SEARCH FOR HYPERLUMINOUS INFRARED DUST-OBSCURED GALAXIES SELECTED WITH WISE AND SDSS

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ABSTRACT

We aim to search for hyperluminous infrared (IR) galaxies (HyLIRGs) with IR luminosity \( L_{\text{IR}} > 10^{13} L_\odot \) by applying the selection method of dust-obscured galaxies (DOGs). They are spatially rare but could correspond to a maximum phase of cosmic star formation (SF) and/or active galactic nucleus (AGN) activity; hence, they are a crucial population for understanding the SF and mass assembly history of galaxies. Combining the optical and IR catalogs obtained from the Sloan Digital Sky Survey (SDSS) and Wide-field Infrared Survey Explorer (WISE), we performed the extensive HyLIRGs survey; we selected 5311 IR-bright DOGs with \( i - [22] > 7.0 \) and flux at 22 \( \mu \)m > 3.8 mJy in 14,555 deg\(^2\), where \( i \) and [22] are \( i \)-band and 22 \( \mu \)m AB magnitudes, respectively. Among them, 67 DOGs have reliable spectroscopic redshifts that enable us to estimate their total IR luminosity based on the spectral energy distribution fitting. Consequently, we successfully discovered 24 HyLIRGs among the 67 spectroscopically confirmed DOGs. We found that (i) \( i - [22] \) color of IR-bright DOGs correlates with the total IR luminosity and (ii) the surface number density of HyLIRGs is \( >0.17 \) deg\(^{-2}\). A large fraction (~73\%) of IR-bright DOGs with \( i - [22] > 7.5 \) show \( L_{\text{IR}} > 10^{13} L_\odot \), and the DOG criterion we adopted could be independently effective against the “WISE dropout method,” based on four WISE bands, for searching hyperluminous IR populations of galaxies.

Key words: catalogs – galaxies: active – infrared: galaxies – methods: statistical – surveys

1. INTRODUCTION

Galaxies whose infrared (IR) luminosity exceeds \( 10^{12} \) and \( 10^{13} L_\odot \) have been termed ultraluminous IR galaxies (ULIRGs; Sanders & Mirabel 1996) and hyperluminous IR galaxies (HyLIRGs; Rowan-Robinson 2000). Recently, galaxies whose IR luminosity exceeds \( 10^{14} L_\odot \) (so-called extremely luminous IR galaxies [ELIRGs]; Tsai et al. 2015) have been discovered. Their IR luminosity is thought to be generated by star formation (SF), active galactic nucleus (AGN) activity, or both. Although ULIRGs/HyLIRGs are very rare populations in the local universe, their relative abundance in galaxies is much higher at higher redshift. Accordingly, they dominate the IR energy density at redshifts \( z \approx 2 \), corresponding to the peak epoch of the cosmic SF and AGN activities (e.g., Caputi et al. 2007; Magnelli et al. 2009; Goto et al. 2011). Therefore, it is important to search for IR luminous galaxies such as ULIRGs and HyLIRGs in order to understand the galaxy formation and evolution and connection to their supermassive black holes (SMBHs).

One of the simple ways to select those IR luminous objects at \( z \approx 2 \) is to use the optical and IR color, \( R - [24] > 7.5 \), where \( R \) and [24] are \( R \)-band (0.65 \( \mu \)m) and Spitzer/MIPS (Rieke et al. 2004; Werner et al. 2004) 24 \( \mu \)m AB magnitude, respectively. This extreme optical–IR color indicates the presence of plenty of dust heated by active SF, AGNs, or both, and the bulk of the optical and ultraviolet (UV) emission from them is absorbed by the surrounding dust. Galaxies selected through this method are termed dust-obscured galaxies (DOGs; Dey et al. 2008). Some surveys with the Spitzer Space Telescope have discovered DOGs and investigated their properties (e.g., Houck et al. 2005; Brand et al. 2007; Brodwin et al. 2008; Bussmann et al. 2009, 2011, 2012; Desai et al. 2009; Melbourne et al. 2009, 2012). Recently, Toba et al. (2015) have discovered 48 DOGs whose IR luminosity is equivalent to that of HyLIRGs with the Hyper Suprime-Cam (HSC; Miyazaki et al. 2012) on the Subaru telescope and the Wide-field Infrared Survey Explorer (WISE: Wright et al. 2010), and they reported their statistical properties. However, since the survey area of these studies is limited to \( \sim 9 \) deg\(^2\) at maximum, it is quite difficult to collect an enormous number of HyLIRGs whose volume densities are extremely low, although they are expected to be a crucial population in terms of the coevolution of galaxies and SMBHs (see Hopkins et al. 2008; Narayanan et al. 2010).

