HERSCHEL FAR-INFRARED PHOTOMETRY OF THE SWIFT BURST ALERT TELESCOPE ACTIVE GALACTIC NUCLEI SAMPLE OF THE LOCAL UNIVERSE. I. PACS OBSERVATIONS*

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ABSTRACT

Far-Infrared (FIR) photometry from the Photodetector Array Camera and Spectrometer on the Herschel Space Observatory is presented for 313 nearby, hard X-ray selected galaxies from the 58 month Swift Burst Alert Telescope (BAT) Active Galactic Nuclei catalog. The present data do not distinguish between the FIR luminosity distributions at 70 and 160 μm for Seyfert 1 and Seyfert 2 galaxies. This result suggests that if the FIR emission is from the nuclear obscuring material surrounding the accretion disk, then it emits isotropically, independent of orientation. Alternatively, a significant fraction of the 70 and 160 μm luminosity could be from star formation, independent of active galactic nucleus (AGN) type. Using a non-parametric test for partial correlation with censored data, we find a statistically significant correlation between the AGN intrinsic power (in the 14–195 keV band) and the FIR emission at 70 and 160 μm for Seyfert 1 galaxies. We find no correlation between the 14–195 keV and FIR luminosities in Seyfert 2 galaxies. The observed correlations suggest two possible scenarios: (1) if we assume that the FIR luminosity is a good tracer of star formation, then there is a connection between star formation and the AGN at sub-kiloparsec scales, or (2) dust heated by the AGN has a statistically significant contribution to the FIR emission. Using a Spearman rank-order analysis, the 14–195 keV luminosities for the Seyfert 1 and 2 galaxies are weakly statistically correlated with the $F_{70}/F_{160}$ ratios.

Key words: galaxies: active – galaxies: nuclei – galaxies: Seyfert – infrared: galaxies – X-rays: galaxies

Online-only material: color figures, figure set, machine-readable table

1. INTRODUCTION

In the past few years, there has been an incredible amount of information regarding the infrared view of our dusty universe. With the advent of very successful space missions such as Spitzer (Werner et al. 2004), NASA’s Wide-field Infrared Survey Explorer (WISE, Wright et al. 2010), AKARI (Murakami et al. 2007), Planck (Planck Collaboration et al. 2011), and Herschel (Pilbratt et al. 2010), the mid-infrared (MIR) and far-infrared (FIR) is beginning to provide a unique perspective into the evolution of galaxies via dust-based star formation rate (SFR) indicators. However, these SFR indicators are not free from systematic uncertainties primarily due to the nature of dust in the galaxy by trapping the starlight and re-emitting (a fraction) in the infrared. Because of this, each MIR and FIR band can be associated with a different dust component, different spatial distributions, and different stellar age populations (see Kennicutt & Evans 2012, for a review). For these reasons, monochromatic infrared emission may be restricted, as a reliable SFR indicator, to large samples of galaxies for statistically significant studies (e.g., Calzetti et al. 2010). On the other hand, SFR indicators that rely on the total FIR emission are subject to uncertainties because they are very susceptible to the shape of the MIR to FIR spectral energy distribution (SED; e.g., Kennicutt 1998). Despite these considerations and given the plethora of new and more sensitive infrared surveys, these SFR metrics are widely used. However, little consideration is given to the possible contribution from dust heated by a non-stellar ionization source, i.e., the active galactic nucleus (AGN) in the center of the galaxy.

Following the unified model of AGNs (where the various types are explained solely by a viewing angle difference; see Antonucci 1993 for details), the hot accretion disk around the galaxy’s supermassive black hole is surrounded by a dusty, molecular torus. In recent years, there has been considerable effort to characterize the nature of this obscuring material both theoretically and observationally. Several models have been proposed to explain the observed and inferred properties of the torus, including a smooth, continuous, geometrically, and optically thick dusty torus (Krolik & Begelman 1988; Beckert & Duschl 2004; Fritz et al. 2006), full radiative transfer clumpy torus models (e.g., Nenkova et al. 2008a; Schartmann et al. 2008; Mor et al. 2009; Höning & Kishimoto 2010; Stalevski et al. 2012), and clumpy winds structures originating from the accretion disk (e.g., Elitzur & Shlosman 2006). However, within their uncertainties (e.g., size of the torus, inclination, dust distribution function, etc.), almost all these models predict some (non-negligible) torus contribution at the MIR and FIR wavelengths where dust-based SFRs are commonly used under the assumption that the FIR luminosity is attributed solely to star formation (SF; e.g., Fritz et al. 2006; Mullaney et al. 2011). Thus, it is of the utmost importance to determine the AGN contribution to the FIR emission.

To investigate the AGN contribution to the FIR emission, it is important to start with a complete and unbiased sample of local AGNs at $z < 0.05$, where we can use Herschel’s unique angular resolution to spatially resolve the FIR emission. Given its high energy band selection, 14–195 keV, the
Table 1

| Name            | R.A. (J2000.0) | Decl. (J2000.0) | Distance (Mpc) | Type | 70 μm (Ty) | 160 μm (Ty) | BAT (70 μm) | Aperture (70 μm) | Aperture (160 μm) | Program ID |
|-----------------|---------------|----------------|---------------|------|------------|------------|-------------|-----------------|-----------------|------------|
| Mrk 335         | 00 06 19.5    | +20 12 10.1    | 11.10         | Sy1  | 0.309 ± 0.016 | 0.15 ± 0.010 | 18.43       | 12              | 22              | 2          |
| 2MASX J00253292+6821442 | 00 25 32.9    | +68 21 44.0    | 51.15         | Sy2  | 0.290 ± 0.015 | 0.303 ± 0.024 | 18.24       | 12              | 22              | 1          |
| CGCG 535-012    | 00 36 21.0    | +45 39 54.4    | 208.70        | Sy1  | 0.145 ± 0.011 | <0.177      | 15.58       | 12              | 22              | 1          |
| NGC 235A        | 00 42 52.8    | −23 32 28.8    | 95.51         | Sy1  | 2.337 ± 0.123 | 2.613 ± 0.173 | 47.65       | 12              | 22              | 1          |
| MCG−02-02-095   | 00 43 08.8    | −11 36 04.0    | 80.87         | Sy2  | 0.081 ± 0.008 | <0.196      | 8.95        | 5.5             | 10.5            | 1          |
| MCG+05-03-013   | 00 51 35.0    | +29 24 04.5    | 156.12        | Sy1  | 0.825 ± 0.046 | 1.890 ± 0.166 | 9.81        | 14              | 24              | 1          |
| MCG+30-03-007   | 00 59 53.3    | +31 49 37.2    | 63.50         | Sy1  | <0.080      | <0.089      | 29.98       | 12              | 22              | 1          |
| ESO 195-IG021NED03 | 01 00 35.0    | −47 52 04.0    | 211.44        | Sy1  | 0.411 ± 0.021 | 0.824 ± 0.106 | 16.30       | 12              | 22              | 1          |
| MCG−07-03-007   | 01 05 26.8    | −12 42 58.2    | 129.16        | Sy2  | 0.313 ± 0.017 | 0.457 ± 0.029 | 11.97       | 12              | 22              | 1          |

