# Where do infrared-bright dust-obscured galaxies lie on the star formation rate-stellar mass plane?

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**ABSTRACT**

We present the relation between stellar mass and star formation rate (SFR) of a sample of infrared (IR)-bright dust-obscured galaxies (DOGs) that are defined by $(i - [22])_{\rm AB} > 7.0$ and flux density at 22 $\mu$m > 3.8 mJy. Combining the Sloan Digital Sky Survey (SDSS), TwoMicron All Sky Survey (TWOMASS), *Wide-field Infrared Survey Explorer* (*WISE*), *Infrared Astronomical Satellite* (*IRAS*), and *AKARI* catalogs, we selected 7 IR-bright DOG at $0 < z_{\rm spec} < 1$. We estimated their stellar mass and SFR based on a spectral energy distribution fitting technique, and compared them with main sequence of star-forming galaxies at $0 < z < 2$ and local ULIRGs. As a result, we found that most of IR-bright DOGs lie significantly above the main sequence of star-forming galaxies at similar redshifts. We conclude that the majority of *IRAS*- and/or *AKARI*-detected IR-bright DOGs are starburst galaxies.

**Keywords:** catalogs — galaxies: active — galaxies: star formation — infrared: galaxies

## 1. INTRODUCTION

The stellar mass ($M_*$) and the star formation rate (SFR) are two of the most fundamental physical quantities of galaxies. It is well-known that there are tight correlation between stellar mass and SFR of galaxies. A majority of galaxies follows a relation so-called main sequence (MS), and this correlation is likely to evolve towards high redshift across all environments (e.g., Whitaker et al. 2012; Koyama et al. 2013; Lee et al. 2015; Tomczak et al. 2016). On the other hand, galaxies undergoing active star formation (SF) that could be induced by major merger processes are located significantly above the MS, and they are referred to as starburst galaxies. So far, many works have investigated this stellar mass and SFR relation for various types of galaxies at various redshifts (e.g, Brinchmann et al. 2004; Daddi et al. 2007; Elbaz et al. 2007; Noeske et al. 2007). However, a comprehensive interpretation of the tight correlation and its redshift evolution is still unclear. In this work, we focus on infrared (IR)-bright dust-obscured galaxies (DOGs: Dey et al. 2008; Toba et al. 2015). Investigating this relation for IR-bright DOGs that trace the maximum phase of the co-evolution (e.g., Narayanan et al. 2010) could have a hint to solve this issue, although where infrared-bright DOGs lie in this plane is unknown. Therefore, we aim to see where IR-bright DOGs locate on the stellar mass and SFR plane in this work.

Recently, we successfully discovered a large number of IR-bright DOGs and investigated their physical and statistical properties such as IR luminosity function (Toba et al. 2015), auto-correlation function (Toba et al. 2017a), ionized-gas properties (Toba et al. 2017c), and molecular gas properties (Toba et al. 2017e). We also search for hyper-luminous IR galaxies among our sample (Toba & Nagao 2016; Toba et al. 2017d). However, their SF properties are still unknown because we lack deep and wide far-IR (FIR) data that are responsible for the SF activity. *AKARI* FIS all-sky survey catalog (Murakami et al. 2007; Kawada et al. 2007; Yamamura et al. 2010) is critical to constrain FIR properties such as SFR of our sample. Throughout this paper, we adopted a flat Universe with $H_0$ = 70 km s$^{-1}$ Mpc$^{-1}$, $\Omega_M$ = 0.3, and $\Omega_\Lambda$ = 0.7.

