Ichikawa, Kohei and Ricci, Claudio and Ueda, Yoshihiro and Bauer, Franz E. and Kawanago, Taiki and Koss, Michael J. and Oh, Kyuseok and Rosario, David J. and Shimizu, T. Taro and Stalevski, Marko and Fuller, Lindsay and Packham, Christopher and Trakhtenbrot, Benny (2019) 'BAT AGN Spectroscopic Survey. XI. The covering factor of dust and gas in swift/BAT active galactic nuclei.', Astrophysical journal., 870 (1). p. 31.

Further information on publisher’s website:
https://doi.org/10.3847/1538-4357/aaef8f

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BAT AGN Spectroscopic Survey. XI. The Covering Factor of Dust and Gas in Swift/BAT Active Galactic Nuclei

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Received 2018 March 7; revised 2018 October 12; accepted 2018 November 2; published 2019 January 2

Abstract

We quantify the luminosity contribution of active galactic nuclei (AGNs) to the 12 μm, mid-infrared (MIR; 5–38 μm), and total IR (5–1000 μm) emission in the local AGNs detected in the all-sky 70 month Swift/Burst Alert Telescope (BAT) ultrahard X-ray survey. We decompose the IR spectral energy distributions (SEDs) of 587 objects into the AGN and starburst components using templates for an AGN torus and a star-forming galaxy. This enables us to recover the emission from the AGN torus including the low-luminosity end, down to \(\log(L_{14-150 \mu m}/erg s^{-1}) \approx 41\), which typically has significant host galaxy contamination. The sample demonstrates that the luminosity contribution of the AGN to the 12 μm, the MIR, and the total IR bands is an increasing function of the 14–150 keV luminosity. We also find that for the most extreme cases, the IR pure-AGN emission from the torus can extend up to 90 μm. The total IR AGN luminosity obtained through the IR SED decomposition enables us to estimate the fraction of the sky obscured by dust, i.e., the dust covering factor. We demonstrate that the median dust covering factor is always smaller than the median X-ray obscuration fraction above an AGN bolometric luminosity of \(\log(L_{bol}/erg s^{-1}) \approx 42.5\). Considering that the X-ray obscuration fraction is equivalent to the covering factor coming from both the dust and gas, this indicates that an additional neutral gas component, along with the dusty torus, is responsible for the absorption of X-ray emission.

Key words: galaxies: active – galaxies: nuclei – infrared: galaxies

Supporting material: figure set, machine-readable table

1. Introduction

One of the fundamental open questions of extragalactic astrophysics is how supermassive black holes (SMBHs) and their host galaxies coevolve (e.g., Alexander & Hickox 2012). Active galactic nuclei (AGNs) are the best targets for understanding this process of coevolution, because they are in the stage where mass accretion onto SMBHs occurs with the release of large amounts of radiation (e.g., Yu & Tremaine 2002; Marconi et al. 2004), until they reach their maximum achievable mass of \(M_{BH} \approx 10^{10.5} M_{\odot}\) (Netzer 2003; McLure & Dunlop 2004; Trakhtenbrot et al. 2014; Jun et al. 2015; Inayoshi & Haiman 2016; Ichikawa & Inayoshi 2017).

Ultrahard (\(E > 10\) keV) X-ray observations are one of the most reliable methods for identifying AGNs. Thanks to the combination of (1) a strong penetration power up to \(\log(N_{HI}/cm^{-2}) \approx 24\) (e.g., Ricci et al. 2015) and (2) the high contrast with stellar X-ray emission (e.g., Mineo et al. 2012), ultrahard X-ray surveys allow an unbiased census of AGNs up to Compton-thick levels (e.g., Koss et al. 2016). Among the recent available surveys, Swift/BAT provides the most sensitive X-ray survey of the whole sky in the 14–195 keV range, reaching a flux level of \((1.0–1.3) \times 10^{-11} erg s^{-1} cm^{-2}\) in the first 70 months of operations (Baumgartner et al. 2013), and a deeper flux of \((7.2–8.4) \times 10^{-12} erg s^{-1} cm^{-2}\) in the recently updated 105 month catalog (Oh et al. 2018).

Infrared (IR) observations also provide an effective method to study AGNs because the central engine of an AGN is expected to be surrounded by a dusty “torus” (Krolik & Begelman 1986), which is heated by the AGN and re-emits thermally in the mid-IR (MIR) (e.g., Gandhi et al. 2009;...
Ichikawa et al. 2012, 2017; Asmus et al. 2015). A recent upward revision of black hole scaling relations (Kormendy & Ho 2013) indicates that the local mass density in black holes should be higher, suggesting that a larger population of heavily obscured AGN gas and dust is required to fill the mass gap of the revised local black hole mass density (e.g., Novak 2013; Comastri et al. 2015). These populations contribute significantly to the infrared background (e.g., Murphy et al. 2011; Delvecchio et al. 2014), especially in the MIR band (Risaliti et al. 2002). However, since star formation from the host galaxy sometimes contaminates the MIR emission, especially for low-luminosity AGNs with L_{44–150} < 10^{43} \text{ erg s}^{-1} (e.g., Ichikawa et al. 2017), and the torus is too compact (<10 pc; e.g., Jaffe et al. 2004) to be fully resolved (e.g., García-Burillo et al. 2016; Imanishi et al. 2018), the precise estimation of AGN thermal activity is not straightforward.

Fortunately, several methods have been proposed to isolate the emission from the torus from the starburst component. One of them is to use MIR observations with high spatial resolution (∼0′′–0′′.7) to resolve the starburst emission of the host galaxies down to scales of 10 pc (Packham et al. 2005; Radomski et al. 2008; Höning et al. 2010; Alonso-Herrero et al. 2011, 2016; Ramos Almeida et al. 2011; González-Martín et al. 2013; Asmus et al. 2014; Ichikawa et al. 2015; Martínez-Paredes et al. 2017). In addition, the advent of IR interferometric observations, with their exquisite resolving power (with baselines up to 130 m), has spatially resolved the dusty nuclear regions and shown that their outer radii in the MIR are typically several parsecs (e.g., Jaffe et al. 2004; Raban et al. 2009; Burtcher et al. 2013). Notably, some show the polar elongated dust emission suggestive of a dusty outflow (Höning et al. 2012, 2013; Tristram et al. 2014; López-Gonzaga et al. 2016, Leftley et al. 2018). However, because of the limited sensitivity and the spatial resolution of current telescopes (see a recent review by Burtcher et al. 2016), these two methods are available only for a few tens of bright sources located in the very local universe (z < 0.01). Another possible approach is to separate the spectral emission of the AGN and the starburst (SB) component. Multiple decomposition methods have been applied to MIR spectra, mainly using aromatic features as a proxy for star formation (e.g., Tran et al. 2001; Lutz et al. 2004; Sajina et al. 2007; Alonso-Herrero et al. 2012; Ichikawa et al. 2014; Hernán-Caballero et al. 2015; Kirkpatrick et al. 2015; Symeonidis et al. 2016), to broadband IR spectral energy distributions (SEDs, e.g., da Cunha et al. 2008; Hatziminaoglou et al. 2008; Xu et al. 2015; Lyu et al. 2016, 2017; Shimizu et al. 2017), and to the combination of both spectra and SEDs (e.g., Mullaney et al. 2011). The advantage of the SED decomposition is that it is less affected by the differing spatial resolutions inherent in aperture photometry, and can be applied to high-z sources (e.g., Stanley et al. 2015; Lyu et al. 2016; Mateos et al. 2016) and/or to large (N > 100) samples, for which MIR imaging and spectroscopy with high spatial resolution would require significant amounts of time on large-diameter (>8 m) telescopes.

In this paper, we decompose the IR SEDs of the ultrahard X-ray-selected Swift/BAT 70 month AGN catalog (Baumgartner et al. 2013) into AGN and host galaxy components. Thanks to intensive follow-up observations by BAT AGN Spectroscopic Survey20 (BASS; Koss et al. 2017; Lamperti et al. 2017; Ricci et al. 2017b), we are able to obtain reliable information on the gas column density (N_H), absorption-corrected 14–150 keV X-ray luminosity, and black hole mass (M_{BH}) of the sample.

The main goal of this work is to quantitatively assess the AGN contribution to the 12 \mu m band, MIR (5–38 \mu m) band, and total IR (5–1000 \mu m) band down to log(L_{14–150}/\text{erg s}^{-1}) ∼ 41 in order to investigate torus (1) the correlation between MIR and X-ray luminosity and (2) the dust covering factor of the torus, minimizing issues related to host galaxy contamination. Throughout the paper, we adopt standard cosmological parameters \(H_0 = 70.0 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_M = 0.3, \text{ and } \Omega_{\Lambda} = 0.7\).