Notes. Column 1: galaxy name. Columns 2 and 3: coordinates. Column 4: luminosity distance in Mpc. To calculate the distance we assumed a universe with a Hubble constant \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_m = 0.73 \), and \( \Omega_{\Lambda} = 0.27 \), with redshift values taken from NASA's ExtraGalactic Database (NED), except for sources with redshift values of \( z < 0.01 \) where distances are taken from The Extragalactic Distance Database (Tully 1988; Tully et al. 2009). Column 5: Galaxy type from Baumgartner et al. (2013), Seyfert galaxies (Sy), LINERs (L), and MCG (from Meléndez et al. 2013). Source identifications are based primarily on the emission from the BAT source.

Swift/Burst Alert Telescope (BAT) survey of AGNs represents such a sample because it is unbiased toward Compton thin AGNs, e.g., sources with hydrogen column densities of less than a few times \( 10^{24} \text{ cm}^{-2} \). In addition, the BAT AGN survey is not sensitive to stellar activity in the host galaxy because SF has a negligible contribution at these high X-ray energies. Thus, the BAT sample can provide a unique perspective into the AGN and SF contributions at the FIR wavelengths, where the dusty torus and the current SF are the competing effects heating the dust. For this purpose, we performed a statistical study of the correlations between the FIR luminosities observed by the Herschel Observatory and the hard X-ray luminosities for more than 300 local BAT AGNs. In Sections 2–3, we present details on the sample selection, Herschel observations, and data processing. Section 4 shows the FIR properties of the BAT sample. Section 5 discusses the observed correlations between the hard X-ray and FIR emission. In Section 6, we present the FIR colors of the BAT sample and their implications for some of the FIR predictions of torus models. Section 7 shows the comparison for the FIR colors between the BAT AGNs and normal star-forming galaxies. Finally, Section 8 lists the main conclusions of this work.

### 2. SAMPLE

The sample presented in this work was selected from the low-redshift (\( z < 0.05 \)) 58 month Swift/BAT survey with a median redshift of \( z \approx 0.025 \).^{6} The 58 month Swift/BAT is an almost uniform hard X-ray all-sky survey and reaches a flux level of \( 1.1 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \) over 50% of the sky and \( 1.48 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \) over 90% of the sky (Baumgartner et al. 2013). Source identifications are based primarily on the X-ray imaging data and a correlation with optical images and catalogs. In some cases, the identifications are based on positional coincidences with previously known AGNs. The main advantage of the BAT AGN sample is that the selection process is completely independent of optical, IR, or radio properties of the host galaxy. Our final sample of galaxies includes 149 Seyfert 1 galaxies (1/1.2/1.5), 157 Seyfert 2 galaxies (1.8/1.9/2.0), 6 LINERs, and 1 unclassified Seyfert galaxy, ESO 464-G016 (Véron-Cetty & Véron 2010). One must note that some of the Seyfert galaxies have dual classifications; see Table 1. For the purpose of grouping galaxies in the rest of the paper, we take the Seyfert classification as the primary types.

### 3. OBSERVATIONS AND DATA PROCESSING

The 58 month BAT sample was observed by the Photodetector Array Camera and Spectrometer (PACS, Poglitsch et al. 2010) on the Herschel Space Observatory. The vast majority of the BAT AGNs presented in this work are from our cycle 1 open-time program (OT1_rumshot_1, PI: R. Mushotzky) with a total of 291 sources. For the sake of completeness, we included 22 BAT sources from different programs publicly available from the Herschel science archive; see Table 1 for details. From this, the total number of BAT AGN sources in our sample is 313. For the sources obtained through our OT1 program, the PACS imaging for the blue 70 μm (60–85 μm) and red 160 μm (130–210 μm) band was obtained simultaneously in scan mode along two scan map position angles at 70° and 110°. Each orientation angle was scanned with a medium scan speed of \( 20' \text{s}^{-1} \), two scan legs of 30' length with 5’ scan leg separation and a repetition factor of one. The total time per observation

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6 http://swift.gsfc.nasa.gov/results/b58mon/
was 52 s. From our OT1 program, the galaxies II SZ 010, Mrk 290, PG 2304+042, and Mrk 841 have a different configuration with 10 scan legs of 3′ length with 4′/0 scan leg separation and a repetition factor of one with a total time per observation of 276 s.

For the PACS data reduction, we use the Herschel Interactive Processing Environment (Ott 2010) version 8.0. The “Level 0” observations (raw data) were processed through the standard pipeline procedure to convert from Level 0 to Level 1 data. This procedure includes the extraction of the calibration tree needed for the data processing, correction for electronic crosstalk, application of the flat-field correction, and finally, deglitching and conversion from volts to Jy pixel$^{-1}$. In order to correct for bolometer drift (low frequency noise), both thermal and non-thermal (uncorrelated noise), and to create the final maps from the Level 1 data, we used the algorithm implemented in Scanamorphos (v19.0; Roussel 2013), which makes use of the redundancy built in the observations to derive the brightness drifts. Because of this, Scanamorphos is independent of any pre-defined noise model because it relies on the fact that each portion of the sky is scanned by multiple bolometers at different times. All final maps have a pixel size of $\sim$1/4 of the point-spread function (PSF) FWHM, i.e., 1′/4 at 70 $\mu$m and 2′/85 at 160 $\mu$m. Scanamorphos also produces an error and weight map. The error map is defined as the error on the mean brightness in each pixel. It is built using the weighted variance because weights are used for the projection of the final map. The error map does not include any error propagation associated with the different steps performed on the pipeline. On the other hand, the weighted map is built by co-adding the weights and is normalized by the average of the weights; see Figure 10 of the Appendix for a sample of the final maps. All the images are available in the online journal. At the median redshift for the sample, 10′ represents $\sim$500 pc. Hence, for example, PACS 70 $\mu$m PSF will sample about 2.8 kpc at $z \sim 0.025$.