In this paper, we present an effective method of searching for HyLIRGs by performing the largest DOG survey based on WISE and the Sloan Digital Sky Survey (SDSS; York et al. 2000). The large survey area of these catalogs is a key for identifying statistically significant samples of rare yet luminous sources. Throughout this paper, the adopted cosmology is a flat universe with \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_M = 0.3 \), and \( \Omega_L = 0.7 \). Unless otherwise noted, all magnitudes refer to the AB system.

2. DATA AND ANALYSIS

2.1. Sample Selection

We selected DOGs based on the WISE and SDSS catalogs.\(^1\) WISE performed an all-sky survey at 3.4 \( \mu \)m (W1), 4.6 \( \mu \)m (W2), 12 \( \mu \)m (W3), and 22 \( \mu \)m (W4) with angular resolutions of 6\(''\)1, 6\(''\)4, 6\(''\)5, and 12\(''\)0, respectively (Wright et al. 2010). We utilized the latest catalog, “AllWISE” Data Release (Cutri et al. 2014), in which the 5\(\sigma\) photometric sensitivity for 3.4, 4.6, 12, and 22 \( \mu \)m is better than 0.054, 0.071, 1, and 6 mJy (corresponding to 19.6, 19.3, 16.4, and

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\(^1\) For the selection process, we employed TOPCAT based on the Starlink Tables Infrastructure Library (STIL), which is an interactive graphical viewer and editor for tabular data (Taylor et al. 2005).
14.5 mag), respectively. The WISE catalog contains the Vega magnitude of each source, and we converted these to AB magnitude, using offset values $\Delta m (m_{AB} = m_{Vega} + \Delta m)$ for 3.4, 4.6, 12, and 22 $\mu$m of 2.699, 3.339, 5.174, and 6.620, respectively, according to the Explanatory Supplement to the AllWISE Data Release Products.\(^2\) SDSS Data Release 12 (DR12) is the final data release of the SDSS-III, containing all SDSS observations (Alam et al. 2015). This catalog contains 469,053,874 unique and primary sources imaged over 14,555 deg\(^2\) in five bands ($u, g, r, i, z$) and 4,355,200 spectra. The limiting magnitudes (95% completeness for point sources) are 22.0, 22.2, 21.3, and 20.5 for $u, g, r, i$, and $z$, respectively. Note that magnitudes in $u$ and $z$ band are slightly different from AB magnitude; we thus used $\Delta m = -0.04$ and 0.02 for $u$ and $z$ band, respectively.\(^3\) The flowchart of our sample selection process is shown in Figure 1.

We first created the “clean” subsample for each catalog, considering the detection and photometry flags that ensure reliable detection and photometry. To avoid the contamination from galactic stars, we narrowed our sample to sources at high galactic latitudes, $|b| > 20^\circ$. In addition, we extracted sources with signal-to-noise ratio ($S/N$) greater than 5 and 3 at $i$ band and 22 $\mu$m, respectively, which yielded 198,137,866 sources in the SDSS sample and 3,471,994 in the WISE sample. In this paper, we employed the profile-fit magnitude and CmodelMag for each source in the WISE and SDSS catalogs, respectively, which traces total flux (hereinafter we use $u, g, r, i$, and $z$ as a shorthand alias for CmodelMag). We do not correct galactic extinction for SDSS photometry since our sample is located at relatively high galactic latitudes. We then cross-identified WISE sources with SDSS sources with a search radius of

![Flowchart of our DOG selection process. Numbers in this figure denote the number of selected objects at each step.](http://wise2.ipac.caltech.edu/docs/release/allwise/expsup/)

\(^2\) http://wise2.ipac.caltech.edu/docs/release/allwise/expsup/

\(^3\) http://www.sdss.org/dr12/algorithms/fluxcal/#SDSStoAB
SDSS pipeline with visual inspection

Figure 2. Redshift distribution of 67 WISE–SDSS spec DOGs. The blue histogram represents redshift determined from the SDSS pipeline. The red histogram represents improved redshift determined by the SDSS pipeline and visual inspection.