2. Sample

Our initial sample is based on the sample of Ichikawa et al. (2017), which contains the 606 non-blazar AGNs from the Swift/BAT 70 month catalog (Baumgartner et al. 2013) at galactic latitudes (|b| > 10°) for which secure spectroscopic redshifts are available. In this study, we use the column density (N_H) and the absorption-corrected 14–150 keV luminosity (L_{14–150}) tabulated in Ricci et al. (2017b). They are also summarized in Table 1.

In Ichikawa et al. (2017), we reported the 3–500 \mu m IR counterparts for our AGN sample, utilizing the IR catalogs obtained from WISE (Wright et al. 2010; Cutri et al. 2013), AKARI (Murakami et al. 2007), IRAS (Beichman et al. 1988), and Herschel (Griffin et al. 2010; Poglitsch et al. 2010). Out of the 606 sources, we identified 604, 560, 601, and 402 counterparts in the total IR, near-IR (NIR; <5 \mu m), MIR, and far-IR (FIR; 60–500 \mu m) bands, respectively. The reader should refer to Ichikawa et al. (2017) for details of the IR catalogs. While Ichikawa et al. (2017) compiled the representative fluxes at 12, 22, 70, and 90 \mu m, by combining similar wavelength bands in the multiple IR catalogs listed above, in this study we regard each IR band with a different central wavelength as independent photometry. Therefore, there are at most 17 available IR photometric bands between 3 and 500 \mu m, as identified in Table 1. For the data points with the same wavelengths (i.e., 12, 25, 60, 100, and 160 \mu m), the adopted photometry was chosen based on the priorities reported in the IR catalog of Ichikawa et al. (2017) to measure the IR emission from both nucleus and host galaxy in a uniform way for the entire AGN sample. The 12 \mu m flux density was obtained with the following priority: WISE, IRAS/Point Source Catalog (PSC), and IRAS/Faint Source Catalog (FSC). For the 25, 60, and 100 \mu m flux densities, on the other hand, we followed a different order (IRAS/PSC and IRAS/FSC), while for the 160 \mu m flux density we used Herschel/PACS and, when not available, AKARI/FIS. The corrected data are obtained from a wide range of different angular resolutions from Herschel/PACS (70 \mu m; 6 arcsec) to IRAS/FIR (100 \mu m; ≈1 arcmin). Using nearly the same sample, Mushotzky et al. (2014) already showed that the bulk of PACS 70 \mu m is point-like at the spatial resolution of Herschel, suggesting that the FIR emission from the host galaxy is really compact (with a median value of 2 kpc FWHM) and unresolved for most of our sample. Thus, we conclude that the aperture dependence with more moderate resolutions obtained by AKARI and IRAS is negligible (see also Meléndez et al. 2014; García-González et al. 2016a; Ichikawa et al. 2017; Lutz et al. 2018).

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20 www.bass-survey.com
Table 1  
Column Descriptions for the IR Catalog of the Swift/BAT 70 Month AGN Survey

| Col. # | Header Name                     | Format | Unit    | Description                                                                 |
|-------|---------------------------------|--------|---------|-----------------------------------------------------------------------------|
| 1     | objID                           | string |         | Swift/BAT ID as shown in Baumgartner et al. (2013)                          |
| 2     | ctp1                            | string |         | optical counterpart name                                                    |
| 3     | z                               | float  |         | redshift                                                                    |
| 4     | NH_log                          | float  |         | logarithmic column density (log(NH/cm²))                                   |
| 5     | lbat_log                        | float  |         | absorption-corrected logarithmic 14–150 keV luminosity (log(L_{14-150}/erg s⁻¹)) |
| 6     | lbol_const_log                  | float  |         | logarithmic bolometric AGN luminosity (log(L_{bol}^{(AGN)}/erg s⁻¹))        |
| 7     | lbol_log                        | float  |         | logarithmic bolometric AGN luminosity (log(L_{bol}^{(AGN)}/erg s⁻¹)) using Marconi et al. (2004) |
| 8 (9) | fnu3p4_{(err)}_fqualmod         | float  | Jy      | 3.4 μm profile-fitting flux density (error) obtained from WISE             |
| 10 (11)| fnu46p6_{(err)}_fqualmod       | float  | Jy      | 4.6 μm profile-fitting flux density (error) obtained from WISE             |
| 12 (13)| fnu65a_{(err)}_fqualmod        | float  | Jy      | 9.0 μm flux density (error) obtained from AKARI/IRC                       |
| 14 (15)| fnu12wipf_{(err)}_fqualmod     | float  | Jy      | 12 μm flux density (error)                                                 |
| 16     | fnu12wipcatalog                 | string |         | reference catalogs for 12 μm: W = WISE, Ip = IRAS/PSC, If = IRAS/FSC        |
| 17 (18)| fnu18a_{(err)}_fqualmod        | float  | Jy      | 18.0 μm flux density (error) obtained from AKARI                          |
| 19 (20)| fnu22w_{(err)}_fqualmod        | float  | Jy      | 22 μm profile-fitting flux density (error) obtained from WISE             |
| 21 (22)| fnu25ipf_{(err)}_fqualmod      | float  | Jy      | 25 μm flux density (error)                                                 |
| 23     | fnu25ipfcatalog                 | string |         | reference catalogs for 25 μm: Ip = IRAS/PSC, If = IRAS/FSC                 |
| 24 (25)| fnu60ipf_{(err)}_fqualmod      | float  | Jy      | 60 μm flux density (error)                                                 |
| 26     | fnu60ipfcatalog                 | string |         | reference catalogs for 60 μm: Ip = IRAS/PSC, If = IRAS/FSC                 |
| 27 (28)| fnu65a_{(err)}_fqualmod        | float  | Jy      | 65 μm flux density (error) obtained from AKARI/IRC                       |
| 29 (30)| fnu70p_{(err)}_fqualmod        | float  | Jy      | 70 μm flux density (error) obtained from Herschel/PACS                    |
| 31 (32)| fnu90a_{(err)}_fqualmod        | float  | Jy      | 90 μm flux density (error) obtained from AKARI/ISR                        |
| 33 (34)| fnu100ipf_{(err)}_fqualmod     | float  | Jy      | 100 μm flux density (error)                                                |
| 35     | fnu100ipfcatalog                | string |         | reference catalogs for 100 μm: Ip = IRAS/PSC, If = IRAS/FSC                |
| 36 (37)| fnu140a_{(err)}_fqualmod       | float  | Jy      | 140 μm flux density (error) obtained from AKARI                          |
| 38 (39)| fnu160pa_{(err)}_fqualmod      | float  | Jy      | 160 μm flux density (error)                                                |
| 40     | fnu160pacatalog                 | string |         | reference catalogs for 160 μm: P = Herschel/PACS, A = AKARI/ISR            |
| 41 (42)| fnu250a_{(err)}_fqualmod       | float  | Jy      | 250 μm flux density (error) obtained from Herschel/SPIRE                  |
| 43 (44)| fnu350a_{(err)}_fqualmod       | float  | Jy      | 350 μm flux density (error) obtained from Herschel/SPIRE                  |
| 45 (46)| fnu500s_{(err)}_fqualmod       | float  | Jy      | 500 μm flux density (error) obtained from Herschel/SPIRE                  |
| 47     | l12_AGN_asSta15_log             | float  |         | logarithmic decomposed 12 μm AGN luminosity log(L_{12μm}^{(AGN)}/erg s⁻¹)    |
| 48     | lMIR_AGN_asSta15_log            | float  |         | logarithmic decomposed MIR AGN luminosity log(L_{12μm}^{(MIR)}/erg s⁻¹)     |
| 49     | lIR_AGN_asSta15_log             | float  |         | logarithmic decomposed total IR luminosity log(L_{IR}^{(AGN)}/erg s⁻¹)     |
| 50     | l2AGNratio_asSta15              | float  |         | ρ_{2μm}/I_{12μm}                                                         |
| 51     | AGNpercentage_MIR_asSta15       | float  |         | f_{MIR}/f_{AGN}                                                           |
| 52     | AGNpercentage_IR_asSta15        | float  |         | (f_{IR}/f_{AGN})                                                         |
| 53     | flag_upperlimit                 | int    |         | flag of AGN: detection (= 0), upper limit (= 1), and lower-limit (= −1)   |
| 54     | R_Sta16_asSta15_log             | float  |         | log R = log(f_{IR}^{(AGN)}/L_{bol}^{(AGN)})                              |
| 55     | CF_Sta16_taur97eq3_asSta15      | float  |         | C(2.2, 3.4, 4.6, 6.7 μm)                                                  |
| 56     | SBtemplate_asSta15              | string |         | SB template used for the SED fitting this study: SB1–SB5                   |

Note. The detail of the selection of the flux is compiled in Section 2. The full catalog is available as a machine readable electronic table. (This table is available in its entirety in machine-readable form.)

