is no detection in the u-band image (Figure 1). This source is a complete dropout at u-band, because of its high redshift, and thus we used the u-band flux density upper limit (see Section 3.2). We confirm that there is no galaxy within a 30″ radius of WISE1013, as shown in the SDSS images (Figure 1) and we have SCUBA-2 and SMA images with high angular resolutions, which give us secure estimates of rest-frame FIR fluxes without suffering from flux contamination of neighborhoods.

3.2. IR Luminosity Derived from the SED Fitting

We estimate the IR luminosity of WISE1013 by using the fitting code SED Analysis using BAYesian Statistics (SEABAS: Rovilos et al. 2014). SEABAS produces a best-fit SED by combining three templates (stellar, AGN, and SF components) based on the maximum likelihood method (see Rovilos et al. 2014; Toba et al. 2017b, for more detail). SEABAS gives stellar templates from Bruzual & Charlot (2003) stellar population models assuming a Chabrier (2003) initial mass function (IMF), and each model are reddened by using a Calzetti et al. (2000) dust extinction law, resulting in the stellar mass and color excess (E(B−V)) of a galaxy as an output. Users can input AGN and SF templates prepared by themselves into the SEABASs code.

For AGN templates, we input the SED library for Silva et al. (2004) as the obscured AGN templates, which consist of four torus templates with varying extinction ranging from N_H = 0, 10^{22}, 10^{23}, and 10^{24} cm^{-2}. We also input the library of Polletta et al. (2007) that provides optically selected AGNs (see Polletta et al. 2007, for more detail). In addition to empirical templates, we input the AGN templates\(^{14}\) created by computing a self-consistent 3D radiative transfer code (Siebenmorgen et al. 2015). In this model, dust can be considered as a clumpy medium or a homogeneous disk, or as a combination of the two. We used the SED library of AGN torus models with a set of model parameters; the viewing angle (θ), the inner radius (r_in), the volume filling factor(η), the optical depth of the clouds (τ_{V,cl}), and the optical depth of the disk midplane (τ_{V,mid}). For the SF templates, we input the library of Chary & Elbaz (2001), Polletta et al. (2007), and Mullaney et al. (2011), in which we cropped at rest-frame wavelengths below 4.5 μm to avoid a duplication of the emission from the stellar component in the same manner as Rovilos et al. (2014).

We took into account the equilibrium between the energy absorbed from the stellar component and the energy emitted in the IR by the SF. Although WISE1013 was not detected by the AKARI FIR all-sky survey (Yamamura et al. 2010), we used the AKARI90 μm flux 3σ upper limit. Also, we used the SDSS u-band flux upper limit. We performed the SED fitting using

\(^{13}\) http://www.sdss.org/dr12/scope/

\(^{14}\) http://www.eso.org/~rsiebenm/agn_models/
Figure 2. SED of WISE1013. The blue, green, orange, yellow, and pink squares represent the data from SDSS, WISE, AKARI (3σ upper limit), SCUBA-2, and SMA, respectively. The contribution from the stellar, AGN, and SF components to the total SEDs are shown as blue, green, and red lines, respectively. The black solid line represents the resultant SED. The best-fit stellar template is a template of stellar population with an age of 0.1 Gyr and solar metallicity assuming a τ model with τ = 0.3 Gyr in Bruzual & Charlot (2003). The best-fit SF template is “NGC6090” (Polletta et al. 2007) with cropping at rest-frame wavelengths below 4.5 μm, while the best-fit AGN template is a template with θ = 19°, r_m = 3 × 10^{13} cm, η = 7.7%, τ_V,cl = 13.5, and τ_{v,mid} = 1000 (Siebenmorgen et al. 2015).

The color excess derived from the SED fitting with stellar component considering a Calzetti dust extinction law is E(B−V) = 0.45 mag that can be translated to \( N_H \) by assuming the following relation (Ricci et al. 2017a, see also Maiolino et al. 2001):

\[
\frac{E(B - V)}{N_H} = 1.5 \times 10^{-23} \text{ cm}^2 \text{ mag.} \tag{1}
\]

As a result, we found \( N_H = 3.0 \times 10^{22} \text{ cm}^{-2} \), suggesting that WISE1013 is a mildly dust-obscured AGN.