3″ and extracted 935,425 objects (hereinafter WISE–SDSS objects). Note that 61,659 WISE objects (~2% of the matched sources) have more than one SDSS candidate counterpart owing to the significant difference of the angular resolution between them. We choose the nearest SDSS object as a counterpart for those cases. For these 935,425 WISE–SDSS objects, we adopted the DOG selection criterion: $i - [22] > 7.0$ (Toba et al. 2015)$^4$, where $i$ and [22] represent i-band (0.75 μm) and 22 μm band magnitude, respectively. As a result, 5311 DOGs (hereinafter WISE–SDSS photo DOGs) were selected. Note that the main difference of the WISE–SDSS photo DOGs and classical DOGs discovered by Dey et al. (2008) is the mid-IR (MIR) flux; we selected DOGs with S/N (22 μm) > 3, corresponding to ∼3.8 mJy, which is much brighter than the 0.3 mJy at 24 μm selected by Dey et al. (2008). We focus on these “IR-bright DOGs” with $i - [22] > 7.0$ and flux at 22 μm > 3.8 mJy. For them, we extracted DOGs with reliable spectroscopic information with SciencePrimary = 1 and zWarning = 0. Finally, 67 DOGs (hereinafter WISE–SDSS spec DOGs) were selected through these steps.

Figure 2 shows the redshift distribution for WISE–SDSS spec DOGs. Note that the pipeline of the SDSS sometimes misidentifies the redshift even for sources with zWarning = 0. We hence checked each spectrum visually and reidentified the redshift for 10 objects that have doubtful redshift. Figure 3 shows the example of spectra of objects whose redshift determined by the SDSS pipeline seems to be misidentified.

As shown in Figure 2, the redshift distribution of the WISE–SDSS spec DOGs is bimodal with peaks around $z \sim 0.8$ and $z \sim 2.6$, which is in good agreement with that of Ross et al. (2015). Although they focused on the extremely red quasars selected from WISE and the SDSS, some of them should be overlapped with our sample. We will present the detailed spectroscopic properties of these WISE–SDSS spec DOGs in a forthcoming paper. Figure 4 presents the 22 μm flux and i-band magnitude distributions for our sample. The average 22 μm flux densities for WISE–SDSS photo DOGs and spec DOGs are ∼13.3 and ∼23.0 mJy, respectively, while their average i-band magnitude are ∼21.5 and ∼20.9 mag, respectively.

2.2. Cross-identification with AKARI

In order to obtain far-IR (FIR) data and perform a reliable spectral energy distribution (SED) fitting, we utilized data from the AKARI satellite. AKARI, the first Japanese space satellite dedicated to IR astronomy, was launched in 2006 (Murakami et al. 2007). AKARI performed an all-sky survey at 9, 18, 65, 90, 140, and 160 μm, whose spatial resolution and sensitivity are much better than those of the Infrared Astronomical Satellite (IRAS); Neugebauer et al. 1984; Beichman et al. 1988), and MIR and FIR point source catalogs are publicly released. The AKARI/IRC MIR all-sky survey catalog (Onaka et al. 2007; Ishihara et al. 2010) contains 870,973 sources observed at 9 and 18 μm, while the AKARI/FIS FIR all-sky survey catalog (Kawada et al. 2007; Yamamura et al. 2010) contains 427,701 sources observed at 65, 90, 140, and 160 μm. In particular, the AKARI FIR survey provides the deepest data in terms of the FIR all-sky data and thus should be useful in deriving the total IR luminosity. We cross-identified 67 WISE–SDSS spec DOGs with both catalogs where search radii for MIR and FIR catalogs are 6″ and 60″, respectively. As a result, however, our sample has no counterparts of AKARI MIR and FIR sources. Nevertheless, this result can constrain the MIR and FIR fluxes for our sample as an upper limit. In this study, we adopted 5σ detection limits, 0.05, 0.12, 2.4, 0.55, 1.4, and 6.3 Jy, as upper limits at 9, 18, 65, 90, 140, and 160 μm, respectively (Kawada et al. 2007; Ishihara et al. 2010).