To acquire IR SEDs with a number of data points sufficient for spectral decomposition we require, for each source, at least three photometric bands within the rest-frame 3–500 μm. This is because three data points are needed to define the normalization of the two components (AGN torus and host galaxy). Applying this criterion, our sample is reduced to 588 sources. In addition, we require at least one data point from either the NIR or FIR band to estimate the host galaxy component, which brings the sample to 587 sources. This is the final sample used for this study, and it represents a large fraction of the initial sample (587/606 = 97%). The redshift distribution of the sample is shown in Figure 1.21

We divide the sample into two AGN types based on N_H obtained by Ricci et al. (2017b). We define the AGNs with N_H < 10²² cm⁻² as unobscured AGNs, and those with N_H ≥ 10²² cm⁻² as obscured ones. Overall we have 300 unobscured and 287 obscured AGNs. The AGN types for the complete BAT 70 month catalog are tabulated in Ricci et al. (2017b), as well as in Table 1. We note that Koss et al. (2017) found a 95% agreement for the unobscured and obscured AGNs with the presence of a broad H/β line for optical types Seyfert 1–1.8 and Seyfert 2.

3. Analysis

We decompose the IR SEDs of AGNs using SB and AGN templates to estimate the intrinsic AGN IR luminosity. We use the IDL script DecompIR coded by Mullaney et al. (2011) and

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21 M81 is not shown in the figure due to its very low redshift of z = 10⁻⁴ (Ricci et al. 2017b).
further developed by Del Moro et al. (2013). This code accepts IR photometry points in the 3–500 μm range as input and properly accounts for the filter and instrument response functions of the photometry points. It then computes the approximate levels of AGN and host galaxy contributions by fitting data that combine a host galaxy component with an AGN. DecompIR contains the mean AGN template produced from the Swift/BAT 9 month catalog (Tueller et al. 2008), which broadly traces the typical spectral forms of face-on and edge-on clumpy torus models (e.g., Nenkova et al. 2008a, 2008b) as shown in Mullaney et al. (2011). It also includes the five star-forming galaxy templates (Mullaney et al. 2011; Del Moro et al. 2013), using the average starburst SEDs derived by Dale et al. (2001). The five galaxy templates are composites of local star-forming galaxies with $L_\text{IR} < 10^{12} L_\odot$ (Brandl et al. 2006). They characterize well the full range of host galaxy SED shapes (Del Moro et al. 2013; Stanley et al. 2015), such as the galaxy template library of Chary & Elbaz (2001). Using these representative templates, we are able to fit the data without suffering from the degeneracy of the fitting procedure caused by the large number of templates. In addition, some of our sources have only three data points, so it is reasonable to keep the number of free parameters as small as possible.

The free parameters of the fitting are the normalizations of the AGN and host galaxy templates; therefore at least three IR data points are needed to fit the SEDs. However, we added one more free parameter for only the very luminous sources. It is known that, in high-luminosity AGNs, the IR SEDs become much flatter at shorter wavelengths, which could be related to the stronger radiation field heating the surrounding dust to higher temperatures than in moderate-luminosity AGNs (e.g., Richards et al. 2006; Netzer et al. 2007; Mullaney et al. 2011; Symeonidis et al. 2016; Lani et al. 2017; Lyu et al. 2017). Our AGN SEDs also show such a tendency, especially at high luminosities ($L_{14–150} > 10^{44}$ erg s$^{-1}$). Therefore, for the sources that have at least four data points and luminosities $L_{44–150} > 10^{44}$ erg s$^{-1}$, we also allow the spectral index $\alpha_1$ of the AGN template (see Mullaney et al. 2011) to be shallower at wavelengths shorter than 19 μm.

To determine the best fitting parameters, we first fit the SED by using the five host galaxy templates (SB1–SB5) and the AGN template. We then check the results obtained using the five different SB templates, and we choose the one that provides the best results according to the chi-squared statistic ($\chi^2$) minimization.

Figure 2 shows examples of the best-fitting SEDs that include both the AGN and star formation components, together with the best-fitting SEDs that require only the host galaxy or the AGN component. All the other SEDs of our sample are compiled in the online journal. Overall, 474 sources required both the AGN and the host galaxy templates, while 94 sources required only the AGN template. For the latter objects, the fitting quality does not improve even when including an additional SB template. Since most of those sources (89 out of 94) are not detected in the FIR bands, and considering that the FIR bands have shallower sensitivities than the MIR ones, the lack of a significant contribution of the SB template in the MIR does not always imply that the host galaxy does not contribute to the total IR luminosity. In order to assess how much the host galaxy could contribute to the total infrared luminosity without affecting the observed SEDs, we calculate the upper limits on the contribution from star formation by following Stanley et al. (2015), where the same SED decomposition routine, DecompIR, was used. This was done by increasing the normalization of the host galaxy template until it reached one of the upper limits or exceeded the 3σ uncertainty of a data point. We then used the star-forming galaxy template that gave the highest value of IR luminosity as our conservative upper limit. For the sources that have an upper limit on the host galaxy component, we show the lower limits of the AGN contribution to the MIR contribution (5–38 μm; $f_{\text{AGN}}^{\text{MIR}}$) and to the total IR flux (5–1000 μm; $f_{\text{AGN}}^{\text{IR}}$) in each SED, as illustrated in the middle panel of Figure 2. The lower limits on $f_{\text{AGN}}^{\text{MIR}}$ and $f_{\text{AGN}}^{\text{IR}}$ are reported in Table 1, and readers can use the flag (flag_limit) to assess whether the values are lower limits or not.

There are 18 sources in our sample that were best fit to the host galaxy template alone ($f_{\text{AGN}}^{\text{IR}} = 0$). Again, in order to assess the contribution of AGNs to the total IR luminosity, we calculate the upper limits on the contribution from the AGN torus with the same methods as for the AGN-dominated SEDs, as discussed above. The upper limits of $f_{\text{AGN}}^{\text{IR}}$ and $f_{\text{AGN}}^{\text{MIR}}$ are also shown in the right panel of Figure 2 (see also Table 1).

Using this SED fitting approach, we have measurements of the AGN luminosity in the 12 μm ($L_{\text{12}\text{μm}}^{\text{AGN}}$), MIR ($L_{\text{MIR}}^{\text{AGN}}$), and total IR ($L_{\text{IR}}^{\text{AGN}}$) bands. All the values, as well as the IR flux densities, are tabulated in Table 1. We do not compile the IR star-forming luminosity, due to the impossibility of obtaining reliable estimates for the sources not detected in the FIR.

4. Results and Discussion

4.1. Fractional Luminosity Contribution of AGNs to the IR Band

Figure 3 shows the median of the AGN contributions to the 12 μm, MIR, and total IR luminosities as a function of $L_{14–150}$. The AGN contribution is calculated from the ratio of the AGN luminosity to the total (SF plus AGN) luminosity:

$$f_{\text{AGN}}^{(12\text{μm},\text{MIR, IR})} = \frac{L_{\text{12\text{μm,MIR, IR}}}(\text{AGN})}{L_{\text{12\text{μm,MIR, IR}}}} + L_{\text{12\text{μm,MIR, IR}}}(\text{SF}),$$

(1)

Figure 3 shows that the luminosity contribution of the AGNs to the 12 μm, MIR, and total IR bands increases with $L_{14–150}$. At the low-luminosity end ($L_{14–150} < 10^{43}$ erg s$^{-1}$), Figure 3 indicates that the host galaxy emission significantly
Figure 2. Example of our IR SEDs and their best-fit models. The orange and blue dashed curves represent fitted the AGN and host galaxy templates, respectively. The black solid curve is the combination of AGN and host galaxy templates, while the red squares with error bars are the flux densities. Each panel also shows the object ID based on the Swift/BAT 70 month catalog, the redshift, and the luminosity contribution of the AGNs to the MIR ($f^\text{AGN}_{\text{MIR}}$) and IR bands ($f^\text{AGN}_{\text{IR}}$). Left panel: an example of a source showing both AGN and host galaxy contributions. Middle panel: an example of an AGN torus-dominated SED. The host galaxy template is plotted as an upper limit. Right panel: an example of a source with a host galaxy-dominated SED, with the AGN template plotted as an upper limit. The complete figure set of all SEDs of our sample (587 images) is available in the online journal.

