Far-infrared Properties of Infrared-bright Dust-obscured Galaxies Selected with IRAS and AKARI Far-infrared All-sky Survey

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Abstract

We investigate the star-forming activity of a sample of infrared (IR)-bright dust-obscured galaxies (DOGs) that show an extreme red color in the optical and IR regime, (\(i - [22]\)) \(>\) 7.0. Combining an IR-bright DOG sample with the flux at 22 \(\mu\)m > 3.8 mJy discovered by Toba & Nagao with the IRAS faint source catalog version 2 and AKARI far-IR (FIR) all-sky survey bright source catalog version 2, we selected 109 DOGs with FIR data. For a subsample of seven IR-bright DOGs with spectroscopic redshifts (0.07 < z < 1.0) that were obtained from the literature, we estimated their IR luminosity, star formation rate (SFR), and stellar mass based on the spectral energy distribution fitting. We found that (1) the WISE 22 \(\mu\)m luminosity at the observed frame is a good indicator of IR luminosity for IR-bright DOGs and (2) the contribution of the active galactic nucleus to IR luminosity increases with IR luminosity. By comparing the stellar mass and SFR relation for our DOG sample and the literature, we found that most of the IR-bright DOGs lie significantly above the main sequence of star-forming galaxies at similar redshift, indicating that the majority of IRAS- or AKARI-detected IR-bright DOGs are starburst galaxies.

Key words: catalogs – galaxies: active – galaxies: star formation – infrared: galaxies

Supporting material: machine-readable table

1. Introduction

Stellar mass \((M_\text{\ast})\) and star formation rate (SFR) are two of the most fundamental and important physical quantities of galaxies. Since a tight correlation between the \(M_\text{\ast}\) and SFR of galaxies has been discovered (e.g., Brinchmann et al. 2004), many authors have intensively investigated this relation for various galaxies at various redshifts (e.g., Daddi et al. 2007; Elbaz et al. 2007; Noeske et al. 2007). It is well known that the majority of galaxies follow a relation called the “main sequence” (MS), and this correlation is seen to evolve toward high redshift across all environments (e.g., Whitaker et al. 2012; Koyama et al. 2013; Lee et al. 2015; Tomczak et al. 2016). However, a comprehensive implication of the tight correlation between stellar mass and SFR and of its redshift evolution is still unclear (see Casey et al. 2014). In addition, it is known that galaxies undergoing active star formation (SF) that could be induced by major merger processes lie significantly above the MS and are referred to as starburst galaxies. Investigating the relation of these starburst galaxies to the MS is important to understanding the origin of the \(M_\text{\ast}\)-SFR connection.

In this work, we focus on dust-obscured galaxies (DOGs; Dey et al. 2008). Their mid-infrared (MIR) flux densities are three orders of magnitude larger than those at optical wavelengths, implying that a significant active galactic nucleus (AGN) or SF activities heat the dust. The optical and ultraviolet (UV) emission originating from these activities is absorbed by heavy surrounding dust that re-emits in the IR wavelength. Their IR luminosity often exceeds \(10^{12} L_\odot\), and they are classified as ultraluminous IR galaxies (ULIRGs; Sanders & Mirabel 1996). Recently, Riguccini et al. (2015) investigated the far-IR (FIR) properties for a sample of 95 DOGs within the COSMOS field, based on spectral energy distribution (SED) fitting. However, their DOG sample is limited to those with flux density less than 3.0 mJy at 24 \(\mu\)m (the mean value is \(\sim\)0.4 mJy). On the other hand, IR-bright DOGs with a much higher MIR flux density are thought to be a maximum phase of SF and AGN activity (e.g., Hopkins et al. 2008), and thus they are likely to be a population crucial to understanding what kinds of physical processes drive the SFR-\(M_\text{\ast}\) relation. Recently, we successfully discovered a large number of IR-bright DOGs and investigated their statistical properties (Toba et al. 2015; Toba & Nagao 2016; Toba et al. 2017). However, their SF properties are still unknown because we lack deep and wide FIR data are critical to investigate the SF activity of galaxies.