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## 2. DATA AND ANALYSIS

The dataset for sample selection and data analysis is summarized in Table 1. The IR-bright DOG parent sample was obtained from Toba & Nagao (2016) who selected 5,311 IR-bright DOGs with $i - [22] > 7.0$ and flux density at 22 $\mu$m > 3.8 mJy, where $i$ and [22] are $i$-band and 22 $\mu$m AB magnitudes, respectively, based on the ALLWISE (Wright et al. 2010; Cutri et al. 2014) and SDSS Data Release 12 (York et al. 2000; Alam et al. 2015) catalogs. We cross-identified this IR-bright DOG sample with *IRAS* FSC version 2 (Neugebauer et al. 1984; Beichman et al. 1988; Moshir et al. 1992) and *AKARI* FIR BSC version 2[1]. We utilized the NASA/IPAC Extragalactic Database (NED[2]) to compile the spectroscopic redshift. Eventually, we selected 7 IR-bright DOGs. In order to derive accurate stellar mass, we also used near-IR data from the TWOMASS Point Source Catalog (Skrutskie et al. 2006; Cutri et al. 2003) if available.

We then executed the SED fitting for the 7 IR-bright DOGs to derive the stellar mass and SFR. We employed the fitting code SEd Analysis using BAyesian Statistics (`SEABASs`[3]: Rovilos et al. 2014) that gives up to three-component fitting of stellar, SF, and active galactic nucleus (AGN) parts based on the maximum likelihood method. `SEABASs` provides a library of 1500 synthetic stellar templates from Bruzual & Charlot (2003) assuming a Chabrier (2003) initial mass function (IMF), and each model are reddened using a Calzetti et al. (2000) dust extinction law. `SEABASs` also calculates the IR luminosity contributed by SF, $L_{\rm IR}^{\rm SF}$ (8–1000 $\mu$m) that can be converted to the SFR by using a relation of $\log {\rm SFR} = \log L_{\rm IR}^{\rm SF} - 9.966$ (Salim et al. 2016, see also Toba et al. 2017b).

**Table 1.** Dataset for data analysis.

| Survey/Satellite name | Catalog version | Wavelength/Bands |
|---|---|---|
| SDSS | DR12 | $u, g, r, i, z$ |
| TWOMASS | PSC | $J, H, K_{\rm S}$ |
| *WISE* | ALLWISE | 3.4, 4.6, 12, 22 $\mu$m |
| *IRAS* | FSC version 2 | 12, 25, 60, 100 $\mu$m |
| *AKARI* | FIS BSC version 2 | 65, 90, 140, 160 $\mu$m |

## 3. WHERE DO IR-BRIGHT DOGS LIE ON THE STELLAR MASS– SFR PLANE?

Figure 1 shows the stellar mass and SFR relation of IR-bright DOGs and other population at various redshifts. The stellar mass and SFR of the main-sequence (MS) for star forming galaxies at $z < 0.3$ selected by the SDSS and *WISE* (Chang et al. 2015) is also shown in Figure 1. We also plotted the $M_*$–SFR relation of the MS of star forming galaxies at $z = 1$ and 2 presented by Elbaz et al. (2007) and Daddi et al. (2007), respectively. Note a possible offset of stellar masses for local SDSS sample is corrected in the same manner as Salim et al. (2016). We also corrected the stellar mass and SFR in the literature to those assumed 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), which indicates that the IR-bright DOG sample detected by *IRAS* and/or *AKARI* is starburst galaxies.

We also compared the $M_*$–SFR relation of IR-bright DOGs with a sample of ultra-luminous IR galaxies (ULIRGs) presented by Kilerci, Goto, & Doi (2014) after correcting a possible offset of stellar mass (Toba et al. 2017b). We found that some IR-bright DOGs have larger SFR value given a same stellar mass although remaining objects overlapped with local ULIRGs in SFR–$M_*$ plane. This offset could be explained by the difference of the redshift distribution. The redshift of our IR-bright DOG sample is less than 1.0 while that of ULIRG sample in Kilerci, Goto, & Doi (2014) is less than 0.5. However, whether of not this offset is statistically robust cannot be determined given the small sample of IR-bright DOGs. Capable instruments with longer wavelength than *AKARI* FIS such as *Herschel* and SCUBA-2/JCMT are available, which enables us to collect a large number of IR-bright DOG sample and to constrain their FIR and submillimeter SED.