2.3. SED Fitting

We estimated the total IR luminosity, $L_{IR}$ (8–1000 μm), for the 67 WISE–SDSS spec DOGs based on the SED fitting technique. We employed the fitting code SED Analysis using BAYesian Statistics (SEABASS);$^5$ Rovilos et al. (2014), which provides up to three-component fitting (AGN, SF, and stellar component) based on the maximum likelihood method. Since we do not have deep rest-frame MIR/FIR photometry responsible for SF activity (see Section 2.2), we simply performed AGN and stellar component fitting for the 15 photometric points ($u, g, r, i, z,$ and $3.4, 4.6, 9, 12, 18, 22, 65, 90, 140,$ and $160 \, \mu m$) with SDSS, WISE, and AKARI data and estimated the total IR luminosity. For the AGN templates, we utilized the library of Silva et al. (2004), which contains torus templates with varying extinction ranging from $N_H$ = 0 to $N_H = 10^{25}$ cm$^{-2}$. We also used the library of Polletta et al. (2007) representing optically selected QSOs with different values of IR/optical flux ratios (QS01, TQS01, and BQS01) and two type 2 QSOs (QSO2, Torus) (see Polletta et al. 2007 for more details). Figure 5 shows the SEDs of the AGN template we used. For the stellar templates, SEABASS gives a library of 1500 synthetic stellar templates from Bruzual & Charlot (2003) stellar population models with solar metallicity and a range of SF histories and ages, and each model is reddened using a Calzetti et al. (2000) dust extinction law.

$^4$ In that paper, we adopted a prior cut ($i - K_s > 1.2$) for HSC sources before cross-matching with WISE to avoid the false identification due to the significant difference of their angular resolutions. In the case of the SDSS and WISE, however, the probability of the false identification is much smaller because the detection limit of the SDSS data is much shallower than that of the HSC. We thus just cross-identified the SDSS and WISE without adopting any prior cut.

$^5$ http://xraygroup.astro.noa.gr/SEABASS/
Note that the uncertainties of the derived $L_{\text{IR}}$ contain not only statistical error but also systematic error. SEABASS can calculate $L_{\text{IR}}$ for “every” trial fit and estimate the likelihood value (corresponding to the chi-square) for each case, and it provides us with the uncertainties as the $2\sigma$ confidence interval. Therefore, the influence of the difference between the inputted SED templates on the derived $L_{\text{IR}}$ is included in the uncertainty. However, the above uncertainty does not consider the influence of the absence of the SF component when executing the SED fitting. We discuss this influence on the derived $L_{\text{IR}}$ in Section 4.1.

Figure 6 shows the example of the SED fitting. The typical uncertainties of $L_{\text{IR}}$ are 5%–8% (but see Section 4.1). The best-fit AGN template tends to favor the “torus” template presented by Silva et al. (2004) or Polletta et al. (2007), which is consistent with the report by Tsi et al. (2015) based on the WISE-selected IR luminous sources.

3. RESULT

Figure 7 shows the histogram of resultant total IR luminosity ($L_{\text{IR}}$) for 67 WISE–SDSS DOGs. Consequently, we successfully discovered 24 HyLIRGs. Among those “hyperluminous DOGs,” 19 objects are $z > 2$, while 5 objects are $z < 2$. In addition, two objects with $L_{\text{IR}} = 1.2^{+0.03}_{-0.04} \times 10^{14} L_\odot$ and $L_{\text{IR}} = 1.1^{+0.10}_{-0.12} \times 10^{15} L_\odot$ were identified to be ELIRGs (but see Section 4.1). The examples of the SDSS spectra are shown in Figure 8. Those 24 hyperluminous DOGs are expected to harbor AGNs since we confirmed the presence of the C iv $\lambda1549$ line for all of the $z > 2$ HyLIRGs and the [Ne v] $\lambda3426$ line for all of the $z < 2$ HyLIRGs. Since the ionization potentials of C iv and [Ne v] are 64.5 and 97.1 eV, respectively, those lines cannot be present without AGNs. Therefore, the AGN activity contributes more or less to the total IR luminosity.