(The complete figure set (587 images) is available.)

contaminates (≈50%–80%) the 12 µm and MIR bands. At the high-luminosity end ($L_{\text{IR}} > 10^{43}$ erg s$^{-1}$), it clearly shows that the AGN component is the dominant (>80%) energy source at 12 µm and in the MIR band. This overall result is broadly consistent with previous studies that explored the AGN contribution using imaging with high spatial resolution (e.g., Asmus et al. 2011, 2014, and references therein). These works are discussed in Appendix A.1. On the other hand, in the total IR band, the AGN component contributes only up to ≈50% even at high luminosities. This result is consistent with the calculations done for local quasars (Lyu et al. 2017), where it is shown that AGNs contribute ≈50% of the flux even if they provide 90% of the MIR emission.

Figure 3 also shows that the scatter of the percentage is ≈20% for $f^\text{AGN}_{\mu m}$ and increases up to ≈35% for $f^\text{AGN}_{\text{IR}}$. The scatter is mostly due to AGN-dominated sources without any detections in the FIR bands. Since no distant sources with $z > 0.05$ have been observed with Herschel (see Meléndez et al. 2014; Shimizu et al. 2016), those sources have very shallow upper limits: 0.2 Jy at 60 µm (IRAS/FSC) and/or 0.55 Jy at 90 µm (AKARI/FIS). This allows a possible contribution of the host galaxy emission to the FIR bands, even when its contribution to the MIR flux is negligible as discussed in Section 3 (see also Lyu & Rieke 2017). Therefore, FIR photometry with higher sensitivity is crucial to quantify the host galaxy contribution for those sources.

4.2. IR Pure-AGN Candidates

Some sources show AGN-dominated SEDs even in the FIR bands. These sources are called IR pure-AGN (Mullaney et al. 2011; Rosario et al. 2012, 2018; Matsuoka & Woo 2015; Ichikawa et al. 2017), and they are ideal candidates for deriving intrinsic AGN IR templates. These IR pure-AGN have a spectral turnover at 20–40 µm (Alonso-Herrero et al. 2012; Hönig et al. 2014; Fuller et al. 2016; Lopez-Rodriguez et al. 2018) and a declining flux density from 40 µm to 160 µm, suggesting a very low contribution from the starburst in the host galaxy. In order to check the SED turnover quantitatively, we plot IR color–color plots of $f_{90\mu m}/f_{160\mu m}$ versus $f_{22\mu m}/f_{90\mu m}$ in Figure 4. Both flux ratios are known to be sensitive to the SED peak, and therefore to the dust temperature (Meléndez et al. 2014; García-González et al. 2016b). The orange shaded area in Figure 4 ($f_{90\mu m}/f_{160\mu m} > 1.0$ and $f_{22\mu m}/f_{90\mu m} > 1.0$) indicates a decline in flux density as a function of wavelength from 22 µm to 160 µm since the sources fulfill $f_{22\mu m} > f_{90\mu m} > f_{160\mu m}$.

Figure 4 also shows the simulated IR color as a function of $f^\text{IR}_{\text{AGN}}$ for the each SB template. All IR colors follow a similar trend: $f_{22\mu m}/f_{90\mu m}$ increases up to $f_{22\mu m}/f_{70\mu m} \simeq 1.0$ with $f^\text{IR}_{\text{AGN}}$ up to 0.9, while $f_{70\mu m}/f_{160\mu m}$ shows a very shallow increase until $f^\text{IR}_{\text{AGN}} \lesssim 0.8$. However, for $f^\text{IR}_{\text{AGN}} > 0.9$, $f_{90\mu m}/f_{160\mu m}$ starts to drastically increase, reaching values up to ≈7.0. Thus, sources located in the orange shaded area should have AGN-dominated IR SEDs with $f^\text{IR}_{\text{AGN}} > 0.90$. In this study we define a source as IR pure-AGN when it fulfills the following criteria: (1) $f^\text{IR}_{\text{AGN}} > 0.90$ and (2) a significant detection at both 60–70 µm and 160 µm. A total of nine sources are selected with these criteria, and they are shown with the black crosses in Figure 4. Most IR pure-AGN are successfully located in the orange shaded area in the color–color plot. Figure 5 shows the SEDs of the nine selected IR pure-AGN. All sources show an SED turnover between ≈20 µm and ≈70 µm, a declining flux density from 70 µm to 160 µm, and no FIR bump due to star formation up to 90 µm, with the exception of Fairall 9 and II SZ 010. Some of the sources in our sample have already been reported as being dominated by emission from the torus in the IR from the study of their Spitzer/IRS spectra (e.g., MCG–05–23–16; Ichikawa et al. 2015), based on the spectral turnover at 20–40 µm (Alonso-Herrero et al. 2012; Hönig et al. 2014; Fuller et al. 2016; Lopez-Rodriguez et al. 2018).

We also check the AGN properties of IR pure-AGN compared to the parent sample. The means and standard deviations of the logarithmic X-ray luminosity, black hole mass, and Eddington ratio of this subsample are $\langle \log L_{\text{X}} \rangle = 43.7 \pm 0.3$ ($\log M_{\text{BH}} = 7.8 \pm 0.5$, and $\log \lambda_{\text{Edd}} = -1.2 \pm 0.3$, respectively. These values are consistent with those of the parent sample of $\langle \log L_{\text{X}} \rangle = 43.7 \pm 0.8$, $\langle \log M_{\text{BH}} \rangle = 8.0 \pm 0.8$, and $\langle \log \lambda_{\text{Edd}} \rangle = -1.5 \pm 0.8$. This result suggests that the dominant contribution of AGNs to the total IR band is not related to their higher AGN luminosities, lower BH masses, or higher Eddington ratio, while it implies that they have weaker star formation luminosities than other AGNs of similar luminosity. Actually, MCG–05–23–16 is one of the pure IR-AGN whose CO emission has not been detected (Rosario et al. 2018) in the Swift/BAT AGN subset of the LLAMA survey (Davies et al. 2015). This suggests that its host galaxy already
lacks the molecular gas to produce the star formation. The ongoing molecular gas observations conducted by the BASS survey (M. Koss et al., in preparation) will explore the origin of the deficit of star formation in these IR pure-AGN sources.

4.3. Correlation between the 12 μm AGN and 14–150 keV Luminosities

Figure 6 shows the relation between $L_{12\mu m}^{\text{AGN}}$, $L_{14-150}^{\text{AGN}}$, and $L_{14-150}$ in the range $10^{40}$ erg s$^{-1} < L_{14-150} < 10^{47}$ erg s$^{-1}$. Blue and red crosses represent unobscured and obscured AGNs, respectively. The upper limits, shown as open circles, represent the host galaxy-dominated sources that have a possible AGN contribution in the 12 μm and MIR bands as discussed in Section 3. The slope of the relation between $L_{12\mu m}^{\text{AGN}}$, $L_{14-150}^{\text{AGN}}$, and $L_{14-150}$ is estimated considering the two variables as independent parameters. Since our data contain both detections and upper limits, we apply the survival analysis method using the Python package$^{22}$ ASURV (Feigelson & Nelson 1985; Isobe et al. 1986; Lavalley et al. 1992) to account for the upper limits on $L_{12\mu m}^{\text{AGN}}$ and $L_{\text{MIR}}^{\text{AGN}}$. We use the slope bisector fits, which minimize the perpendicular distance from the slope line to data points. The fits, with the form of $\log \left( \frac{L_{12\mu m}^{\text{AGN}}}{10^{43}\text{ erg s}^{-1}} \right) = (a \pm \Delta a) + (b \pm \Delta b) \log(L_{14-150}/10^{43} \text{ erg s}^{-1})$, where $\Delta a$ and $\Delta b$ are the standard deviations of $a$ and $b$, respectively, result in

$$\log \left( \frac{L_{14-150}^{\text{AGN}}}{10^{43}\text{ erg s}^{-1}} \right) = (-0.24 \pm 0.03) + (1.08 \pm 0.03) \times \log \left( \frac{L_{14-150}}{10^{43}\text{ erg s}^{-1}} \right),$$

and they are also summarized in Table 2. We find that both luminosity–luminosity and flux–flux correlations are significant (see also Appendix B for the flux–flux correlations).