In order to estimate the FIR luminosity of IR-bright DOGs and investigate their SF properties, we utilized data from the Infrared Astronomical Satellite (IRAS) and the AKARI satellite. IRAS is the first satellite that performed an all-sky survey in four IR bands centered at 12, 25, 60, and 100 \(\mu\)m (Neugebauer et al. 1984; Beichman et al. 1988). In this work, we utilized the IRAS Faint Source Catalog (FSC), version 2.0 (Moshir et al. 1992), reaching a depth of \(\sim\)0.2 Jy at 12, 25, and 60 \(\mu\)m and \(\sim\)1.0 Jy at 100 \(\mu\)m. AKARI is the first Japanese space satellite dedicated to IR astronomy and was launched in 2006 (Murakami et al. 2007). AKARI performed an all-sky
survey at 9, 18, 65, 90, 140, and 160 μm with a spatial resolution and sensitivity much higher than those of IRAS. In this work, we utilized the AKARI Far-infrared Surveyor (FIS; Kawada et al. 2007) bright source catalog (BSC) version 2.0 (I. Yamamura et al. 2017, in preparation), which provides the positions and flux densities in the four FIR wavelengths centered at 65, 90, 140, and 160 μm. The 5σ sensitivity at each band is about 2.4, 0.55, 1.4, and 6.3 Jy, respectively, which is the deepest data in terms of the FIR all-sky data, and thus these data should be useful in deriving the total IR luminosity and SFR of IR-bright DOGs.

In this paper, we present the IR luminosity, stellar mass, and SFR for IR-bright DOGs detected by the Sloan Digital Sky Survey (SDSS; York et al. 2000) and the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) and at least detected by the IRAS or AKARI FIR all-sky survey. These multiwavelength data are critical for investigating where IR-bright DOGs lie in the SFR–stellar mass (SFR–M∗) plane. Throughout this paper, we adopt H0 = 70 km s−1 Mpc−1, ΩM = 0.3, and ΩΛ = 0.7. Unless otherwise noted, all magnitudes refer to the AB system.

2. Data and Analysis

2.1. Sample Selection

We selected eight IR-bright DOGs with spectroscopic information based on the WISE, SDSS, IRAS, and AKARI catalogs.9 The flow chart of our sample selection process is shown in Figure 1.

The DOG parent sample (hereafter WISE–SDSS photo DOGs) was selected from Toba & Nagao (2016), who discovered 5,311 IR-bright DOGs with i − [22] > 7.0 and flux at 22 μm > 3.8 mJy, where i and [22] are the i-band and 22 μm AB magnitudes, respectively, based on the ALLWISE (Cutri et al. 2014) and SDSS Data Release 12 (SDSS DR12; Alam et al. 2015) catalogs. For them, we first cross-identified IRAS FSC version 2, which includes 173,044 sources. Before cross-matching, we conservatively selected 52,139 sources that are not affected by cirrus and confusion by adopting CIRRUS = 0 and CONFUSE = 0. Using a matching radius of 1′, 59 DOGs (hereafter WISE–SDSS–IRAS DOGs) were selected. Note that we checked the quality of the IRAS flux in each band (fqual_12/25/60/100), and we confirmed that the flux for at least one band is measured with good quality (i.e., fqual_12/25/60/100 ≥ 2). For 5,311 − 59 = 5,252 DOGs that are not cross-identified with IRAS FSC (hereafter WISE–SDSS–non-IRAS DOGs), we cross-identified with AKARI FIR BSC version 2, which includes 918,054 sources. Before cross-matching, we limited ourselves to 501,444 sources with high detection reliability (GRADE = 3), that is, are detected by at least two wavelength bands or in four or more scans in one wavelength band. Using a matching radius of 20″, which is determined by considering the point-spread function size of ~40″ of the AKARI/90 μm data, 50 DOGs (hereafter WISE–SDSS-non-IRAS–AKARI DOGs) were selected. Only one AKARI object has two counterpart candidates in the WISE–SDSS–non-IRAS DOGs within the search radius. We choose the nearest one as the counterpart. Note that we also cross-identified with AKARI FSC BSC ver. 2 even for WISE–SDSS–IRAS DOGs to collect more FIR information for the matched sources. Consequently, we selected 59 + 50 = 109 DOGs (hereafter WISE–SDSS–IRAS/AKARI DOGs) in this work. The main difference between the WISE–SDSS–IRAS/AKARI DOGs and the classical DOGs discovered by Dey et al. (2008) is the MIR flux; the typical (median) flux density at 22 μm of our DOG sample is 10.4 mJy, which is much brighter than 0.3 mJy at 24 μm as selected by Dey et al. (2008); see also Section 4.2.2.