Since this SED fitting code does not just freely scale each SED template to fit the data because of the requirement for energy conservation as described above, the resultant SED is useful to investigate the physical properties of WISE1013. In order to confirm a robustness of physical quantities derived by our method with SEABASs, we also perform the SED fitting with other SED fitting codes and check the consistency of resultant physical quantities. Here, we utilized MAGPHYS\(^\text{16}\) (Multiwavelength Analysis of Galaxy Physical Properties; da Cunha et al. 2008, 2015) and CIGALE\(^\text{17}\) (Code Investigating GALaxy Emission; Burgarella et al. 2005; Noll et al. 2009), allowing us to do a detailed SED modeling in a self-consistent framework (see also Ciesla et al. 2015; Chang et al. 2017). We confirmed that the resultant quantities; \( L_{IR}, E(B−V), L_{IR}(AGN)/L_{IR}, \) and stellar mass and star formation rate (SFR; see Section 3.4) are in good agreement with each other, which means that the derived values that are relevant to this work are not changed within an error regardless of the SED fitting techniques, given the limited number of photometric data. Nevertheless, it should be noted that we still do not have data at rest-frame 10–100 μm that could correspond to the peak of AGN and SF emission, which may induce the large uncertainty of the quantities obtained from the SED fitting (see Sections 3.3 and 3.4). Hereafter, we should keep in mind this possible uncertainty.

We also note that its IR luminosity is potentially amplified by the effect of beaming and/or gravitational lensing even if

\[^{15}\text{http://www.iap.fr/cigale.lam.fr}\]  
\[^{16}\text{http://www.iap.fr/magphys/}\]  
\[^{17}\text{https://cigale.lam.fr/}\]
the derived $L_{IR}$ is reliable, as discussed in Tsi et al. (2015). It is quite difficult to rule out these possibilities quantitatively based on the current data set. Hence, we briefly mention these possibilities.

Since the beaming effect is related to small-scale physics and thus AGNs with highly collimated outflow (e.g., Blazars) tends to show a variability of flux density over a wide range of wavelengths (e.g., Lister et al. 2001). In order to see if WISE1013 shows variability, we checked its variability flag (var_flag)\(^1\) in the ALLWISE catalog. This flag is a four-character string where each character gives a measure of the probability that the source is variable in each band estimated from multi-epoch photometric data. Each character has values of 0–9; the objects with higher values in a band indicate a higher probability of variability at that band. On the other hand, when var_flag = “n” appears in an object’s band, it means that data are insufficient or inadequate to justify a variability at that band. We found that WISE1013 has var_flag = “n000,” which indicates that there is no sufficient high-quality photometry for a variability assessment at 3.4 $\mu$m and there is no variability at 4.6, 12, and 22 $\mu$m over a timescale of a few months. In addition, since WISE1013 was undetected by Faint Images of the Radio Sky at Twenty cm survey (Becker et al. 1995) where the detection limit is about 1 mJy at 20 cm, this object is unlikely to be a radio-loud AGN. These results suggest that the beaming effect of this object is expected to be small.

For the possibility of lensing, we confirmed that there are no massive foreground galaxies that can act as a lens (see Figure 1), meaning that the lensing effect is also expected to be small. Nevertheless, in order to quantify this effect, we need follow-up observations with high angular resolution and need to estimate the magnification factor, which is beyond the scope of this paper and will be included in a future work.