In Figure 6, some of the fits reported by recent works are also overplotted. Since most previous studies used the 2–10 keV luminosity, we apply a conversion factor of $L_{14-150}/L_{2-10} = 2.36$ under the assumption of the photon index $\Gamma = 1.8$, which is the median value of the Swift/BAT 70 month AGN sample (Ricci et al. 2017b), for overplotting in the same figure. Since the AGN template used in this study has a ratio of $L_{\text{MIR}}^{\text{AGN}}/L_{12\mu m}^{\text{AGN}} = 1.92$, we also apply it to the slopes from the previous studies for overplotting in the relation between $L_{\text{MIR}}$ and $L_{14-150}$.

Compared to Ichikawa et al. (2017), where we found $b = 0.96 \pm 0.02$, the sample used here shows a smaller 12 μm contribution from AGN at the low-luminosity end. This is because the sources with lower $L_{14-150}$ have a significant host galaxy contamination even in the MIR, as shown in Figure 3 and also in the right panel of Figure 11. Indeed, Ichikawa et al. (2017) also reported that the slope becomes slightly steeper with $b = 1.05 \pm 0.03$ when one considers sources with $L_{14-150} > 10^{43}$ erg s$^{-1}$, for which the host galaxy contamination in the MIR is negligible. This is also consistent with the value of $b = 1.08 \pm 0.03$ in this study.

We compare our results with what was found by Gandhi et al. (2009) and Asmus et al. (2015) using observations with high spatial resolution of X-ray-selected AGNs down to the low-luminosity end. The MIR emission in those studies is most likely dominated by the AGN torus, and they have a relatively

\[^{22}\text{http://python-asurv.sourceforge.net/}\]
low level of host galaxy contamination thanks to their spatially resolved images. As shown in Figure 6, our study finds a similar slope to that reported in Gandhi et al. (2009) ($b = 1.11 \pm 0.07$), and it is also within the $3\sigma$ uncertainty of that of Asmus et al. (2015) ($b = 0.97 \pm 0.03$). This strongly supports the idea that our SED decomposition method nicely reproduces the flux at high spatial resolution, which is thought to be dominated by AGN torus emission.

4.4. Covering Factor of AGNs as a Function of Bolometric Luminosity

The ratio of the AGN IR luminosity and the AGN bolometric luminosity ($R = L_{\text{IR}}^{\text{AGN}}/L_{\text{bol}}^{\text{AGN}}$) has been interpreted as an indirect indicator of the dust covering factor ($C_{\text{dust}}$), since, for a given AGN luminosity, $L_{\text{IR}}^{\text{AGN}}$ should be proportional to $C_{\text{dust}}$ ($L_{\text{IR}}^{\text{AGN}} \propto C_{\text{dust}} \times L_{\text{bol}}^{\text{AGN}}$; Maiolino et al. 2007; Treister et al. 2008; Elitzur 2012). Since the flux of the accretion disk cannot be directly measured for all the sources of our sample, we used $L_{\text{IR}}^{\text{AGN}}$ to estimate the bolometric luminosity. We apply a constant bolometric correction of $L_{\text{bol}}^{\text{AGN}}/L_{\text{IR}}^{\text{AGN}} = 20$, which is equivalent to $L_{\text{bol}}^{\text{AGN}}/L_{1.1-150} = 8.47$ under the assumption of $\Gamma = 1.8$, which is the median value of the Swift/BAT 70 month AGN sample (Ricci et al. 2017b). We note that our main results do not change significantly when adopting different bolometric corrections, including luminosity-dependent ones (Marconi et al. 2004). We briefly discuss this in Appendix C.2.

To calculate $R$, we proceed in the same manner as Stalevski et al. (2016). We use the total IR AGN luminosity integrated over 1–1000 $\mu$m ($L_{\text{IR}}^{\text{AGN}}$) instead of $L_{\text{IR}}^{\text{AGN}}$, which integrates the SED over 5–1000 $\mu$m. This is because Stalevski et al. (2016) recommend using the AGN SEDs including NIR, which sometimes contributes to the total IR luminosity at a non-negligible level. Since we do not have an IR AGN template down to 1 $\mu$m, we extrapolate the AGN template using the same spectral index of $\alpha$ used at wavelengths shorter than 19 $\mu$m. Therefore, $R$ is calculated based on $R = L_{\text{IR}}^{\text{AGN}}/L_{\text{bol}}^{\text{AGN}}$ in the following study. Figure 7 shows the relation between $R$ and the AGN bolometric luminosity. The black dashed line represents the fit obtained using ASURV to account for the sources with an upper limit:

$$\log R = (4.52 \pm 1.25) + (-0.12 \pm 0.03) \log \left( \frac{L_{\text{bol}}^{\text{AGN}}}{\text{erg s}^{-1}} \right).$$

This shows that $R$ is a very weak function of AGN bolometric luminosity. However, $R$ does not always represent the actual $C_{\text{dust}}$, because the standard geometrically thin and optically thick disk emits radiation anisotropically (Netzer 1987; Lusso et al. 2013). Thus we also estimate $C_{\text{dust}}$ exploiting the recent results of Stalevski et al. (2016),
who computed the correction function between the covering factor ($C_T$ (dust)) and $R$ using a clumpy two-phase medium with a sharp boundary between the dusty and dust-free environments. They compute the $C_T$ (dust) - $R$ relation for a range of equatorial torus thickness ($\tau_{9,7} = 3-10$). We consider here the function for $\tau_{9,7} = 3$:

$$C_T(\text{dust}) = \begin{cases} 
-0.178R^4 + 0.875R^3 - 1.487R^2 \\
+1.408R + 0.192 \text{(type 1)} \\
2.039R^3 - 3.976R^2 + 2.765R + 0.205 \text{(type 2)}.
\end{cases}$$

(5)

We use Equation (5) for type-1/type-2 AGN to unobscured/obscured AGNs in this study. According to Stalevski et al. (2016) the relations reported above are valid only for $R \leq R_{\text{max}}$, where $R_{\text{max}} = 1.3$ for unobscured AGNs and $R_{\text{max}} = 1.0$ for obscured AGNs, so we removed five sources with $R > R_{\text{max}}$ from the sample. Figure 8 shows $C_T(\text{dust})$ as a function of $L_{\text{bol}}$.

Besides the dust covering factor $C_T(\text{dust})$, we also calculate the fraction of obscured AGNs ($N_{\text{H}}$/$\text{cm}^{-2} \geq 2.20 \times 10^{22}$), including the Compton-thick sources for each $L_{\text{bol}}$ bin as shown in Figure 8 (orange crosses). Since X-rays are absorbed by both gas and dust, the fraction of obscured AGNs is a proxy for the covering factor of the obscuring material, and is sensitive to both gas and dust [$C_T(\text{gas + dust})$]. We follow the same approach to obtain $C_T(\text{gas + dust})$ as done by Ricci et al. (2017a). The column density $N_{\text{H}}$ for our sample is obtained through detailed X-ray spectral fitting using follow-up X-ray observations (Ricci et al. 2017b). In the X-ray fitting, both photoelectric absorption and Compton scattering are considered, and they are listed in Table 5 of Ricci et al. (2017b). $C_T(\text{gas + dust})$ is defined as $C_T(\text{gas + dust}) = f_{\text{Chin}} + f_{\text{CT}}$, where $f_{\text{Chin}}$ is the fraction of Compton-thin obscured AGNs ($22 < \log(N_{\text{H}}/\text{cm}^{-2}) < 24.0$) in each $L_{\text{bol}}$ bin, while the Compton-thick fraction is $f_{\text{CT}} = 0.32$ for $\log(L_{\text{bol}})^{\text{AGN}}/\text{erg s}^{-1} < 43.5$ and $f_{\text{CT}} = 0.21$ for $\log(L_{\text{bol}})^{\text{AGN}}/\text{erg s}^{-1} > 43.5$ obtained from the intrinsic $N_{\text{H}}$ distribution (Ricci et al. 2015). The reason for using $f_{\text{CT}}$ above is because even though Swift/BAT sources are unbiased for $N_{\text{H}} < 10^{24} \text{cm}^{-2}$, they can still be affected by obscuration for $N_{\text{H}} > 10^{24} \text{cm}^{-2}$.

### 4.4.1. $L_{\text{bol}}$-dependent Trend of $C_T(\text{dust})$

Figure 8 shows that both $C_T(\text{dust})$ and $C_T(\text{gas + dust})$ seem to decrease as functions of AGN bolometric luminosity, and at the high-luminosity end the two finally converge. This luminosity-dependent trend of $C_T$ has been observationally reported in multiple wavelengths from studies in the IR (e.g., Maiolino et al. 2007; Alonso-Herrero et al. 2011), optical (Simpson 2005), and X-rays (Ueda et al. 2003, 2011, 2014; Beckmann et al. 2009; Ricci et al. 2013).