For the 109 WISE–SDSS–IRAS/AKARI DOGs, we compiled spectroscopic redshift information by utilizing the NASA/IPAC Extragalactic Database (NED10) and the Set of Identifications, Measurements, and Bibliography for Astronomical Data (SIMBAD).11 For spectroscopically confirmed DOGs, we rejected nearby galaxies with redshift smaller than 0.07 to ensure reliable photometry at each band because the photometry we employed is not optimized for extended sources (see Section 2.2). Finally, we visually checked the optical, MIR, and FIR images and excluded a suspicious object that is affected by a nearby bright star or that cannot be deblended by the SDSS pipeline. As a result, we selected eight objects with spectroscopic redshift (hereafter WISE–SDSS–IRAS/AKARI specz DOGs) with 0.07 < z < 1.0 (its mean redshift is ~0.54). We note that only one object has a SDSS spectrum with meaningful quality because the mean i-band magnitude of our DOG sample is ~19.4, which is fainter than that of typical SDSS spectroscopic galaxies. Figure 2 shows cutout images at optical, MIR, and FIR wavelengths. All of the information for our DOG sample is tabulated in Table 1. We note that AKARI J09150+2418 (ID = 2) was selected as extremely red quasars in Ross et al. (2015) who selected quasars with extreme red color by adopting similar color cut as ours (see Ross et al. 2015 in detail).

We confirmed that this object is mostly dominated by AGN (see Figure 3) and should satisfy the selection criteria in Ross et al. (2015).

2.2. SED Fitting to Derive the IR Luminosity

We performed the SED fitting for the eight WISE–SDSS–IRAS/AKARI specz DOG samples to derive the total IR luminosity, LIR (8–100 μm). We employed the fitting code SED Analysis using BAYesian Statistics (SEABASs12; Rovilos et al. 2014), which provides up to three-component fitting (AGN, SF, and stellar components) based on the maximum likelihood method. For the AGN templates, we utilized the library of Silva et al. (2004), which contains torus templates with varying extinction ranging from NH = 0 to NH = 1025 cm−2. For the SF templates, we utilized the library of Chary & Elbaz (2001) and Mullaney et al. (2011). We also used the library of Polletta et al. (2007) representing optically selected AGNs and SF galaxies (see Polletta et al. 2007 for more detail). For the stellar templates, SEABASs gives a library of 1,500 synthetic stellar templates from Bruzual & Charlot (2003) stellar population models with solar metallicity and a range of SF histories and ages assuming a Chabrier (2003) initial mass function (IMF), and each model is reddened using a Calzetti et al. (2000) dust extinction law. In order to derive the total IR luminosity and stellar mass with small uncertainties, we used data only with fqual_25/60/100 ≥ 2 and

9 For the selection process, we employed TOPCAT, which is an interactive graphical viewer and editor for tabular data (Taylor et al. 2005).
10 http://ned.ipac.caltech.edu/
11 http://simbad.u-strasbg.fr/simbad/
12 http://xraygroup.astro.noa.gr/SEABASs/
Figure 1. Flow chart of our DOG selection process. Numbers in this figure denote the number of selected objects at each step. The blue-shaded part is exactly the same as Figure 1 of Toba & Nagao (2016).
One possible reason is that this object has only one photometric point in the FIR regime, which would not be enough to constrain the FIR SEDs. Another possibility is that its 90 μm flux density might be overestimated due to the deblending issue, and thus SEABASs, with considering the energy balance between the UV/optical and IR, cannot reproduce the FIR emission. Therefore, we excluded this object for the SED fitting, and we derive the stellar mass, total IR luminosity, and SFR for the remaining seven DOGs with ID = 2–8 (see Table 1). Hereinafter, we focus on these objects.