PACS fluxes are measured using a combination of circular and elliptical apertures for sources that are visually identified as point-like (and/or relatively point-like) and extended sources, respectively. The apertures are chosen by eye to contain all of the observed emission at each wavelength. In addition, background subtraction is performed locally with a circular or elliptical annulus around the source. For point-like sources, the background annulus was set to be 20′$-$25′ and 24′′$-$28′′ in radius for the blue and red camera, respectively. For extended sources, the background annulus was set to encompass a clean, uncontaminated sky region close to the source. Table 1 shows the different aperture sizes used in this work.

Aperture corrections are applied to the background subtracted fluxes. For point-like sources, we applied the correction outlined in Table 15 of the technical report PICC-ME-TN-037. To derive aperture corrections for extended sources, we used higher-resolution images from Spitzer/Infrared Array Camera (IRAC) 8.0 $\mu$m and measured the total flux with the same aperture employed for the PACS analysis. We then convolved the same image with the right kernel to bring it to the PACS resolution and remeasured the flux in the same aperture. The ratio of the unconvolved to the convolved (the same PSF as the Herschel PACS) flux is used as an estimate of the aperture correction. From the list of the extended sources, there are 53 BAT AGN sources with Spitzer/IRAC 8.0 $\mu$m images available through the Spitzer Enhanced Imaging Products archive. For these sources, we find the aperture corrections to be very small, with values not greater than 1.03 ($<3\%$) and with a mean value very close to unity. Therefore, for large, extended sources without higher-resolution images, we apply no correction, so we added a 3% flux uncertainty. Caution must be taken because aperture corrections derived from this empirical method assume that the spatial distribution is the same at PACS (FIR) and IRAC (MIR) wavelengths.

The total uncertainty for the integrated photometry is a combination of the error on the mean brightness in each pixel added in quadrature within the source aperture (the error map produced by Scanamorphos), the standard deviation of all the pixels in the background aperture, and the PACS photometer flux calibration accuracy. In some cases, the dominant source of error is background fluctuations especially in sources contaminated by cirrus (see Table 1); however, almost all of our sources have a clean, flat extragalactic field. The PACS calibration uncertainties are $\sigma_{\text{cal}}$, 5%, according to version 2.4 of the PACS Observer’s Manual. Finally, we take as an upper limit five times the total uncertainty for the integrated photometry (5$\sigma$). Table 1 presents the spatially integrated flux densities for all 313 galaxies for the PACS blue and red photometric bands. The tabulated flux densities include aperture corrections. No reddening and color corrections have been applied to the data in Table 1. From this, 295 and 260 sources are detected by PACS at 70 and 160 $\mu$m, implying a detection rate of 94% and 83%, respectively. Only two sources, namely, MCG-01-09-045 and UGC03995A, are detected at PACS 160 $\mu$m with no detections at 70 $\mu$m.

To investigate the nature of the 16 undetected sources in both PACS bands, we used values from the WISE All-sky source catalog at 3.4, 4.6, 12, and 22 $\mu$m to construct the AGN SED between 3.4 and 160 $\mu$m. We then compared the WISE and median SEDs for the entire sample with those from the PACS undetected sources. The upper panel in Figure 1 shows a comparison of the SEDs of the sources with detections in both PACS bands and the undetected PACS sources (the individual SEDs of the BAT AGNs are normalized to the flux in the WISE 22 $\mu$m band). It can be seen that the undetected sources are characterized by a flatter infrared SED than that for the entire sample. Note that the entire sample was detected by WISE, except for Mrk 3. The WISE fluxes, we selected the magnitude measured with profile-fitting photometry for sources flagged by WISE as point sources, and for extended sources, we selected the magnitude measured via elliptical aperture photometry, which is measured using areas that are scaled from the Two Micron All Sky Survey Extended Source Catalog morphologies (Skrutskie et al. 2006). In addition, we inspected the low-resolution MIR spectra of six PACS undetected sources observed by Spitzer (lower panel in Figure 1). We retrieved the low-resolution MIR spectra for these sources, namely, ESO121-IG028, Mrk352, Mrk50, PG2304+042, SBS1301+540, and UM614, via the Cornell atlas of Spitzer/Infrared Spectrograph (IRS) sources (Lebouteiller et al. 2011). From this comparison, it is clear that, on average, these sources show a systematic decrease in their MIR emission toward longer wavelengths, $\lambda > 20 \mu$m. Moreover, the low-resolution MIR spectra show no strong SF features (e.g., polycyclic aromatic hydrocarbon emission). Overall, these results suggest that PACS undetected BAT AGNs
reside in cold, dust-depleted systems with no active SF. We define this group of objects as X-ray Bright Far-infrared Faint sources (XBFF). A more detailed analysis of the BAT SEDs and the nature of the XBFF sources will be presented in subsequent papers in the BAT Herschel series.

Figure 2 shows the comparison between the PACS 70 μm measurements and observations from the Infrared Astronomical Satellite (IRAS) at 60 μm (Neugebauer et al. 1984). Note that in most cases, given the PACS instrument’s better photometric sensitivity, it was not possible to find IRAS fluxes for all galaxies in the sample. In total, 205 sources from the BAT sample had IRAS detections at 60 μm, mainly from the IRAS Faint Source Catalog for faint point sources (Moshir et al. 1990), the Point Source Catalog (V2.0; Helou & Walker 1988), and the catalog of large optical galaxies (Rice et al. 1988). From this comparison, we found very good agreement between the PACS and IRAS fluxes with $S_{60}$ density fluxes (IRAS) slightly below the 1:1 line, as expected (an increasing flux density at wavelengths shorter than the FIR peak; Dale et al. 2001, 2012; Dale & Helou 2002; Draine & Li 2007; Casey 2012). The good correlation between the fluxes suggests that the size of our aperture photometry extractions encompasses the FIR emission from the galaxy because the beam size used for the IRAS catalog is larger, approximately 1’ at 60 μm, than the majority of the aperture sizes used in this work. This result is corroborated by the spatial analysis presented in Mushotzky et al. (2014), where we show that in the majority of the BAT sources, the bulk of the FIR radiation is point-like at the spatial resolution of Herschel (a median value of 2 kpc FWHM). Note that some of the brightest sources in our sample, e.g., Centaurus A, are extended; thus, the point source extraction from IRAS, even at 1’ resolution, underpredicts the flux at 60 μm. On the other hand, there may be contamination from a neighboring source that lies within IRAS’ bigger aperture, thereby overpredicting the flux at 60 μm. For example, there is an IR bright companion source (GALEXASC J154634.12+692844.7) ~56:4 from 2MASXJ15462424+6929102 (see Figure 2).