However, recent studies have also reported contradictory results that the luminosity dependence of $C_T(\text{dust})$ is actually really weak, or that the trend even disappears after considering some possible biases. Netzer et al. (2016) argue that using the different bolometric corrections would make the reported luminosity dependence of $C_T(\text{dust})$ disappear. Stalevski et al. (2016) also found that the dependence on luminosity is always less pronounced after considering the anisotropy of the emission from the torus. A similar weak or insignificant dependence on luminosity is reported by Mateos et al. (2016), and a more detailed review is given by Netzer (2015).

In order to understand this trend in more detail, we conduct a simulation to assess the luminosity dependence of $C_T(\text{dust})$. We first generate the two random populations of $L_{14-150}$ for unobscured and obscured AGNs in a total of $10^6$ samples with the same number ratio as our parent sample (unobscured/obscured = 300/287; see Section 2). Each sample is generated based on our parent sample, using a Gaussian distribution with median log($L_{14-150}/\text{erg s}^{-1}$) of (43.9, 43.6) and standard deviation of (0.85 dex, 0.67 dex) for unobscured and obscured AGNs, respectively. Then the distribution of $L_{14-150}^{\text{AGN,1-1000}/\mu m}$ is...
calculated under the assumption that two populations follow the luminosity correlation of $L_{\text{IR}}^{\text{(AGN;1–1000\,\mu m)}} - L_{14-150}$ with a scatter of $\sigma = 0.4$ dex, and finally the distribution of $C_T^{(\text{dust})}$ is computed in the same manner. The result is shown in Figure 9: the computed $C_T^{(\text{dust})}$ distribution (gray cross bins) roughly reproduces the luminosity dependence of the black solid line. Next, we assume that all AGNs should follow the luminosity correlation of $L_{\text{IR}}^{\text{(AGN;1–1000\,\mu m)}} - L_{14-150}$ and the intrinsic population should have the narrower scatter, down to $\sigma = 0.1$ dex. The result is plotted with pink bins in Figure 9, showing that the luminosity dependence has disappeared and the binned $C_T^{(\text{dust})}$ has an almost constant value of $C_T^{(\text{dust})} \approx 0.4$ over the entire $L_{\text{bol}}^{\text{(AGN)}}$ range. Therefore, we conclude that this apparent dependence on luminosity can be produced purely by the scatter of the distribution, and our results confirm the recent arguments that the luminosity dependence of $C_T^{(\text{dust})}$ is actually really weak, or that the trend even disappears.

4.4.2. Relation between $C_T^{(\text{dust})}$ and $C_T^{(\text{gas + dust})}$

The other interesting result from Figure 8 is that $C_T^{(\text{gas + dust})}$ is always same as or larger than the binned $C_T^{(\text{dust})}$ over the entire AGN luminosity range. This relation still holds if $C_T^{(\text{dust})} \approx 0.4 \leq C_T^{(\text{gas + dust})}$ in our simulation as shown in Figure 9. This result suggests the presence of dust-free gas, possibly located in the broad-line region (BLR), and is responsible for part of the X-ray absorption. Observationally, found evidence of occultation events in the X-rays, and the locations of those gas clumps are in the dust-free region or at the inner edge of the dusty torus (e.g., Risaliti et al. 2007, 2011; Maiolino et al. 2010; Ricci et al. 2016). In addition, Minezaki & Matsushita (2015) and Gandhi et al. (2015) have suggested that the location of narrow Fe Kα line-emitting material could be between the BLR and the dusty torus. Those observations imply the presence of gas at radii inside the sublimation radius.

Several studies have also proposed that the AGN gas disk inside the dust sublimation radius could significantly contribute to the observed column density in Compton-thick AGNs, since such disks are often found to have large inclination angles (e.g., Davies et al. 2015; Masini et al. 2016; Ramos Almeida & Ricci 2017). We also check whether the similar trend of $C_T^{(\text{dust})} \leq C_T^{(\text{gas + dust})}$ can be seen using only the MIR fluxes before the SED decomposition. This is discussed in Appendix C.1.

Figure 8 also shows that both $C_T^{(\text{dust})}$ and $C_T^{(\text{gas + dust})}$ seem to suggest a peak at $\log L_{\text{bol}} \approx 43$, and they both seem to decrease at lower luminosities. However, since the number of samples is limited in this bin range, we cannot confirm the statistical significance of this trend at the current stage (see also the discussion in Appendix C.2).

4.4.3. Comparison of $C_T^{(\text{dust})}$ between Unobscured and Obscured AGNs

We compare $C_T^{(\text{dust})}$ between the AGN subgroups. The left panel of Figure 10 shows $C_T^{(\text{dust})}$ of unobscured (blue) and obscured (red) AGNs as a function of $L_{\text{bol}}^{\text{(AGN)}}$. Although the scatter is large, the binned $C_T^{(\text{dust})}$ of obscured AGNs is always systematically higher than that of unobscured AGNs.

The right panel of Figure 10 shows the distribution of $C_T^{(\text{dust})}$ for unobscured (blue) and obscured (red) AGNs. The $C_T^{(\text{dust})}$ distribution for unobscured AGNs is clustered at smaller values of $C_T^{(\text{dust})} = 0.41$, while obscured AGNs are distributed over a wider $C_T^{(\text{dust})}$ range, reaching $C_T^{(\text{dust})} \approx 1.0$. We apply the Kolmogorov–Smirnov (KS) test to these two samples: the $p$-value of the null hypothesis is $5.7 \times 10^{-8}$ and the KS statistic is 0.24, suggesting that the two distributions are
One possible origin of the difference is that the smaller $C_{\text{dust}}$ for unobscured AGNs could be due to larger $L_{\text{bol}}^{\text{AGN}}$. However, as discussed in Section 4.4.1, the luminosity dependence of $C_{\text{T}}$ is unlikely, and the KS test shows that the distribution of $C_{\text{T}}$ for unobscured and obscured AGNs is statistically significant even in each $L_{\text{bol}}^{\text{AGN}}$ bin for $42.5 < \log(L_{\text{bol}}^{\text{AGN}}/\text{erg s}^{-1}) < 47$, with $p$-values of $p < 10^{-5}$ for $42.5 < \log(L_{\text{bol}}^{\text{AGN}}/\text{erg s}^{-1}) < 45.5$ and $p = 0.02$ for $45.5 < \log(L_{\text{bol}}^{\text{AGN}}/\text{erg s}^{-1}) < 47$.

Another possible interpretation of the difference is as a consequence of the selection of unobscured and obscured AGNs. Several authors argue that AGN classification depends on the distribution of $C_{\text{dust}}$; unobscured AGNs would be preferentially observed from AGNs with lower $C_{\text{dust}}$, and obscured AGNs from AGNs with higher $C_{\text{dust}}$ (e.g., Ramos Almeida et al. 2011; Elitzur 2012; Ichikawa et al. 2015; Lanz et al. 2018).

## 5. Conclusions

We have constructed the IR (3–500 μm) SED for 587 nearby AGNs detected in the 70 month Swift/BAT all-sky survey. Using this almost complete (587 out of 606; 94%) sample, we have decomposed the IR (3–500 μm) SEDs into SB and AGN components. The decomposition enabled us to estimate the AGN contribution to the 12 μm ($f_{12\mu m}^{\text{AGN}}$), MIR ($f_{\text{MIR}}^{\text{AGN}}$), and total IR ($f_{\text{IR}}^{\text{AGN}}$) luminosities, as well as the contribution of AGN luminosity to the 12 μm ($f_{12\mu m}^{\text{AGN}}$), MIR ($f_{\text{MIR}}^{\text{AGN}}$), and total IR ($f_{\text{IR}}^{\text{AGN}}$) emission. Our results are summarized as follows.

1. The luminosity contribution of the AGN to the 12 μm, MIR, and total IR band flux increases with the 14–150 keV luminosity. The AGN contributions to the 12 μm, MIR, and total IR are almost 80%, 80%, and 50% at the high-luminosity end, respectively.
2. We find nine pure IR-AGN whose IR emission is dominated by the AGN torus at least up to 90 μm. These pure IR-AGN could be good candidates to create templates of the IR AGN SED, with an expanded range up to 90 μm. Those sources could be easily selected using the color selection of \( f_{30μm}/f_{160μm} > 1.0 \) and \( f_{22μm}/f_{70μm} > 1.0 \).