3.2. Energy Contribution of the AGN to the IR Luminosity

Since SEABASs executes the three-component SED fitting of the stellar, AGN, and SF components, we can calculate the energy contribution of each component to the IR luminosity. Figure 4 shows the luminosity contribution of the AGN to the IR luminosity (LIR (AGN)/LIR) as a function of IR luminosity. We found that the energy contribution of the AGN to the IR luminosity increases with increasing IR luminosity. This result is in good agreement with those from AKARI-selected LIRGs/ULIRGs (e.g., Lee et al. 2012; Ichikawa et al. 2014) and those from IR-faint DOGs (e.g., Riguccini et al. 2015), in the sense that more IR-luminous sources tend to be more AGN-dominated. The fact that the luminous IR sources tend to be relatively more AGN-dominated as reported by several authors can be applicable for IR-bright DOGs.

4. Discussions

4.1. Predicting LIR from 22 and 90 μm Flux Density

Here we discuss the correlation among the MIR luminosity, FIR luminosity, and total IR luminosity for IR-bright DOGs. As shown in Figure 3, the SEDs of DOGs in the MIR regime appear flat, which gives the possibility of estimating their IR luminosities from an MIR luminosity at the “observed frame” without considering a k correction. We derive the 22 and 90 μm luminosity density at the observed frame, L_22^{obs} (22 μm) or 90 μm) just from the observed flux density by multiplying 4πd_l^2 for each DOG, where d_l is the luminosity distance.

Figure 5(a) shows the relation between the 22 and 90 μm luminosity in the observed frame and IR luminosity. We see tight correlations between the 22 μm luminosity and IR luminosity, and between 90 μm luminosity and IR luminosity. Figure 5(b) shows the ratios of 22 and 90 μm and IR luminosity.

3. Results

3.1. Result of SED Fitting

Figure 3 shows the example of the SED fitting. The best-fit AGN template for our IR-bright DOG sample tends to favor the “torus” template presented by Silva et al. (2004) or Polletta et al. (2007), which is consistent with the report by Tsai et al. (2015) based on the WISE-selected IR-luminous sources. A remarkable aspect we found is that IR-bright DOGs have a flat SED in the MIR region, which provides a clue of an empirical relation in their MIR and IR luminosities (see Section 4.1). It should be noted that one object with ID = 1 cannot be well fitted by the SEABASs code. 90 μm provided by the SED fitting are significantly lower than the observed flux at 90 μm.
### Table 1
Eight WISE–SDSS–IRAS/AKARI Specz DOGs Identified In This Work

| ID    | FIS ID     | Objname     | R.A. $^a$ | Decl. $^a$ | Redshift $^b$ | imag AB mag | gmag AB mag | rmag AB mag | imag AB mag | zmag AB mag | hmag AB mag |
|-------|------------|-------------|-----------|------------|--------------|--------------|-------------|-------------|--------------|--------------|-------------|
| 1     | 5007582    | AKARI J00260+1041 | 00:26:06.6 | +10:41:26.5 | 0.57          | 21.89±0.27   | 21.37±0.06   | 20.37±0.04   | 19.92±0.05   | 19.79±0.13   | ...         |
| 2     | 5204882    | AKARI J09150+2418 | 09:15:01.7 | +24:18:12.1 | 0.84          | 20.91±0.06   | 20.59±0.03   | 20.28±0.03   | 19.95±0.03   | 19.01±0.04   | 17.43±0.17   |
| 3     | 5291698    | AKARI J3070+2338 | 13:07:00.6 | +23:38:05.1 | 0.28          | 21.46±0.18   | 20.58±0.03   | 19.38±0.02   | 19.02±0.02   | 18.56±0.05   | 17.66±0.16   |
| 4     | ...        | IRAS F13073+6057 | 13:09:16.9 | +60:42:08.9 | 0.64          | 22.65±0.32   | 22.91±0.15   | 21.59±0.12   | 20.47±0.06   | 19.42±0.11   | 18.76       |
| 5     | 5317429    | AKARI J14063+0103 | 14:06:38.2 | +01:02:54.5 | 0.24          | 19.40±0.05   | 18.69±0.01   | 18.10±0.01   | 17.70±0.01   | 17.64±0.03   | 17.91±0.20   |
| 6     | ...        | IRAS F14481+4454 | 14:49:53.6 | +44:41:50.3 | 0.67          | 21.16±0.08   | 20.74±0.03   | 20.56±0.03   | 20.47±0.04   | 20.02±0.14   | ...         |
| 7     | 5365228    | AKARI J15324+3242 | 15:32:44.0 | +32:42:46.6 | 0.93          | 20.18±0.05   | 19.91±0.02   | 19.53±0.02   | 19.23±0.02   | 18.40±0.04   | ...         |
| 8     | ...        | IRAS F23497-0448 | 23:52:15.1 | -04:32:10.5 | 0.16          | 19.98±0.07   | 19.47±0.01   | 18.86±0.01   | 18.74±0.02   | 19.19±0.09   | ...         |