Figure 9 shows the relation between the redshift and $L_{\text{IR}}$ for WISE–SDSS spec DOGs. Note that those IR luminosities are to be a lower limit since we do not use the SF template when performing the SED fitting, although one should keep in mind that there could be a large uncertainty due to the lack of good constraints at FIR (see Section 4.1).

4. DISCUSSION

4.1. Uncertainties in the Derived IR Luminosity

In this study, we derived $L_{\text{IR}}$ based on the SED fitting given the SED template of stellar and AGN components, without...
considering the SF component. However, one caution is that the current data do not always constrain the peak of the SED. In the case of high-$z$ objects, in particular, the peak wavelength of the SED contributed from AGNs is beyond the longest detection at 22 μm (see, e.g., the lower right panel of Figure 6), which induces the large uncertainties of $L_{\text{IR}}$. If the SF component affects their 12 and 22 μm flux, the derived $L_{\text{IR}}$ has a potential not only of underestimating, as described in Section 2.3, but also of overestimating owing to the lack of data covering the peak of the SED of the AGN component. We discuss here how the AGN template will be affected and how the overall SED and derived $L_{\text{IR}}$ will change correspondingly, when executing the SED fitting with or without the SF component for our data.

We evaluate this effect based on the 113 DOGs presented by Melbourne et al. (2012), who also derived the $L_{\text{IR}}$ for DOGs by performing the SED fitting. The DOG sample used for the SED fitting was originally discovered by deep optical and MIR imaging taken with the NOAO Deep Wide-field Survey (Jannuzi & Dey 1999) and Spitzer. They have 11 photometries ($B_w$, $R$, $I$, and 3.6, 4.5, 5.8, 8.0, 24, 250, 350, 500 μm), where the optical, MIR, and FIR data are taken with KPNO, Spitzer/IRAC (Fazio et al. 2004) and MIPS, and Herschel/SPIRE (Griffin et al. 2010; Pilbratt et al. 2010), respectively, and have spectroscopic redshift. In particular, deep FIR data are used for determining their precise $L_{\text{IR}}$, and photometric data and resultant $L_{\text{IR}}$ for each DOG are available in Melbourne et al. (2012).

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First, we check the consistency of the $L_{\text{IR}}$ derived from our method (i.e., the SED fitting with SEABASS) and those in Melbourne et al. (2012); we calculated the $L_{\text{IR}}$ for the same

Figure 6. Examples of the SED fitting for our sample. The blue diamond and pink square represent the data from the SDSS and WISE, respectively. The green circle represents the 5σ upper limit obtained from AKARI data. The contributions from the stellar and AGN components to the total SEDs are shown with blue and red lines, respectively. The black solid line represents the resultant (the combination of the stellar and AGN) SEDs.

Figure 7. Distribution of the total IR luminosity for WISE–SDSS DOGs. The orange histogram represents $L_{\text{IR}}$ for HyLIRGs, while the red histogram represents that for ELIRGs. Numbers in parentheses denote the number of objects.
data as Melbourne et al. (2012) by executing SEABASs with stellar/AGN/SF components and compared them with the $L_{\text{IR}}$ given in Melbourne et al. (2012). For the SF components, we utilized the SED library presented by Polletta et al. (2007). Figure 10 shows the comparison of $L_{\text{IR}}$ derived by SEABASs and Melbourne et al. (2012), which indicates that they are roughly consistent with each other.

Next, we calculate the $L_{\text{IR}}$ based on SEABASs without the SF template (i.e., stellar + AGN templates) for the same data and compare them with those in Melbourne et al. (2012), as shown in Figure 11. This result indicates that the lack of an SF component basically induces the underestimate of $L_{\text{IR}}$ when performing the SED fitting, whereas the absence of the SF component has the potential of overestimating DOGs with a very large $L_{\text{IR}}$. Figure 12 shows an example of the SED fitting with or without the SF component for two DOGs (we call them “DOG 1” and “DOG 2” tentatively). The $L_{\text{IR}}$ derived by Melbourne et al. (2012) is $7.3 \times 10^{12} L_\odot$ and $4.9 \times 10^{13} L_\odot$ for DOG 1 and DOG 2, respectively. The $L_{\text{IR}}$ derived by SEABASs with the SF component is $7.72 \times 10^{12} L_\odot$ and $4.42 \times 10^{13} L_\odot$ for DOG 1 and DOG 2, respectively, which is in good agreement with those of Melbourne et al. (2012). On the other hand, the $L_{\text{IR}}$ derived by SEABASs without the SF component is $2.20 \times 10^{12} L_\odot$ and $1.27 \times 10^{13} L_\odot$ for DOG 1 and DOG 2, respectively, which means that we underestimate the IR luminosity for DOG 1 while we overestimate it for DOG 2. In this case, the absence of the SF component influences the
derived $L_{\text{IR}}$ by a factor of 3–4. In any case, one should keep in mind this uncertainty when discussing the $L_{\text{IR}}$.