4. FAR-INFRARED PROPERTIES OF THE BAT SAMPLE

Figure 3 presents the histograms comparing the 70 μm, 160 μm, and BAT 14–195 keV luminosities of the Seyfert 1 and Seyfert 2 galaxies. We performed a Kolmogorov–Smirnov (K-S) test on the detected sources to determine whether the BAT Seyfert 1 and 2 galaxy populations are drawn from the same parent distribution. A K-S probability value of less than 5% is the probability that two samples drawn from the same parent population would differ this much 5% of the time, i.e., that they are statistically different. A strong level of significance is obtained for values smaller than 1% (e.g., Press et al. 1992; Bevington & Robinson 2003). The number of sources, mean values, standard deviations, and the K-S probability of the null hypothesis for the sample are presented in Table 2. The K-S test for the luminosity distribution at 70 μm returns a 70.0% probability of the null hypothesis (i.e., the Seyfert 1 and Seyfert 2 galaxy populations are not distinguished by the present data).
Figure 3. Distributions of the monochromatic luminosities for the emission at 70 and 160 μm and the integrated 14–195 keV luminosities for the sample of BAT AGNs presented in this work. Upper limits are not included in the distribution. (A color version of this figure is available in the online journal.)

Table 2

| Observable | Measurements Available | Mean | Standard Deviation | Measurements Available | Mean | Standard Deviation | p |
|------------|------------------------|------|--------------------|------------------------|------|--------------------|---|
| log $L_{70 \mu m}$ | 137 | 30.83 | 0.05 | 151 | 30.88 | 0.04 | 7.0 $\times 10^{-1}$ |
| log $L_{160 \mu m}$ | 113 | 31.08 | 0.04 | 141 | 31.07 | 0.05 | 5.2 $\times 10^{-1}$ |
| log $L_{BAT}$ | 149 | 43.56 | 0.04 | 157 | 43.26 | 0.04 | 5.0 $\times 10^{-2}$ |
| $log L_{70 \mu m}/L_{160 \mu m}$ | 113 | 0.81 | 0.43 | 139 | 0.77 | 0.47 | 5.4 $\times 10^{-1}$ |

Statistical Analysis (Censored Data)

| log $L_{70 \mu m}$ a | 149 (12) | 30.73 | 0.05 | 157 (6) | 30.84 | 0.04 | 2.4 $\times 10^{-1}$ |
| log $L_{160 \mu m}$ a | 149 (36) | 30.72 | 0.08 | 157 (16) | 30.98 | 0.05 | 5.0 $\times 10^{-2}$ |

Notes. Column 1: the observed data used for the correlation analysis. Column 2: number of Seyfert 1 galaxies used for the correlation analysis. Column 3: mean value for Seyfert 1 galaxies. Column 4: standard deviation for Seyfert 1 galaxies. Columns (5)–(7) are the same as Columns (2)–(4) but for Seyfert 2 galaxies. Column (8): the K-S test null probability for the detected data points and Gehan’s generalized Wilcoxon test probability when upper limits are considered. In order to calculate the mean value and standard deviations with “censored” data points (number of sources with upper limits in parentheses), we used the Kaplan–Meier estimator with randomly censored data (Kaplan & Meier 1958).

a The mean values and standard deviations are given by the Kaplan–Meier estimator. The two-sample test probability is given by Gehan’s generalized Wilcoxon test.

Similarly, the K-S null probability for the luminosity distribution at 160 μm is 52.0%. A similar situation for the Seyfert galaxies in the BAT sample has also been found in the luminosities of MIR narrow emission lines (Weaver et al. 2010) and of optical, reddening-corrected emission lines (Winter et al. 2010).

Caution must be taken when applying statistical tests to data sets that contain non-detections (upper limits), or “censored”, data points. In order to deal with these problems, we used the Astronomy SURVival analysis software package ASURV Rev 1.2 (Isobe et al. 1986; Lavalley et al. 1992). We performed statistical two-sample tests and found that the luminosity distribution at 70 μm returns a 23.8% probability when using Gehan’s generalized Wilcoxon test; in other words, two samples drawn from the same parent population would differ this much 23.8% of the time. This result is in agreement, within the statistical significance, with the K-S test on the detected sources. On the other hand, the luminosity distribution at 160 μm returns a Gehan’s generalized Wilcoxon test probability of 5.3%. A similar two-sample test for censored data, the Peto–Prentice generalized Wilcoxon test, returns a probability of only 4.2% that the Seyfert 1 and 2 galaxy populations at 160 μm are drawn from the same parent population. Thus, the luminosity distributions of the Seyfert 1 and 2 galaxy populations at 160 μm differ at a weak but possibly statistically significant level when non-detections are included in the analysis. From this, we find that Seyfert 2 galaxies have a very slightly
higher mean luminosity at 160 μm, log $L_{160\mu m} = 30.98 \pm 0.05$ (erg s$^{-1}$ Hz$^{-1}$), than Seyfert 1 galaxies, log $L_{160\mu m} = 30.72 \pm 0.08$ (erg s$^{-1}$ Hz$^{-1}$). By comparison, the six sources uniquely identified as LINERs in our sample have mean luminosities at 70 and 160 μm of log $L_{70\mu m} = 30.70 \pm 0.34$ (erg s$^{-1}$ Hz$^{-1}$) and log $L_{160\mu m} = 30.92 \pm 0.29$ (erg s$^{-1}$ Hz$^{-1}$), respectively, different than the Seyfert 1 and Seyfert 2 galaxies. The number of sources with detected and “censored” data points and the Gehan’s generalized Wilcoxon test probability of the null hypothesis for the sample are presented in Table 2. In addition, Table 2 also shows the mean value for the entire sample of Seyfert 1 and 2 galaxies (including detections and non-detections) based on the Kaplan–Meier estimator with randomly censored data (Kaplan & Meier 1958).