| kmag AB mag | 3.4 μm flux mJy | 4.6 μm flux mJy | 12 μm flux mJy | 22 μm flux mJy | 25 μm flux (qual_25) mJy | 60 μm flux (qual_60) mJy | 65 μm flux (qual_65) mJy | 90 μm flux (qual_90) mJy | 100 μm flux (qual_100) mJy |
|-------------|-----------------|-----------------|----------------|-----------------|-------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| ...         | 0.15±0.01       | 0.13±0.01       | 7.09±0.29      | 29.68±1.57      | ...                     | ...                      | 359.96±150.89 (1)         | 417.40±150.29 (3)         | ...                     |
| 15.65±0.04  | 8.20±0.17       | 16.61±0.31      | 41.92±0.63     | 96.12±2.41      | ...                     | ...                      | 396.88±64.55 (3)          | ...                     |
| 15.31±0.04  | 8.65±0.18       | 14.71±0.28      | 26.38±0.42     | 75.79±2.14      | ...                     | ...                      | 557.62±61.57 (3)          | ...                     |
| 16.64±0.11  | 2.23±0.05       | 4.23±0.08       | 10.86±0.22     | 26.94±1.07      | 84.43±17.73 (1)         | 194.70±42.83 (3)         | ...                      | 818.30±171.84 (1)         | ...                     |
| 16.65±0.13  | 3.09±0.07       | 8.87±0.18       | 75.79±1.07     | 236.16±4.45     | ...                     | ...                      | 598.65±252.74 (1)         | 684.26±55.28 (3)          | ...                     |
| ...         | 2.02±0.04       | 5.50±0.10       | 24.57±0.41     | 65.77±1.65      | 85.09±17.87 (2)         | 189.70±32.25 (3)         | ...                      | 500.50±115.12 (1)         | ...                     |
| ...         | 0.41±0.01       | 0.82±0.05       | 10.52±0.22     | 48.31±1.22      | 71.03±21.31 (2)         | 234.10±35.12 (3)         | 61.96±191.01 (1)          | 398.36±46.21 (3)          | 711.80±170.83 (1)         |
| ...         | 0.19±0.01       | 1.25±0.03       | 18.78±03.9     | 128.23±2.98     | 311.50±93.45 (1)        | 396.30±67.37 (3)         | ...                      | 571.50±165.73 (1)         | ...                     |

| 140 μm flux (qual_140) mJy | 160 μm flux (qual_160) mJy | log $L_{IR}$ $/L_{⊙}$ | log $M_*$ $/M_{⊙}$ | log SFR $M_{⊙}$ yr$^{-1}$ |
|---------------------------|---------------------------|-------------------------|---------------------|---------------------------|
| 407.51±231.02 (1)         | ...                       | ...                     | ...                 | ...                       |
| 40.05±258.74 (1)          | ...                       | 13.52±0.04              | 12.60±0.18          | 2.56±0.25                 |
| 507.33±344.22 (1)         | 53.72±338.50 (1)          | 12.33±0.06              | 9.86±0.10           | 1.95±0.04                 |
| ...                       | ...                       | 12.75±0.11              | 11.67±0.16          | 2.55±0.16                 |
| 1332.88±255.74 (1)        | ...                       | 12.63±0.07              | 10.28±0.17          | 2.59±0.10                 |
| ...                       | ...                       | 13.29±0.03              | 9.16±0.09           | 3.16±0.15                 |
| 983.85±189.00 (1)         | 433.56±325.80 (1)         | 13.43±0.04              | 10.85±0.02          | 2.88±0.04                 |
| ...                       | ...                       | 11.98±0.07              | 9.65±0.01           | 1.94±0.07                 |

**Notes.**

$^a$ The coordinates in the SDSS DR12.