The large offset of IR-bright DOG from MS in the stellar mass and SFR plane seems to be inconsistent with that of IR-faint DOGs with flux density at 24 $\mu$m < 1 mJy (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 author reported that they are widely distributed on SFR–$M_*$ plane (Calanog et al. 2013; Corral et al. 2016). However, the IR-bright DOG sample is relatively low-redshift ($z \sim 0.54$) compared with IR-faint DOG sample ($z \sim 2$). In addition, the MIR flux range of them is different. Therefore, the SF properties of IR-bright DOGs is not necessary to same as IR-faint (i.e.,

[1] http://www.ir.isas.jaxa.jp/AKARI/Observation/update/20160425_preliminary_release.html
[2] http://ned.ipac.caltech.edu/
[3] http://xraygroup.astro.noa.gr/SEABASs/

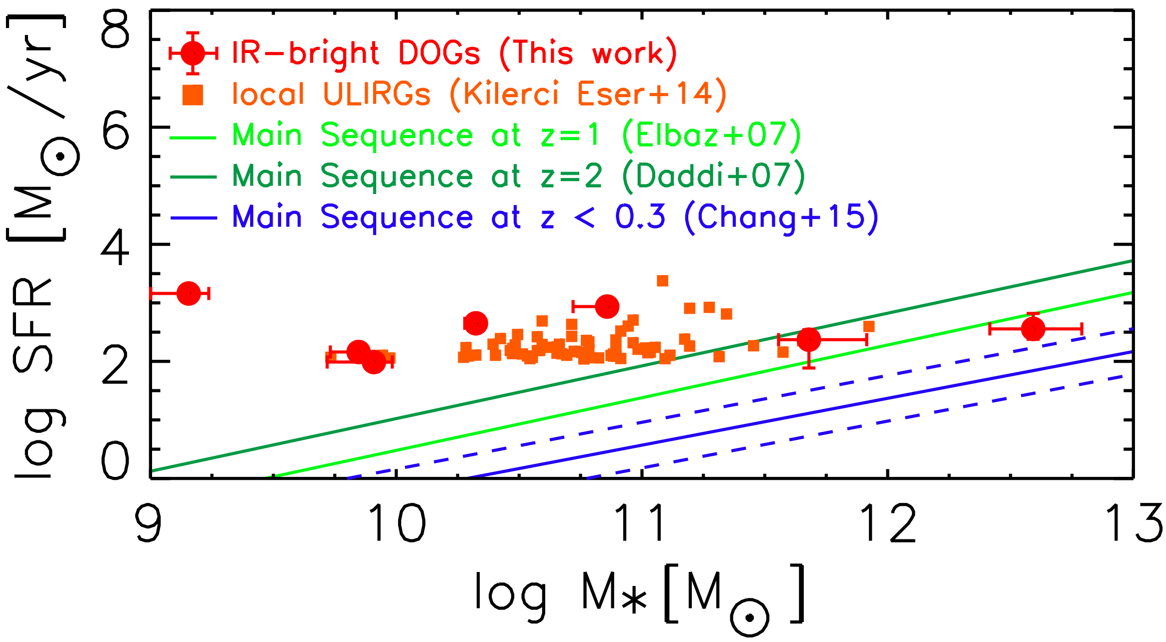


**Figure 1.** The relation between stellar mass and SFR for 7 IR-bright DOGs. Te orange squares represent SFR–$M_*$ relation for a sample of *AKAR*I-selected ULIRGs (Kilerci, Goto, & Doi 2014). The blue solid line is main sequence (MS) of star forming galaxies selected from the SDSS (Chang et al. 2015) with scatter of 0.39 dex (blue dotted line). The bin size is 0.2 × 0.2 in the units given in the plot. The light green line is MS of SF galaxies at $z$ = 1 (Elbaz et al. 2007) while the dark green lines are MS of star forming galaxies at $z$ = 2 (Daddi et al. 2007).

classical) DOGs. This work enables us to constrain 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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