The similar FIR luminosities in these two types of Seyfert galaxies implies that radiation at these wavelengths is roughly isotropic, e.g., independent of orientation. This result suggests two plausible scenarios: (1) SF is isotropic, and hence the FIR luminosities of Seyfert 1 and 2 galaxies would be indistinguishable, and/or (2) the AGN torus is isotropic at FIR wavelengths. In the former scenario, we find that a large number of BAT sources are point-like in the PACS 70 μm images, implying a compact FIR nucleus of less than 6′′ (which typically encompasses regions of less than a couple of kiloparsecs). Thus, if SF is the culprit for most of the FIR emission, then it has to happen in a very compact, nuclear region, suggesting a connection between the AGN and the nuclear cold molecular gas (see Mushotzky et al. 2014). The latter scenario is in agreement with some theoretical calculations of the dusty, obscuring material surrounding the accretion disk that predict a similar shape for the FIR part of the SED for both types of galaxy populations (e.g., Kennicutt et al. 2003; Stalevski et al. 2012). Note that some torus models predict an angle dependence on the FIR luminosity, with Seyfert 1 galaxies having higher luminosities than Seyfert 2 galaxies (e.g., Fritz et al. 2006). Thus, in order to match the observed FIR part of the SED, predictions from these models require an extra contribution from a circumnuclear starburst in edge-on systems. In general, much of the light would have its origin in SF.

On the other hand, the 14–195 keV X-ray luminosities (Figure 3, bottom panel) are statistically different between the Seyfert types with a K-S test probability of 8.0 × 10$^{-3}$%, e.g., two samples drawn from the same parent population would differ this much 8.0 × 10$^{-3}$% of the time. We find that Seyfert 2 galaxies have, on average, smaller luminosities, log $L_{\text{BAT}} = 43.26 \pm 0.04$ (erg s$^{-1}$), than Seyfert 1 galaxies with log $L_{\text{BAT}} = 43.57 \pm 0.05$ (erg s$^{-1}$), in agreement with previous results (Meléndez et al. 2008a; Winter et al. 2009; Weaver et al. 2010; Burlon et al. 2011; Ichikawa et al. 2012). This result suggests two possible scenarios: (1) Compton down scattering, even in the high energy 14–195 keV band, for some of the Seyfert 2 galaxies may be important in reducing the observed flux (e.g., Ikeda et al. 2009; Murphy & Yaqoob 2009), or (2) the statistical differences between absorbed (Seyfert 2s) and unabsorbed (Seyfert 1s) AGNs are more fundamental with absorbed AGNs being intrinsically less luminous than unabsorbed AGNs, in agreement with previous studies (e.g., Cowie et al. 2003; Steffen et al. 2003; Ueda et al. 2003; Barger et al. 2005; La Franca et al. 2005; Hasinger et al. 2005; Burlon et al. 2011). Regarding the former scenario, one must consider that there is no observational evidence of a dominant population of Compton-thick (CT) AGNs in the BAT survey (e.g., Burlon et al. 2011). Moreover, the fraction of CT objects in deep, hard X-ray surveys has been estimated with some precision to be only ∼17% (e.g., Bassani et al. 2013).

The latter scenario, an intrinsic difference between the luminosities of Seyfert types, is supported by the difference in the luminosity break found in the luminosity function between the two classes of objects for the BAT sample, with absorbed AGNs having (on average) lower luminosities than unabsorbed AGNs (e.g., Burlon et al. 2011). Overall, this scenario provides a test for the basic predictions from the unified model of AGNs in which the intrinsic AGN luminosity should be independent of obscuration, that is, one must consider a model where the physical properties of the dusty, molecular torus change as a function of the intrinsic properties of the AGN central engine, e.g., accretion rate, power, etc. (e.g., Lawrence 1991). For the purpose of this paper, we shall consider both scenarios as plausible and discuss their implications in the context of the FIR emission of AGNs.

5. FAR-INFRARED AND HARD X-RAY CORRELATIONS

As we mentioned before, FIR emission is widely used as a probe of SF. However, it is clear that if the AGN has some contribution at FIR wavelengths, then one must correct these SFR indicators accordingly. Figure 4 shows 14–195 keV luminosities versus the 70 μm or 160 μm luminosity. Due to redshift effects, luminosity–luminosity plots will almost always show some correlation. We therefore used a non-parametric test for partial correlation with censored data (Akritas & Siebert 1996) in order to exclude the redshift effect. From this, we find that the 14–195 keV luminosities are statistically correlated with the FIR luminosities in the Seyfert 1 galaxies with a partial Kendall $\tau_p = 0.201$ and a probability of $P_\tau = 5.3 \times 10^{-5}$ at 70 μm, and $P_\tau = 0.116$ and $P_\tau = 6.7 \times 10^{-4}$ at 160 μm. We find no statistically significant correlation between the 14–195 keV and FIR luminosities in the Seyfert 2 galaxies; in other words, the 14–195 keV and FIR luminosity distributions are independent (see Table 3 for details). In order to test whether these correlations are dependent on the BAT luminosity, we used the partial Kendall test in two different groups: sources with log $L_{\text{BAT}} > 43.0$ (log $L_{\text{BAT}} > 42.5$) and log $L_{\text{BAT}} > 44.0$ (log $L_{\text{BAT}} > 43.5$) for Seyfert 1 (Seyfert 2) galaxies. For Seyfert 1 galaxies at 70 μm, we find $\tau_p = 0.189$ and $P_\tau = 1.6 \times 10^{-4}$ (log $L_{\text{BAT}} > 43.0$), and $\tau_p = 0.258$ and $P_\tau = 3.0 \times 10^{-2}$ (log $L_{\text{BAT}} > 44.0$). Similarly, at 160 μm, we find $\tau_p = 0.117$ and $P_\tau = 1.8 \times 10^{-2}$ (log $L_{\text{BAT}} > 43.0$), and $\tau_p = 0.226$ and $P_\tau = 2.3 \times 10^{-2}$ (log $L_{\text{BAT}} > 44.0$). Again, we find no statistically significant correlation between the 14–195 keV and FIR luminosities in the Seyfert 2 galaxies within the luminosity groups (see Table 3 for details). Note that in the Seyfert 1 galaxies the FIR–X-ray correlations get stronger for the most X-ray luminous objects suggesting that the AGN contribution overwhelms the SF contribution at high luminosities.