$^b$ NED.

(This table is available in its entirety in machine-readable form.)
as a function of IR luminosity. The ratios of WISE 22 μm and IR luminosity have similar values regardless of IR luminosity, which suggests that 22 μm luminosity has a more linear relationship with IR luminosity. We obtained the following conversion formulae:

\[
\log L_{22} = (1.00 \pm 0.02) \log [\nu L_{\nu}^{\text{obs}}(22 \, \mu m)] \\
+ (0.48 \pm 0.28),
\]

(1)

\[
\log L_{IR} = (0.97 \pm 0.06) \log [\nu L_{\nu}^{\text{obs}}(90 \, \mu m)] \\
+ (0.76 \pm 0.79).
\]

(2)

The Spearman rank correlation coefficients for each relationship are ∼1.00 and 0.60 with null hypothesis probability \( P \approx 0 \) and 4.0 \times 10^{-1}, respectively, indicating that 22 μm luminosity can be used to predict the total IR luminosity for IR-bright DOGs with 0.07 < z < 1.0 without considering a k correction. At the same time, we should keep in mind that whether or not this empirical relation is applicable to other galaxies is unknown, and thus this relation may be useful only for IR-bright DOGs.

4.2. Stellar Mass and SFR

Since SEABASs has the advantage of being able to decompose the total SED into stellar, AGN, and SF components, we used the IR luminosity contributed from SF activity and convert it to SFR using the Kennicutt (1998) equation with the Chabrier IMF calibrated by Salim et al. (2016):

\[
\text{SFR} = \log L_{\text{IR}} \text{ (SF)} - 9.966,
\]

(3)

where SFR and \( L_{\text{IR}} \text{ (SF)} \) are given in units of \( M_{\odot} \text{ yr}^{-1} \) and \( L_{\odot} \), respectively. For the stellar mass, we used the output from the SED fitting based on SEABASs assuming the same IMF. Note that the rest-frame UV continuum may be contributed by scattered light from AGNs, particularly for luminous DOGs (e.g., Hamann et al. 2017), which induces an uncertainty in the estimated stellar mass.

4.2.1. One-to-one Comparison with the Literature

Before comparing the SFR–\( M_\star \) relation of the IR-bright DOG sample with that of other populations, we investigate whether or not the estimates of stellar mass and SFR based on SEABASs have a systematic offset compared to those derived from previous works using some local galaxies/ULIRGs. One caution here is that the difference of the assumed IMF also affects the
stellar mass and SFR (e.g., Rieke et al. 2009; Casey et al. 2014), which induces a systematic offset on the SFR–$M_*$ plane. Therefore, we corrected the stellar mass and SFR in the literature to those assuming a Chabrier IMF by dividing them by 1.58 (Salim et al. 2007; see also Tacconi et al. 2008) if needed.

First, we compare stellar mass and SFR with those of local galaxies at $z < 0.3$ estimated by Salim et al. (2016). They recently provided a catalog (the GALEX–SDSS–WISE Legacy Catalog, GSWLC) of physical properties, including stellar masses and SFRs that were derived by the SED fitting following a Bayesian methodology for UV/optical data. Note that in addition to SFRs derived from the SED fitting, they provided MIR SFRs derived from IR templates based on WISE 22 μm data to avoid potential systematics. This is because they do not use the FIR data to derive the SFR, which could induce large uncertainties (see, e.g., Toba & Nagao 2016). So, we first cross-matched the GSWLC catalog with AKARI FIS BSC ver. 2 and derived the stellar mass and SFR of matched sources as described above. We then compared each quantity of them with those in GSWLC where we used the MIR-SFR derived from the ALLWISE catalog.

Figure 6 shows the comparison of stellar masses derived from our method and those in GSWLC. Our estimate of SFR is in good agreement with that in Salim et al. (2016), while the stellar mass we estimated is slightly smaller than that in Salim et al. (2016); the typical offset of stellar mass is $\sim 0.15$ dex. This offset is roughly consistent with the results from the comparison between GSWLC and the Max Planck Institute for Astrophysics/Johns Hopkins University (MPA/JHU) catalog (Kaufmann et al. 2003; Brinchmann et al. 2004; see Salim et al. 2016 in detail). We should keep in mind this offset when comparing the stellar masses with local SDSS galaxies.