As discussed above, in the case of having the deep Herschel data, the derived $L_{\text{IR}}$ is reliable with small uncertainties. However, in this study, we performed the SED fitting for including AKARI data that give the upper limit of the FIR flux. If we do not have deep Herschel data but have only much shallower AKARI/FIS data as in this work, can AKARI data do a similar job in having good constraints to the IR luminosity? To address this issue, we estimate the $L_{\text{IR}}$ for KPNO+Spitzer+AKARI/FIS data for DOG 1 and DOG 2 and compare with those derived from KPNO+Spitzer+Herschel. The resultant $L_{\text{IR}}$ are $2.39 \times 10^{12} L_\odot$ and $2.96 \times 10^{14} L_\odot$, which is 0.31 and 6.70 times larger than those derived with Herschel data, respectively. Therefore, the upper limit of AKARI/FIS photometry could not work very well for high-$L_{\text{IR}}$ objects because they are usually those with a fitted AGN peak at much longer wavelengths than 22 $\mu$m. In addition to the absence of the SF component, one should keep in mind that the absence of deep FIR data also influences the derived $L_{\text{IR}}$.

4.2. A New Effective Method for Searching for HyLIRGs

The relation between $i - [22]$ and $L_{\text{IR}}$ as shown in Figure 13 gives us a clue of the effective search for HyLIRGs. This figure indicates that objects with redder $i - [22]$ color tend to have higher IR luminosity, although there is large scatter. In order to investigate how reliable this correlation is quantitatively, we performed the Spearman’s rank order test for individual data. The resultant Spearman’s rank coefficient for this correlation is 0.51, corresponding to a null hypothesis probability of $9.9 \times 10^{-5}$. This means that $i - [22]$ and $L_{\text{IR}}$ for IR-bright DOGs have a positive correlation with a high significance. This correlation can be interpreted qualitatively as follows: The IR luminosity is generated by a combination of SF, AGNs, or both, and the contribution of AGNs to the IR luminosity increases with increasing IR luminosity (e.g., Sanders & Mirabel 1996; Yuan et al. 2010; Ichikawa et al. 2014). On the other hand, the $i - [22]$ value mostly corresponds to the extinction, which correlates with SFR at larger stellar mass (e.g., Zahid et al. 2013). In the scenario that ULIRGs/HyLIRGs emerged through the major merger (e.g., Kartaltepe et al. 2010), the absolute contribution of both AGNs and SF can be increased and HyLIRGs could correspond to maximum phase in terms of AGN and SF activity (see also Hatziminaoglou et al. 2010). This leads to a positive correlation between $L_{\text{IR}}$ and $i - [22]$ color.

Figure 14 shows the fraction of HyLIRGs as a function of $i - [22]$ color. When focusing on DOGs with $i - [22] > 7.5$, almost 70% of objects are HyLIRGs, which is a valuable guideline for performing systematic surveys of HyLIRGs/ELIRGs. The number of SDSS–WISE photo DOGs with $i - [22] > 7.5$ is 1327; thus, this sample probably contains ~930 HyLIRGs. Note that the above correlation is seen in DOGs with 22 $\mu$m flux greater than 3.8 mJy, and thus our result may not be applicable for IR-faint DOGs. Therefore, further studies on the relation between the $i - [22]$ color and the HyLIRG fraction are needed to generalize this method for HyLIRG searches, which is beyond the scope of this paper.