Overall, for the Seyfert 1 galaxies, we find a better correlation at 70 μm than at 160 μm. This result is in agreement with previous works where the correlations between 14–195 keV luminosities and different monochromatic infrared luminosities get weaker at longer wavelengths where the contribution from SF might be greater. For example, the tightest and most significant correlations are found between the 14–195 keV luminosities and the 9, 12, and 18 μm emission (e.g., Gandhi et al. 2009; Matsuta et al. 2012; Ichikawa et al. 2012), and the correlations get less significant at longer FIR wavelengths (e.g., Meléndez et al. 2008b; Nenkova et al. 2008b; Matsuta et al. 2012).
Figure 4. Left panels: correlation between the monochromatic luminosities at 70 and 160 μm and the 14–195 keV luminosity (L_{BAT}) in Seyfert 1 (black circles), Seyfert 2 (red triangles), LINERs (green stars), and AGNs (blue square). AGN refers to unidentified or previously unknown AGNs. The dashed and solid lines represent the linear regression using the OLS and bisector methods, respectively, separated into Seyfert 1 (black lines) and Seyfert 2 (red lines) galaxies. Right panels: binned correlation between the monochromatic luminosity at 70 and 160 μm and the 14–195 keV luminosity in Seyfert 1 (black) and Seyfert 2 (red) galaxies. We choose five equally spaced bins within the range of the FIR monochromatic and BAT luminosities. The error bars are the standard deviations for each quantity. The solid line in the upper right panel is the AGN-dominated line from Netzer (2009) (see the text for details).

(A color version of this figure is available in the online journal.)

2012; Ichikawa et al. 2012). However, this is the first time that a weak but possibly statistically significant correlation between the intrinsic power of the AGN and the FIR emission at 160 μm has been found. These results suggest two possible scenarios: (1) if we assume that the FIR luminosity is a good tracer of SF (e.g., Calzetti et al. 2010), then there is a connection between SF and the AGN at sub-kiloparsec scales (e.g., Mushotzky et al. 2014), or (2) dust heated by the AGN has a statistically significant contribution to the FIR emission at 70 and 160 μm. In the latter scenario, SFR indicators that rely on FIR emission, either through the individual infrared bands (Calzetti et al. 2010) or the total FIR emission (8–1000 μm; Kennicutt 1998), need to consider the AGN contribution in their predictions. Note that in order to increase the FIR emission predicted from the outer (and colder) regions of many torus models (AGN contribution), one could use any combination of free parameters, such as an increase of the torus radius with a constant optical depth, a flatter radial density profile, and/or an edge-on orientation (e.g., Nenkova et al. 2008b; Stalevski et al. 2012). Within these parameters (uncertainties), smooth, continuous torus models seem to be able to predict higher FIR fluxes than clumpy torus calculations (with a broader range of SED shapes); however, clumpy models provide a better match to the MIR portion of the SED (e.g., Mullaney et al. 2011).

In addition, Figure 4 shows different linear regression methods applied to the sample (see Table 4 for values). In order to test the effect of the upper limits in our sample, we estimated the linear regression coefficients using the expectation–maximization (EM) algorithm with censored data (Isobe et al. 1986) and an ordinary least-squares regression of the dependent variable, Y, against the independent variable, X, (ordinary least squares, hereafter OLS) without the inclusion of censored data (only
detections). Both methods show a good agreement within their uncertainties, suggesting that the non-detections in our sample do not significantly change the results. However, it is not clear that the FIR luminosity is a direct consequence of the BAT luminosity; thus, a bisector method may be more appropriate to investigate the underlying functional relationship between the hard X-ray and FIR luminosities (Isobe et al. 1990). From this, we find a nearly linear relationship between the AGN and PACS monochromatic luminosities, with Seyfert 1 and Seyfert 2 galaxies having similar slopes within the given uncertainties. Overall, these values are in agreement with the slopes found by Matsuta et al. (2012) between the 14–195 keV and 90 μm luminosities.

Included as well in Figure 4 is the relation between \( L_{\text{bol}} \) and \( L_{\text{bol}} \) for AGN-dominated sources from Netzer (2009; black line in upper right panel). In order to compare this relation with our sample, we assumed a mean ratio of \( S_{70}/S_{60} = 1.09 \), as derived from the PACS–IRAS comparison presented in Figure 2 and a constant ratio of 10.5 to transfer the 14–195 keV luminosity to bolometric luminosity (Winter et al. 2012). Overall, the Netzer (2009) relationship for AGN-dominated sources is in fair agreement with the mean values of our sample and it extends linearly over our range of X-ray luminosities. Note that systems above this straight line may be dominated by SF in the host galaxy, resulting in the flatter slope observed in Seyfert 2 galaxies at low BAT luminosities, log \( L_{\text{BAT}} < \sim 42.5 \text{ erg s}^{-1} \) (or log \( L_{\text{bol}} < \sim 43.7 \text{ erg s}^{-1} \)). This luminosity is smaller, by a factor of \( \sim 3 \), than the turnover value found by Rosario et al. (2012) for local AGNs, log \( L_{\text{bol}} = 44.23 \pm 0.13 \) (erg s\(^{-1}\)); however, Seyfert 1 galaxies show no turnover over our range of X-ray luminosities. Netzer (2009) suggested a time evolution scenario to explain the \( L_{\text{bol}} \) versus \( L_{\text{bol}} \) linear correlation, where the galaxy transitions from a pure starburst to a powerful composite starburst–AGN and, finally, to a weak composite starburst–AGN phase. In this scenario, after a long SF period, some of the cold gas is funneled to the center of the galaxy and feeds the black hole, resulting in a short period of intense AGN and stellar activity with high SF and accretion rate. This stage is characterized by sources rising and moving horizontally above the straight line in the upper right panel in Figure 4. As the cold gas supply diminishes, both the SF and the central AGN...
much flatter. Derived from the bisector method, whereas the OLS slopes are analogous evolutionary connection between the Seyfert 1 and in Netzer 2009). Interestingly, this scenario may suggest an fade in parallel and fall below the straight line (see Figure 14 The Astrophysical Journal AKARI the of a correlation found between the 14–195keV luminosities and ing the FIR emission. This scenario is in agreement with the lack hard X-ray by reducing the X-ray flux and perhaps increas- 14–195 keV and FIR luminosities in Seyfert 2 galaxies. In the effect of these scenarios in the FIR and hard X-ray relationship Seyfert 2 galaxies are intrinsically less luminous than Seyfert 1 galaxies, dominated by SF, are above the straight line. As they evolve in time, they reach their maximum AGNs and SF activity until the Seyfert 1 and Seyfert 2 galaxy branches grow together at high SF, L_{70}, and AGN luminosity, L_{BAT}. As the supply of cold gas is reduced, the AGNs and SF luminosity fade together below the straight line, evolving into the observed Seyfert 1 galaxy branch. Note that the slope of the Netzer (2009) relationship (L_{60} \propto L_{bol}^{-0.8}) is in good agreement with our values derived from the bisector method, whereas the OLS slopes are much flatter.