Next, we compare stellar mass and SFR with those of local ULIRGs at $z < 0.3$ estimated by Kilerci Eser et al. (2014). They constructed a ULIRG sample by cross-matching the AKARI FIS BSC version 1 (Yamamura et al. 2010) with the SDSS DR10 (Ahn et al. 2014). Figure 7 shows the comparison of stellar masses and SFRs derived from our method with those in Kilerci Eser et al. (2014). Our estimate of SFR is roughly consistent with that in Kilerci Eser et al. (2014), although we underestimate significantly the SFR for some ULIRGs, while the stellar mass we estimated is obviously larger than that in Kilerci Eser et al. (2014); the typical offset of stellar mass is $\sim 0.5$ dex. We note that Kilerci Eser et al. (2014) reported that all of the adopted stellar mass values in their work might be underestimated by $\sim 0.5$ dex by comparing the derived stellar mass with previous works, which could be a possible interpretation of the discrepancy of our estimate of stellar mass. We should keep in mind this offset when comparing the stellar mass with local ULIRGs.

4.2.2. Stellar Mass and SFR Relation

We discuss where IR-bright DOGs lie in the SFR–$M_*$ plane and compare it with that from the literature. We first estimated the SFR based on the IR luminosity from SF.
stellar mass (dotted line is the one-to-one line. The inserted as employed in this work and Kilerci Eser et al. Comparison of stellar mass distribution: the redshift of the sample in Kilerci Eser et al. 2005 selected by SDSS and Galaxy Evolution Explorer by the et al. 2005 mass and SFR of the MS presented by Elbaz et al. Daddi et al. 2007 – 0.4 dex (Savaglio et al. 2005; Lara-López et al. 2010), the large offset of IR-bright DOGs cannot be explained only by metallicity. Therefore, taking into account the redshift evolution of the SFR–$M_*$ relation (Whitaker et al. 2012; Lee et al. 2015; Tomczak et al. 2016) and the uncertainty of SFR–$M_*$ for the MS due to the dispersion of at least metallicity, our IR-bright DOGs detected by IRAS or AKARI seem to be a more specific population compared with IR-faint DOGs regarding the SFR–$M_*$ relation.

The authors appreciate the referee’s thoughtful feedback that improved the manuscript. This research is based on observations with AKARI, a JAXA project with the participation of ESA. This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration. Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the US Department of Energy Office of Science. The SDSS-III website is http://www.sdss3.org/. SDSS-III is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS-III Collaboration, including the University of Arizona, the Brazilian Participation Group, Brookhaven National Laboratory, Carnegie Mellon University, University of Florida, the French Participation Group, the German Participation Group, Harvard University, (2014) is less than 0.5. However, it is difficult to conclude that this offset is statistically robust, because of the small sample size, and thus it will be a focus of future work. The tendency of the large offset of IR-bright DOGs from the MS in the SFR–$M_*$ plane is likely to be inconsistent with that of IR-faint DOGs (Kartaltepe et al. 2012; Riguccini et al. 2015). They reported that IR-faint DOGs with no significant AGN contribution are mainly located within the star-forming MS, although some authors reported that they are widely distributed on the SFR–$M_*$ plane (Calanog et al. 2013; Corral et al. 2016). Note that our sample is relatively low in redshift ($z \sim 0.54$) compared with the IR-faint DOG sample ($z \sim 2$). Also, the MIR flux range for them is significantly different. Taking these results into account, the SF properties of IR-bright DOGs are not necessarily the same as that of IR-faint (i.e., classical) DOGs. This work enables us to constrain the SFR–$M_*$ relation of previously unknown, IR-bright DOGs whose properties differ from those of classical, IR-faint DOGs for the first time.