3. We find a good luminosity correlation between the MIR and ultrahard X-ray bands over five orders of magnitude (41 < \( \log(L_{bol}/\text{erg s}^{-1}) \) < 46). Our slope is almost consistent with that obtained by studies carried out using observations with high spatial resolution of nearby Seyfert galaxies, supporting our SED decomposition method, which would nicely estimate the intrinsic MIR emission without the contamination of star formation from the host galaxies.

4. We find that the average of the covering factor of gas and dust inferred from X-ray observations always exceeds the average of the covering factor of the dust torus, suggesting that the dust-free gas contributes to the absorption in X-rays. This gas could be located inside the dust sublimation radius, in agreement with previous observations based on X-ray occultation and spectral fitting studies of nearby AGNs.

5. The luminosity-dependent trend of \( C_T(\text{dust}) \) might originate from the large scatter of the luminosity correlations between \( L_{1.1-1000μm}^{\text{IR}} \) and \( L_{14-150μm} \), and the trend would disappear once the scatter is removed.

6. Obscured AGNs tend to have larger \( C_T(\text{dust}) \) than unobscured AGNs. This difference originates from the AGN classification, which depends on the distribution of the obscuring material.

We thank the anonymous referee for a careful reading of the manuscript and helpful suggestions that greatly strengthened the paper. We thank James Mullaney and Agnese Del Moro for providing the SB SED templates in this study, and Satoshi Takeishi for the technical discussion of IDL routine. We also thank Masatoshi Imanishi, Ryo Tazaki, and Daniel Asmus for fruitful discussions. K.I. thanks the Department of Astronomy at Kyoto university, where a part of the research was conducted. This study benefited from financial support from the Grant-in-Aid for JSPS fellow for young researchers (P.D., K.I.), JSPS KAKENHI (18K13584; K.I.), and JST grant “Building of Consortia for the Development of Human Resources in Science and Technology” (K.I.). C.R. acknowledges the CONICYT-PFI Convocatoria Nacional subvención a instalacion en la academia convocatoria año 2017 PAI77170080. F.E.B. acknowledges support from CONICYT-Chile (Basal-CATA PFB-06/2007, Fondecyt Reguler 1141218), the Ministry of Economy, Development, and Tourism’s Millennium Science Initiative through grant IC120009, awarded to The Millennium Institute of Astrophysics, MAS. K.O. is an International Research Fellow of the Japan Society for the Promotion of Science (JSPS) (ID: P17321). D.J.R. acknowledges the support of UK Science and Technology Facilities Council through grant code ST/P000541/1.

**Appendix A**

Comparison with Studies from the Literature

\textbf{A.1. Comparison with the High-spatial-resolution Flux Obtained with Ground-based 8 m Class Telescopes}

Here we compare the results in this study with the high-spatial-resolution flux observations by Asmus et al. (2014, 2015). Out of 122 high-spatial-resolution sources, we found 112 sources also used in this study. The remaining 10 sources were not found because they are located at low Galactic latitudes \( |b| < 10^\circ \), which we initially removed from the parent sample as discussed in Ichikawa et al. (2017).

The top left panel of Figure 11 shows the 12 μm luminosity correlation between the high-spatial-resolution MIR observations \( L_{12μm}^{\text{Asmus}} \). The figure clearly shows that our decomposition method successfully follows the one-to-one relation with the high-spatial-resolution observations down to...
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\[ \log(L^{\text{AGN}}_{12\mu m} / \text{erg s}^{-1}) \approx 41.0. \] The average of two parameters is \( \langle \log L^{\text{AGN}}_{12\mu m} / L^{\text{AGN}}_{12\mu m} \rangle = 0.05. \) The standard deviation is \( \sigma = 0.35. \)

The top middle and top right panels of Figure 11 show the luminosity relation between \( L^{\text{AGN}}_{12\mu m} \) and \( L^{\text{K17}}_{12\mu m} \), and the low-resolution 12 \( \mu m \) luminosity before the SED decomposition (\( L^{\text{KI17}}_{12\mu m} \)), which is taken from Ichikawa et al. (2017). Both panels show that the points are distributed equally to or below the one-to-one relations and suggest contamination of the host galaxy component in \( L^{\text{KI17}}_{12\mu m} \). The mean and standard deviation are \( \langle \log L^{\text{AGN}}_{12\mu m} / L^{\text{K17}}_{12\mu m} \rangle = -0.10 \pm 0.43. \) This shows that the correlation between \( L^{\text{AGN}}_{12\mu m} \) and \( L^{\text{K17}}_{12\mu m} \) is tighter than that between \( L^{\text{AGN}}_{12\mu m} \) and \( L^{\text{KI17}}_{12\mu m} \), indicating that our decomposition method nicely reduces the contamination in the 12 \( \mu m \) band from the host galaxies.

The bottom panels of Figure 11 show the same relations as those in the top panels, but for 12 \( \mu m \) flux densities. All three panels also show a similar trend to the luminosity relations. One notable difference is that the flux density of the high-spatial-resolution observation (\( f^{\text{KI17}}_{12\mu m} \)) shows a decline in the number of sources at around \( f^{\text{KI17}}_{12\mu m} \approx 10^{-3} \text{ Jy} \). This is almost consistent with the lower bound of the flux density observable with ground-based 8 m class telescopes with significant signal-to-noise ratio (Asmus et al. 2014). Our study can explore flux densities down to \( 10^{-3} \) Jy, which is equivalent to the detection limit of the WISE W3 (12 \( \mu m \)) band. This is one of the advantages of the SED decomposition method using low-resolution, but sensitive space IR satellites compared to ground-based studies.

A.2. Comparison with Different Models from the Literature

In this appendix we briefly compare the IR AGN luminosity obtained in this study and the ones obtained in Shimizu et al. (2017). They applied a different IR SED model to the IR data set, which is similar to ours but obtained from the Herschel observations in the Swift/BAT 58 month AGN catalog to study mainly the global star-forming properties in the host galaxies. Instead of using the AGN/host galaxy templates, they provided functions of the hot dust and the host galaxy respectively by following Casey (2012), and their functions are given by

\[ f(\nu) = N_{\nu} \left( \frac{\nu}{\nu_c} \right)^{-\alpha} e^{-\nu/\nu_c^2} + S_{MBB}(\nu, M_{\text{dust}}, T_{\text{dust}}). \]  

where the first term stands for the AGN component with the normalization \( N_{\nu} \) and cut-off frequency \( \nu_c \), and the second term represents the host galaxy component of a single modified blackbody with a parameter of dust mass \( M_{\text{dust}} \) and a dust temperature \( T_{\text{dust}} \). The fitting method used in their study is also different from ours. They use a Bayesian framework with a
Markov chain Monte Carlo procedure to obtain the posterior probability distribution function, and then use the median to obtain the best fitted parameters. Out of 307 sources in their sample, 204 sources have at least one Herschel detection and a reliable fitting quality (\text{lir\_agn\_flag} = 0). After cross-matching with our sample, we found 180 sources in common. Again, the 24 sources removed are located at low Galactic latitude |b| < 10°.

Since Shimizu et al. (2017) do not provide any 12\,$\mu$m AGN flux or luminosity, we compare the total IR AGN luminosity obtained from their AGN component. The left panel of Figure 12 shows the correlation between the IR AGN luminosities obtained from Shimizu et al. (2017) ($L_{\text{IR}}^{(\text{AGN}; \text{Shimizu})}$) and those obtained from this study ($L_{\text{IR}}^{(\text{AGN})}$). Blue crosses represent individual sources, and the orange dashed line represents the 1:1 relation. Right: histogram of $r = \log(L_{\text{IR}}^{(\text{AGN}; \text{Shimizu})})/L_{\text{IR}}^{(\text{AGN})}$)$. The mean $\mu$, standard deviation $\sigma$, and median absolute deviation (MAD) of $r$ are also shown.

![Figure 12](image)

Figure 12. Left: scatter plot of total IR AGN luminosities obtained from Shimizu et al. (2017) ($L_{\text{IR}}^{(\text{AGN}; \text{Shimizu})}$) and those obtained from this study ($L_{\text{IR}}^{(\text{AGN})}$). Blue crosses represent individual sources, and the orange dashed line represents the 1:1 relation. Right: histogram of $r = \log(L_{\text{IR}}^{(\text{AGN}; \text{Shimizu})})/L_{\text{IR}}^{(\text{AGN})})$. The mean $\mu$, standard deviation $\sigma$, and median absolute deviation (MAD) of $r$ are also shown.