5.1. Seyfert 2 Galaxies

In the previous section, we proposed two scenarios to explain the statistical differences in the 14–195 keV luminosity distribution between Seyfert 1 and Seyfert 2 galaxies: (1) the effect of Compton scattering in the Seyfert 2 population, or (2) that Seyfert 2 galaxies are intrinsically less luminous than Seyfert 1 galaxies. In the following discussion, we will investigate the effect of these scenarios in the FIR and hard X-ray relationship in order to find the culprit for the lack of correlation between the 14–195 keV and FIR luminosities in Seyfert 2 galaxies. In the former scenario, if Compton scattering in the 14–195 keV band is important, then the more heavily obscured sources are responsible for breaking the intrinsic correlation between the FIR and the hard X-ray by reducing the X-ray flux and perhaps increasing the FIR emission. This scenario is in agreement with the lack of a correlation found between the 14–195 keV luminosities and the AKARI infrared luminosities at 90 μm in CT AGNs for the 22 month BAT survey (Matsuta et al. 2012). Moreover, in this sample, Seyfert 2 galaxies are correlated if CT AGNs are excluded. In order to test the effect of high X-ray column densities on the FIR and X-ray correlations, we have compiled published values for the X-ray column densities of Seyfert 2 galaxies in our sample (see Tueller et al. 2008; Winter et al. 2009; Burlon et al. 2011; Vasudevan et al. 2013, and references therein). From this, we found that 106 out of 157 Seyfert 2 galaxies have published X-ray column densities with 18 sources having high X-ray column densities, N_{H} > 10^{24} cm^{-2} (see Table 5). We use the same partial correlation analysis as before and find that, even when excluding the CT sources presented in Table 5, there is no statistically significant correlation between the 14–195 keV and FIR luminosities (70 and 160 μm) in Seyfert 2 galaxies when the influence of distance is excluded (see Table 3).

As we mentioned before, the fraction of CT AGNs in deep, hard X-ray surveys is 17% ± 3% (Bassani et al. 2013). This fraction of CT AGNs is in agreement with the value derived from the northern Galactic cap of the 58 month BAT catalog, where they found that up to 15% of their sample could be CT (Vasudevan et al. 2013). Since we identified only 18 CT candidates in our sample, this suggests that there may be some heavily obscured Seyfert 2 galaxies that are unaccounted for. In order to have an estimate of the X-ray column density for the sources without published values (51 out of 157), we used a simple color–color diagram initially presented in Winter et al. (2008) and later in Winter et al. (2009). Figure 5 shows the soft (0.5–2 keV) and medium (2–10 keV) X-rays were taken from the seven-year Swift–XRT point source catalog (D’Elia et al. 2013). For comparison, we identified the Compton thick sources (Table 5) as open red triangles and circles. It is clear from this comparison that our CT sources position for the CT sources in our sample (open red triangles and circles). It is clear from this comparison that our CT sources are located in the same branch of heavily obscured sources N_{H} > 10^{23} cm^{-2}, which extends toward the upper right side of the diagram (see Figure 3 in Winter et al. 2009). We find that the vast majority of the CT sources have hard/medium

| Name       | N_{H} (10^{24}cm^{-2}) | Reference |
|------------|-------------------------|-----------|
| CGCG 420–015 | 1.46                    | (1)       |
| ESO 005–G004 | 1.01                    | (2)       |
| ESO 137–G034 | > 1.5                   | (3)       |
| MCG–01-30-041 | 1.45                    | (4)       |
| Mrk 3        | 1.36                    | (5)       |
| Mrk 417      | 1.20                    | (4)       |
| NGC 424      | 1.00                    | (6)       |
| NGC 1365     | 4.00                    | (7)       |
| NGC 3079     | 5.40                    | (6)       |
| NGC 3281     | 2.00                    | (8)       |
| NGC 3393     | 4.50                    | (6)       |
| NGC 4939     | > 10.00                 | (9)       |
| NGC 4941     | 1.32                    | (4)       |
| NGC 5728     | 1.39                    | (10)      |
| NGC 6240     | 1.83                    | (6)       |
| NGC 6552     | > 1.00                  | (11)      |
| NGC 7582     | 1.10                    | (6)       |
| UGC 05881    | 2.45                    | (4)       |

Notes. Column 1: galaxy name. Column 2: X-ray absorbing column density. Column 3: references for the column density—(1) Sey- ergni et al. 2011; (2) Ueda et al. 2007; (3) Malizia et al. 2009; (4) Vasudevan et al. 2013; (5) Bianchi et al. 2005; (6) Burlon et al. 2011; (7) Risaliti et al. 2009; (8) Vignali & Comastri 2002; (9) Maiolino et al. 1998; (10) Comastri et al. 2010; (11) Bassani et al. 1999.

Figure 5. Color–color diagram for the Seyfert 2 galaxies in our sample without published X-ray column density values (solid red triangles). Fluxes for the soft (0.5–2 keV) and medium (2–10 keV) X-rays were taken from the seven-year Swift–XRT point source catalog (D’Elia et al. 2013). For comparison, we identified the Compton thick sources (Table 5) as open red triangles and circles. (A color version of this figure is available in the online journal.)
Table 6

| Name | $F_{14-195keV}/F_{2-10keV}$ | $F_{0.5-2keV}/F_{2-10keV}$ | $F_{0.5-2keV}/F_{2-10keV}$ |
|------|----------------------------|-----------------------------|----------------------------|
| (1)  | (2)                        | (3)                         | (4)                        |
| 2MASX J01064523+0638015 | 10.66                       | 0.05                        |                              |
| 2MASX J01073965+1139117 | 22.57                       | 0.07                        |                              |
| 2MASX J01423409+0408017 | 32.92                       | 0.10                        |                              |
| 2MASX J06411806+3249313 | 10.86                       | 0.04                        |                              |
| 2MASX J06561197+4919499 | 56.87                       | 0.16                        |                              |
| 2MASX J07262635−3554214 | 21.36                       | 0.09                        |                              |
| 2MASX J09360622+6548336 | 15.92                       | 0.13                        |                              |
| 2MASX J20101740+4800214 | 24.76                       | 0.05                        |                              |
| 2MFGC 02280              | 118.83                      | 0.10                        |                              |
| CGCG 102−048             | 43.07                       | 0.10                        |                              |
| CGCG 312−012             | 16.68                       | 0.07                        |                              |
| ESO 244−IG030            | 21.50                       | 0.17                        |                              |
| ESO 374-G044             | 14.45                       | 0.06                        |                              |
| ESO 439-G009             | 34.23                       | 0.26                        |                              |
| ESO 565-G019             | 23.37                       | 0.07                        |                              |
| II Zw 083                | 15.20                       | 0.11                        |                              |
| MCG−07-03-007            | 68.01                       | 0.14                        |                              |
| MCG+02-21-013            | 29.70                       | 0.10                        |                              |
| MCG+06-16-028            | 85.26                       | 0.47                        |                              |
| MCG+06-49-019            | 10.88                       | 0.38                        |                              |
| MCG+11-11-032            | 12.23                       | 0.03                        |                              |
| NGC 1106                 | 98.05                       | 0.77                        |                              |
| NGC 1125                 | 62.47                       | 0.28                        |                              |
| SBS 0915+556             | 23.30                       | 0.12                        |                              |
| UGC 01479                | 22.92                       | 0.07                        |                              |
| VII Zw 073               | 37.26                       | 0.13                        |                              |