It should be noted that the SFR–$M_*$ relation of the MS is also related to its other physical properties such as metallicity (e.g., Mannucci et al. 2010), molecular gas fraction (e.g., Daddi et al. 2010; Sargent et al. 2014), and starburst compactness (e.g., Elbaz et al. 2011). However, a full explanation of how each physical property of IR-bright DOGs affects the SFR–$M_*$ relation requires further observations to derive each quantity, which is beyond the scope of this paper and will be in a future work. We here just discuss a possibility that the large offset of our DOG sample from the MS can be explained based on the metallicity of IR-bright DOGs and the MS. Since the dispersion of SFR and stellar mass due to the metallicity of the MS is 0.2–0.4 dex (Savaglio et al. 2005; Lara-López et al. 2010), the large offset of IR-bright DOGs cannot be explained only by metallicity. Therefore, taking into account the redshift evolution of the SFR–$M_*$ relation (Whitaker et al. 2012; Lee et al. 2015; Tomczak et al. 2016) and the uncertainty of SFR–$M_*$ for the MS due to the dispersion of at least metallicity, our IR-bright DOGs detected by IRAS or AKARI seem to be a more specific population compared with IR-faint DOGs regarding the SFR–$M_*$ relation.

Figure 7. Comparison of stellar mass (top) and SFR (bottom) derived from SEABAS as employed in this work and Kilerci Eser et al. (2014). The red dotted line is the one-to-one line. The inserted figure shows the histogram of the ratio of each quantity derived in this work and Kilerci Eser et al. (2014) for stellar mass (top) and SFR (bottom).

Figure 8 shows the resultant stellar mass and SFR relation for our DOG sample, the MS sample for star-forming galaxies selected by SDSS and WISE (Chang et al. 2015), and selected by the Galaxy Evolution Explorer (GALEX) satellite (Martin et al. 2005), SDSS, and WISE (Salim et al. 2016). The stellar mass and SFR of the MS presented by Elbaz et al. (2007) and Daddi et al. (2007) for star-forming galaxies at $z = 1$ and 2, respectively, are also shown in Figure 8. Note that we corrected a possible offset of stellar masses discussed in Section 4.2.1 for the local SDSS sample provided by Salim et al. (2016). We remind readers that we corrected the stellar mass and SFR in the literature to those assuming a Chabrier IMF if needed. We found that most IR-bright DOGs lie above these relations significantly, although the redshift of our DOG sample is less than 1.0. They cover a locus of merger-driven starburst galaxies (e.g., Rodighiero et al. 2011), indicating that our IR-bright DOG sample detected by IRAS or AKARI is basically starburst galaxies. The stellar mass and SFR of a ULIRG sample presented by Kilerci Eser et al. (2014) are also plotted. We also corrected a possible offset of stellar masses discussed in Section 4.2.1 for them. We found that some IR-bright DOGs have a larger SFR value given the same stellar mass (although remaining objects overlapped with local ULIRGs in the SFR–$M_*$ plane). This is partially due to the difference of the redshift distribution: the redshift of the sample in Kilerci Eser et al. (2014) is less than 0.5. However, it is difficult to conclude that this offset is statistically robust, because of the small sample size, and thus it will be a focus of future work. The tendency of the large offset of IR-bright DOGs from the MS in the SFR–$M_*$ plane is likely to be inconsistent with that of IR-faint DOGs (Kartaltepe et al. 2012; Riguccini et al. 2015). They reported that IR-faint DOGs with no significant AGN contribution are mainly located within the star-forming MS, although some authors reported that they are widely distributed on the SFR–$M_*$ plane (Calanog et al. 2013; Corral et al. 2016). Note that our sample is relatively low in redshift ($z \sim 0.54$) compared with the IR-faint DOG sample ($z \sim 2$). Also, the MIR flux range for them is significantly different. Taking these results into account, the SF properties of IR-bright DOGs are not necessarily the same as that of IR-faint (i.e., classical) DOGs. This work enables us to constrain the SFR–$M_*$ relation of previously unknown, IR-bright DOGs whose properties differ from those of classical, IR-faint DOGs for the first time.

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Figure 8. Stellar mass and SFR for seven IR-bright DOGs (red squares) and 75 AKARI-selected ULIRGs (Kilerci Eser et al. 2014). The blue solid line is the main sequence 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 the GALEX–SDSS–WISE Legacy Catalog (Salim et al. 2016) at $z < 0.3$. The bin size is $0.2 \times 0.2$ in the units given in the plot. The light green line is the MS of normal SF galaxies at $z = 1$ (Elbaz et al. 2007), while the dark green lines are the MSs of SF galaxies at $z = 2$ (Daddi et al. 2007) and 10 times above this relationship.
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