Appendix B
Flux Correlation between 12\,$\mu$m, MIR, and 14–150 keV Bands

Figure 13 shows the flux correlation between the AGN 12\,$\mu$m, MIR, and 14–150 keV bands, revealing a clear correlation between the bands even in the flux–flux plane. The Spearman’s rank coefficient is 0.43 and the probability of the null hypothesis is $P = 10^{-28}$ for both flux–flux correlations, suggesting that the correlation is significant. The slopes are $b = 1.48$ for the AGN 12\,$\mu$m band and $b = 1.49$ for the AGN MIR band, respectively. As we discussed in Ichikawa et al. (2017), there is a clear decline in the number of sources at $f_{14–150} < 10^{-11}\,$erg s$^{-1}\,$cm$^{-2}$, while MIR flux can go down to $3 \times 10^{-13}\,$erg s$^{-1}\,$cm$^{-2}$, which is the typical detection limit of the MIR band. This trend suggests that the sample is limited by the detection limit of the X-ray flux.
Comparison of Relation between $C_T$ and $L_{\text{bol}}^{\text{AGN}}$ using Different Values

C.1. $C_T$ (dust) Estimated from the Observed 12 $\mu$m Luminosity

It is important to check whether the same result in Figure 8 is obtained using the MIR fluxes without host galaxy subtraction. To achieve this, we estimate the total IR AGN luminosity by assuming that the observed 12 $\mu$m luminosity originates from the AGN emission. Then we use the conversion factor of $L_{\text{AGN};1-1000/\mu m}/L_{12/\mu m}^{\text{AGN}} = 2.77$ estimated from the AGN template in this study. The calculation of $R$ and then $C_T$ (dust) is performed in the same manner as we discussed in Section 4.4. The left panel of Figure 14 shows the relation between $C_T$ and $L_{\text{bol}}^{\text{AGN}}$ using $C_T$ (dust) estimated above. It clearly shows that while the result $C_T$ (dust) $< C_T$ (gas + dust) holds for $43.5 < \log L_{\text{bol}}^{\text{AGN}} < 45.5$, $C_T$ (dust) becomes almost equal to $C_T$ (gas + dust) in the luminosity bin $42.5 < \log L_{\text{bol}}^{\text{AGN}} < 43.5$, which is not seen in Figure 8. We also apply the KS test between $C_T$ (dust) and $C_T$ (gas + dust) for each $L_{\text{bol}}^{\text{AGN}}$ luminosity bin. In order to apply this test, we make a Gaussian distribution of $C_T$ (gas + dust) in which the central value is the average of $C_T$ (gas + dust) and 1$\sigma$ is its standard deviation, and the number of sources is the same as for $C_T$ (dust) in the same $L_{\text{bol}}^{\text{AGN}}$ bin. As a result, we find a significant difference for the luminosity bins with $43.5 < \log L_{\text{bol}}^{\text{AGN}} < 45.5$ with $p$-values of $p < 10^{-30}$, while the clear significance is not obtained for the luminosity bins $\log L_{\text{bol}}^{\text{AGN}} < 43.5$ ($p > 0.5$) and $45.5 < \log L_{\text{bol}}^{\text{AGN}}$ ($p = 0.26$). This difference originates from the flux subtraction after the SED decomposition, especially at the lower AGN luminosity end, suggesting its importance and its effect on estimating the dust covering factor.

C.2. Dependence of the Bolometric Corrections

Here we summarize whether different bolometric corrections can affect the relation shown in Figure 8. In this study, following the method used in Ricci et al. (2017a), we use a constant bolometric correction of $L_{\text{bol}}^{\text{AGN}}/L_{14-150} = 8.47$, which is based on $L_{\text{bol}}^{\text{AGN}}/L_{14-150} = 20$ under the assumption of $\Gamma = 1.8$, the median value of the Swift/BAT 70 month AGN sample (Ricci et al. 2017b). On the other hand, Marconi et al. (2004) account for variations in AGN SEDs to obtain the bolometric correction with AGN luminosity. They assume a varying relation between optical/UV and X-ray luminosity, which is called a luminosity-dependent bolometric correction. This gives a larger bolometric correction than the constant one at the higher AGN luminosity end, which would make average $L_{\text{bol}}^{\text{AGN}}$ larger and $C_T$ smaller.

The right panel of Figure 14 shows the same plot as Figure 8, but using the luminosity-dependent bolometric correction of Marconi et al. (2004). As expected from the luminosity-dependent bolometric correction, the distribution is slightly shifted to the right and downward in the figure. Actually, the median values of AGN bolometric luminosity and $C_T$ (dust) change from $(\log L_{\text{bol}}^{\text{AGN}}, C_T \text{ (dust)}) = (44.65, 0.46)$ to $(\log L_{\text{bol}}^{\text{AGN}}, C_T \text{ (dust)}) = (44.79, 0.39)$.

The figure clearly retains the trend of $C_T$ (gas + dust) $\geq C_T$ (dust) over the entire AGN luminosity range. On the other hand, the slight decline in $C_T$ (dust) in the lowest AGN bolometric luminosity bin disappears in Figure 14. This is mainly because of the small statistics in the lowest luminosity bin and some sources being shifted into a higher luminosity bin because of the larger bolometric correction by Marconi et al. (2004).

C.3. Dependence of Additional Torus Parameters

We here discuss how the dust covering factor changes when we change the set of the torus parameters. In this study we have only considered the spectral power-law index ($\alpha_1$) at $\lambda < 19 \mu m$ for the high-luminosity end with $\log L_{14-150} > 44$, and not considered the dust extinction for obscured AGNs, which could be one of the most significant parameters shaping the torus SEDs. The left panel of Figure 15 shows $C_T$ (dust) as a function of $L_{\text{bol}}^{\text{AGN}}$ after addition of the dust extinction for obscured AGNs using the absorption profile of Draine (2003) (see also Mullaney et al. 2011). $C_T$ (dust) becomes slightly larger, but the overall sense does not change. The middle panel shows the same plot using a fixed power-law index $\alpha_1 = 1.8$ for all sources without the dust extinction. $C_T$ (dust) shows a flatter distribution than Figure 8, but the overall trend of $C_T$ (dust) $< C_T$ (gas + dust) still holds.
C.4. Dependence of Other SB Templates

In this study, we used the best SB template based on the lowest $\chi^2$ value as discussed in Section 3. However, other SB templates sometimes show fitting results of similar quality with small $\Delta\chi^2$ between the best one and the others. Therefore, we investigate here how the result could be affected by using such different SB templates. We consider here that the fitting result is indistinguishable if $\Delta\chi^2$ between the best fitting SB template and the other SB ones is smaller than $c_{\text{max}}^2$, which is the maximum allowed $\chi^2$ corresponding to a $p$-value of $p = 0.05$ of $\chi^2$ distributions with the degree of freedom for each source. If one source has $\geq 2$ indistinguishable SB templates, we then measure the averaged $C_\ell$ of the SB templates as discussed in Appendix C.4.

Figure 14. Same as Figure 8, but estimating the values differently. Left: the covering factors used here are based on the estimation using the observed 12$\mu m$ luminosities in Ichikawa et al. (2017) before the IR SED decomposition. Right: the bolometric corrections used are dependent on the bolometric luminosity ($L_{\text{bol}}^{(\text{M04})}$, Marconi et al. 2004), not the constant bolometric correction.

Figure 15. Same as Figure 8, but using a different set of free parameters for (left) the addition of dust extinction and (middle) a fixed power-law index $\alpha_1 = 1.8$. Right: same as Figure 8, but using the averaged $C_\ell$ of the SB templates as discussed in Appendix C.4.

C.4. Dependence of Other SB Templates

In this study, we used the best SB template based on the lowest $\chi^2$ value as discussed in Section 3. However, other SB templates sometimes show fitting results of similar quality with small $\Delta\chi^2$ between the best one and the others. Therefore, we investigate here how the result could be affected by using such different SB templates. We consider here that the fitting result is indistinguishable if $\Delta\chi^2$ between the best fitting SB template and the other SB ones is smaller than $\chi^2_{\text{max}}$, which is the maximum allowed $\chi^2$ corresponding to a $p$-value of $p = 0.05$ of $\chi^2$ distributions with the degree of freedom for each source. If one source has $\geq 2$ indistinguishable SB templates, we then measure the averaged $C_\ell$ of the SB templates and the standard deviation $\Delta C_\ell$ of dust extinction and (middle) a fixed power-law index $\alpha_1 = 1.8$. Right: same as Figure 8, but using the averaged $C_\ell$ of the SB templates as discussed in Appendix C.4.

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