Recent studies have discovered many HyLIRGs and some ELIRGs based on the “W1W2 dropout” method (Eisenhardt et al. 2012; Wu et al. 2012). They are faint or undetected by WISE at 3.4 $\mu$m (W1) and 4.6 $\mu$m (W2) but are well detected at 12 $\mu$m (W3) or 22 $\mu$m (W4), and hence called “W1W2 dropouts” or “Hot DOGs.” W1W2 dropouts are also thought to be a key population to understand the coevolution of galaxies and SMBHs and have been intensively investigated for their properties (e.g., Assaf et al. 2015; Fan et al. 2016). Figure 3 shows the comparison of the best-fit SED of WISE1013 and a composite SED of 20 W1W2 dropouts (Tsai et al. 2015), where both SEDs are normalized by flux density at 22 $\mu$m. Both SEDs are similar in the MIR to FIR regime, indicating that WISE1013 has similar AGN/SF properties as W1W2 dropouts (see Section 3.3). On the other hand, the near-IR (NIR) SED of WISE1013 is relatively bright compared to W1W2 dropouts due to a selection effect (i.e., by definition, W1W2 dropouts are very faint at 3.4 and 4.6 $\mu$m). Actually, WISE1013 does not satisfy the selection criteria of W1W2 dropouts, and thus our sample selection method and W1W2 dropout method are complementary in terms of HyLIRGs/ELIRGs search (see also Toba & Nagao 2016).

### 3.3. Dust Properties of WISE1013

Following that, we discuss the dust properties of WISE1013 and compare them with other populations. Figure 4 shows the ratio of flux densities at the observed frame between 850 and 22 $\mu$m ($R_{850, 22}$), which trace cold and hot dust components, respectively. This ratio could tell us which component is more dominant in a galaxy. $R_{850, 22}$ values of other populations obtained from the literature (Magnelli et al. 2012; Wu et al. 2012; Jones et al. 2014, 2015; Wang et al. 2016; Fan et al. 2017) and estimated from SED templates (Silva et al. 2004; Polletta et al. 2007) are also shown in this figure. Note that we used 24 $\mu$m flux densities instead of 22 $\mu$m flux densities for submillimeter galaxies (SMGs) and BR 1202-0725 (Leipski et al. 2010). We converted from 800 $\mu$m to 850 $\mu$m flux density assuming $f_{\nu} \propto \nu^{3.7 \pm 2}$ where $\beta = 1.5$ for BR 1202-0725.

The derived $R_{850, 22}$ of WISE1013 is 1.25 $\pm$ 0.13, which is significantly lower than those of SMGs, indicating that hot dust is more dominant in WISE1013 compared to the SMGs. On the other hand, $R_{850, 22}$ of WISE1013 is comparable or slightly larger than those of W1W2 dropouts. This indicates that the dust temperature of W1W2 dropouts (Hot DOGs) tends to be hotter than normal DOGs, which supports the previous works (e.g., Wu et al. 2012). Comparing with $R_{850, 22}$ calculated using SED templates, Arp220 and M82 templates (Polletta et al. 2007) can reproduce the $R_{850, 22}$ of SMGs, while typical optically selected AGNs cannot explain the $R_{850, 22}$ of our sample. This supports that hot dust in WISE1013 is more dominant than that in normal AGNs. On the other hand, most W1W2 dropouts and WISE1013 are roughly consistent with those estimated from torus templates with varying extinction ranging from $N_H = 0$ to $N_H = 10^{23}$ cm$^{-2}$ (Silva et al. 2004).

### 3.4. Star Formation Rate and Stellar Mass Relation

Finally, we discuss the stellar mass ($M_*$) and SFR of WISE1013 at $z = 3.703$. We estimated $M_*$ and SFR in the same manner as Toba et al. (2017b); $M_*$ was derived from the SED fitting by SEABASS, while SFR was derived from $L_{IR}$ (SF) using log SFR = log $L_{IR}$ (SF) − 9.966 (Salim et al. 2016). The derived $M_*$ and SFR are log($M_*/M_\odot$) = 11.2$^{+0.6}_{-0.2}$ and log($SFR/M_\odot$ yr$^{-1}$) = 3.1$^{+0.6}_{-0.2}$, respectively. Note that we confirmed that the choice of SF template with cropping at rest-frame wavelengths below 4.5 $\mu$m is insensitive to the derived SFR although SEABASS preferred “NGC6090” as a best-fit SF template (see Section 3.2). On the other hand, the best-fit stellar