Note also that IR luminosities of those ELIRGs are potentially amplified by the effect of beaming and/or gravitational lensing even if the derived $L_{\text{IR}}$ is reliable. It is quite difficult to reject these possibilities quantitatively based on the currently available data. Hence, we just mention here some observational supports for possible HyLIRGs. For the potential of the beaming effect, we checked their variability flag at 22 $\mu$m in the ALLWISE catalog because the beaming effect could induce rapid variability as discussed in Tsai et al. (2015). As a result, 10 objects, including possibly two ELIRGs, have var_flg = 0, which means that they are expected to show no variability, while four objects have 1 < var_flg < 2, meaning that they could show very weak variability. The remaining 10 objects have var_flg = “n,” which indicates insufficient or inadequate data to make a determination of possible variability. Note that although the estimate of the flux variability is unreliable for an extended source with ext_flg > 0 or for one contaminated by an image artifact with cc_flag $\neq 0$ in the pipeline of ALLWISE, our sample has ext_flg = 0 and cc_flag = 0; hence, the estimate of the flux variability should be reliable. For the potential of a lensing effect, $i - [22]$ color dependence of IR luminosity indicates that the extreme IR luminosities of those HyLIRGs are unlikely due to the lensing. If their IR luminosities are just amplified by lensing, their $i - [22]$ colors are expected to be comparable to those of ULIRGs, but indeed their $i - [22]$ colors get redder. Therefore, the influence of the beaming and lensing on $L_{\text{IR}}$ for most HyLIRGs discovered in this work could be expected to be small.

4.3. Relation with “W1W2-dropouts”

Recently, some authors have reported that a method based on the WISE color is also useful to discover HyLIRGs and ELIRGs (e.g., Eisenhardt et al. 2012; Wu et al. 2012; Tsai et al. 2015). Most of objects that 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) can be classified as HyLIRGs, and some of them are ELIRGs. These objects are termed “W1W2-dropouts” or “Hot DOGs” (Eisenhardt et al. 2012; Wu et al. 2012). Since our sample of HyLIRGs/ELIRGs is selected based on WISE data, we checked whether our sample satisfies the criteria for W1W2-dropouts.

The most critical selection criteria for W1W2-dropouts are $W1 > 17.4$ and either (i) $W4 < 7.7$ and $W2 - W4 > 8.2$ or (ii) $W3 < 10.6$ and $W2 - W3 > 5.3$, where all magnitudes are Vega magnitudes (for details, see Eisenhardt et al. 2012). When
adopting the above criteria for WISE–SDSS spec DOGs, only one object satisfied the criteria. This object is located at $z = 3.14$ and classified as a HyLIRG in our sample, which is represented by a blue square in Figure 9. The fact that almost none of the objects in our sample satisfy the criteria of W1W2-dropouts is reasonable because W1W2-dropouts are expected to be very faint in the optical owing to their steep continuum, and thus relatively shallow imaging in the SDSS spectroscopic catalog could miss a large number of W1W2-dropouts.

Figure 12. Examples of the SED fitting for two DOGs in Melbourne et al. (2012). The upper and lower panels show an example of the underestimate and overestimate of the $L_{IR}$, respectively. The blue diamond, pink square, and green circle represent the data from KPNO, Spitzer, and Herschel, respectively. The contributions from the stellar, AGN, and SF components to the total SEDs are shown with blue, red, and green lines, respectively. The black solid line represents the resultant (the combination of the stellar and AGN, or stellar, AGN, and SF) SEDs.

Figure 13. Relation between $L_{IR}$ and $i - [22]$ color for WISE–SDSS spec DOGs. The pink asterisks represent the individual data, while the red squares represent the average and its standard deviation per log $L_{IR}$ bin.

Figure 14. Fraction of HyLIRGs as a function of $i - [22]$ color for WISE–SDSS spec DOGs. Error in the fraction was estimated using binomial statistics (see Gehrels 1986). The color interval is optimized to keep the data points more or less equal for each bin.
dropouts. In other words, most HyLIRGs selected based on $i - [22]$ color do not duplicate those in the W1W2-dropout method, suggesting that our selection method could be independently useful for selecting HyLIRGs. We emphasize that those selection methods are complementary. The W1W2-dropout method could be sensitive to heavily absorbed HyLIRGs, while our method is sensitive to less or moderately absorbed (compared with W1W2-dropouts) HyLIRGs. In that sense, our method is complemental compared with the W1W2-dropout method.

4.4. Surface Number Density of Hyperluminous DOGs

We here estimate the surface number density of hyperluminous DOGs (IR-bright DOGs that satisfy HyLIRGs’ criterion in a strict sense) and compared it with that of other samples presented by Bridge et al. (2013), who selected HyLIRGs based on a WISE color similar to W1W2-dropouts with an optical magnitude cut ($r \sim 22$). They reported that these objects have a surface density of $\sim 0.1$ deg$^{-2}$. It should be noted that since DOGs are generally faint in the optical, our HyLIRG search with SDSS could induce a significant sample incompleteness. In addition, the selection function of the SDSS spectroscopic survey is complicated. In this paper, we hence simply estimate the lower limit of surface number density by assuming that (i) the $22 \mu$m flux of the hyperluminous DOGs almost reaches the 100% completeness (i.e., completeness correction in terms of the WISE survey can be neglected) and (ii) the WISE–SDSS photo DOGs are approximately completely selected by at least the depth of the SDSS spectroscopic survey, which is shallower than the photometric survey.

Under these assumptions, the surface number density of hyperluminous DOGs ($N_{\text{HyLIRG}}$) can be derived as the sum of the expected number of possible HyLIRGs in the WISE–SDSS photo DOG sample and HyLIRGs discovered in this study, per each apparent $i$-band magnitude bin:

$$N_{\text{HyLIRG}} = \frac{1}{A} \sum_{j} N S_j(m_i) \times n^p_j(m_i) + n^H_j(m_i),$$

(1)

where $N$ is the number of apparent $i$-band magnitude bins, $A$ is the survey area ($14,555$ deg$^2$) in this study, and $S_j(m_i)$ is the scaling factor that is the ratio of the number of hyperluminous DOGs to the WISE–SDSS spec DOGs in each $j$ bin. $n^p_j(m_i)$ and $n^H_j(m_i)$ are the number of WISE–SDSS photo DOGs without spectroscopic information and hyperluminous DOGs discovered in this study, in each $j$ bin, respectively. As a result, we obtained $N_{\text{HyLIRG}} > 0.17$ deg$^{-2}$, which is roughly consistent with those derived by Bridge et al. (2013).

5. SUMMARY

In this work, we performed a search for HyLIRGs with $L_{IR} > 10^{13} L_{\odot}$, which are most likely to be traced to the maximum phase in terms of the SF and AGN activity and thus are an important population for understanding the SMBH–galaxy co-evolution. We utilized the latest WISE and SDSS catalogs and selected 67 candidates of hyperluminous DOGs with $22 \mu$m flux $>3.8$ mJy based on the criterion of the DOG selection ($i - [22] > 7.0$). We then executed the SED fitting for the data obtained from AKARI, WISE, and SDSS to estimate their $L_{IR}$. The main results are as follows:

1. We succeed in discovering 24 HyLIRGs, including two possible ELIRGs with $L_{IR} > 10^{13} L_{\odot}$.
2. Their $i - [22]$ color correlates with $L_{IR}$; the detection rate of HyLIRGs is about 73% when extracting the IR-bright DOGs with $i - [22] > 7.5$, which is a useful method to search for these IR luminous galaxies.
3. Among 24 HyLIRGs, only one object satisfies the criteria of W12-dropouts, whose $L_{IR}$ are equivalent to those of HyLIRGs selected based only on WISE data, which means that the suggested method in this study could be independently effective against the W12-dropout method.
4. The surface number density of 24 hyperluminous DOGs is $\sim 0.17$ deg$^{-2}$, which is roughly consistent with that of previous works.

This study is based on WISE and SDSS spectroscopic data, with photometric sensitivities shallower than those of the SDSS photometric data, which means that our sample is biased to optically bright sources. We are proposing to follow up with observations for WISE–SDSS photo DOGs to extend our HyLIRG survey to more optically faint HyLIRGs. We will check whether or not the correlation between $i - [22]$ and $L_{IR}$ can be seen for optically faint HyLIRGs. In that sense, this work is an important benchmark for forthcoming HyLIRG surveys.

We are planning to summarize their spectroscopic properties and to report the relation among these quantities, such as equivalent width of emission lines and IR luminosities. All of the information for 67 WISE–SDSS spec DOGs, including the specobjID, coordinates, and IR luminosity, will be presented in a forthcoming paper.

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