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1. The quantitative definition is described in the Explanatory Supplement to the AllWISE Data Release Products (http://wise2.ipac.caltech.edu/docs/release/allwise/expsup/sec5_3bvi.html).
Figure 4. Ratio of 850 and 22 μm flux density as a function of redshift. The red star represents our sample (WISE1013). Green triangles represent SMGs (Magnelli et al. 2012). Orange square, yellow asterisk, yellow diamonds, and purple circles are W1W2 dropouts obtained from Wu et al. (2012), Jones et al. (2014, 2015), and Fan et al. (2017) respectively. Cyan and blue crosses represent ultraluminous quasars at z = 4.7 (Leipski et al. 2010) and at z = 6.3 (Wu et al. 2015; Wang et al. 2016), respectively. Dashed lines represent flux ratios of Arp220, M82, Mrk231, type 1 quasars, and type 2 quasars calculated with SED templates (Polletta et al. 2007). The pink shaded region represents flux ratio estimated from torus templates with varying extinction ranging from N_H = 0 to N_H = 10^{22} cm^{-2} (Silva et al. 2004).

Figure 5. Stellar mass and SFR for WISE1013 (red star). The yellow circles represent those for IR-bright DOGs detected with AKARI or IRAS (Toba et al. 2017b). The blue solid line is the main sequence (MS) of normal SF galaxies selected from the SDSS (Chang et al. 2015) with a scatter of 0.39 dex (blue dotted line). The cyan contours represent the SFR–M_⋆ relation for a sample of GALEX–SDSS–WISE Legacy Catalog (GSLC; Salim et al. 2016) at z < 0.3. The bin size is 0.2 × 0.2 in the units given in the plot. The green line is MS of SF galaxies at z = 2 (Daddi et al. 2007). The existence of the broad line indicates that we can see the broad line region and radiation from AGN can contribute to the UV/ optical fluxes. Since we estimate the stellar mass based on the best-fit stellar template that fits the optical and NIR data, if AGN emission would boost optical flux, the derived stellar mass in this work could be overestimated. Although we input type 1 AGN templates in addition to type 2/obscured AGN templates when conducting the SED fitting and most templates we input cover the optical regions, we are still not able to rule out the possibility of the AGN contribution to the derived
stellar mass. However, it is hard to estimate AGN contribution and its influence on the stellar mass precisely. We thus discuss the upper limit of the AGN contribution to the optical bands using a prior probability. SEABASs allows us to have prior information, e.g., the bulk of the flux in some filters comes from the AGN (see Rovilos et al. 2014 for more detail). Figure 6 shows the resultant SEDs when assuming 5%, 20%, and 35% contribution of AGN flux to the SDSS bands as a prior probability. The derived stellar mass of each case is log (M_{\text{star}}/M_\odot) = 11.2, 11.3, and 11.2, respectively. We found that SEABASs seems to fit the data moderately well when assuming 5%–20% contribution of AGN, while it does not seem to fit the data when assuming a >35% contribution as shown in Figure 6. This suggests that the possible AGN contribution to the SDSS bands may be less than 35%, and even if we use the best-fit template for each case to derive the stellar mass, the resultant stellar mass is not significantly changed.

4. Conclusions

In this paper, we report the discovery of an extremely luminous DOG (WISE J101326.25+611220.1) at z_{\text{spec}} = 3.703. Thanks to the multiwavelength data set of the SDSS, WISE, AKARI, SCUBA-2, and SMA, we pinned down its SED at rest-frame 0.1–300 \mu m. We derived its physical quantities such as IR luminosity based on the SED fitting. Main results are summarized as follows:

1. The derived IR luminosity by using the SEABASs code is L_{\text{IR}} = 2.2^{+1.5}_{-1.0} \times 10^{14} L_\odot, making it one of the most luminous IR galaxies in the universe.

2. The ratio of flux densities at the observed frame between 850 and 22 \mu m (R_{850/22}) of WISE1013 is significantly lower than those of SMGs, while it is comparable or slightly larger than those of W1W2 dropouts, meaning that the dust temperature of WISE1013 is hotter than that of SMGs but it is slightly cooler than that of W1W2 dropouts.

3. The WISE1013 covers a locus of starburst galaxies on the stellar mass and SFR plane, while the AGN contribution to the IR luminosity derived from the SED fitting is about 94%, which suggests that this extremely luminous DOG shows significant AGN and SF activity that provides a good laboratory to investigate the maximum phase of galaxy–SMBH coevolution.

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