Notes. Column 1: galaxy name. Column 2: the soft/medium (0.5–2 keV flux/2–10 keV flux). Column 3: the hard/medium (14–195 keV flux/2–10 keV flux). Fluxes for the soft (0.5–2 keV) and medium (2–10 keV) X-ray were taken from the seven-year Swift/XRT point-source catalog (D’Elia et al. 2013).

6. THE FAR-INFRARED COLORS OF THE BAT SAMPLE

Typically, FIR emission from galaxies peaks between ~100–160 μm. Thus, the $F_{70}/F_{160}$ versus $F_{100}/F_{160}$ can be used to trace the peak of the galaxy SED (e.g., Remy-Ruyer et al. 2013). However, in the absence of 100 μm observations, the $F_{70}/F_{160}$ ratio may still provide useful information regarding the peak of the FIR SED and the dust properties. Figure 6 shows the distribution of this ratios for between Seyfert 1 and Seyfert 2 galaxies in the BAT sample. The K-S test null probability is 53.5%, which indicates that the two galaxy populations have similar FIR colors, in agreement with the statistical similarities between the monochromatic luminosities at 70 and 160 μm (see Table 2).

Figure 7 shows the $F_{70}/F_{160}$ ratio versus the intrinsic X-ray luminosity of the AGN. We find a trend of increasing $F_{70}/F_{160}$ with BAT luminosity. Our analysis reveals a weak but statistically significant correlation with a generalized Spearman rank-order correlation coefficient and probability (with censored data), $\rho = 0.174$, $P_\rho = 4.3 \times 10^{-2}$ for Seyfert 1 galaxies and a similar correlation for Seyfert 2 galaxies with $\rho = 0.236$, $P_\rho = 3.9 \times 10^{-3}$. This result implies that there may be a dust grain distribution with a warm (nuclear) dust component, heated by the very energetic environment in the proximity of the AGN (with a strong contribution to the 70 μm continuum), and a colder dust component farther out in the outer regions of the AGN torus and/or the host galaxy (the primary contributor to the 160 μm continuum). In order to investigate the AGN contribution to the FIR colors, we compared our observed colors with predictions from three different torus models: the smooth, continuous torus from Fritz et al. (2006),11 and the clumpy torus models from Hönig & Kishimoto (2010)12 and Stalevski et al. (2012); “smooth,” “two-phase,” and “clumps only”).13 We find that there is no region in parameter space (input parameters for the different models) that can reproduce $F_{70}/F_{160}$ ratios less than unity. In addition, the vast majority of the BAT AGNs (74% of

11 http://users.ugent.be/~jfritz/jfhp/TORUS.html
12 http://www.sungrazer.org/CAT3D.html
13 https://sites.google.com/site/skirtorus/home
all the sources with detections in both FIR bands have \( F_{70}/F_{160} \) ratios less than unity.

All these models, on average, overpredict the \( F_{70}/F_{160} \) ratios by at least a factor of two to three (Fritz et al. 2006; Hönig & Kishimoto 2010) and as much as a factor of \( \sim 20 \) (Fritz et al. 2006; Stalevski et al. 2012; see Figure 8). Continuous models with a torus full-opening angle of \( \Theta = 60^\circ \) (covering factor; Fritz et al. 2006) can reproduce the most extreme sources in our sample at the high end of the observed FIR color distribution with \( F_{70}/F_{160} > \sim 2.5 \), namely Mrk 841, MCG–05-23-016, and ESO 103-035. Note that the observed BAT FIR SED is the combined effect from the AGN (nonthermal) and a stellar (thermal) radiation field. Therefore, it is not unexpected for the torus models to underpredict the observed FIR part of the SED without an extra stellar component (see discussion in Section 4). However, the weak but probably statistically significant correlation between the intrinsic power of the AGN and the FIR emission in Seyfert 1 galaxies suggests that there is a subset of the BAT AGNs in which the FIR emission is dominated by the non-stellar contribution (AGNs). This population includes AGN-dominated sources with weak or no signatures of SF at other wavelengths (e.g., Hönig et al. 2014). Therefore, the previous results suggest that current torus models may underpredict the intrinsic AGN emission at 160 \( \mu m \), relative to the 70 \( \mu m \), by having a steeper FIR SED.

7. COMPARISON WITH NORMAL GALAXIES

The \( F_{70}/F_{160} \) ratio provides useful information when comparing with other samples of galaxies. Figure 9 shows the \( F_{70}/F_{160} \) distribution between the BAT AGNs, the Key Insights on Nearby Galaxies: a Far-Infrared Survey with Herschel (KINGFISH) sample of nearby galaxies (Dale et al. 2012) and the dwarf galaxy survey (DGS; Rémy-Ruyer et al. 2013). The KINGFISH sample is an imaging and spectroscopic survey of 61 nearby \( (d < 30 \text{ Mpc}) \) galaxies drawn mainly from the Spitzer Infrared Nearby Galaxies Survey (see Kennicutt et al. 2003, for details). The KINGFISH sample covers a wide range of galaxy properties and local interstellar medium environments found in the nearby universe. The Herschel DGS is a photometric and spectroscopic sample of dwarf galaxies in the local universe chosen to cover a wide range of physical conditions, including a wide range of metallicities (Madden et al. 2013).
For the KINGFISH sample, we selected only the “normal” galaxies, e.g., the non-AGN galaxies as classified by their optical spectra (Moustakas et al. 2010). Conversely, for the comparison, we included all BAT AGNs. From Figure 9, it is clear that the BAT AGNs and the KINGFISH normal galaxies span a similar range of values with a K-S null probability of 31%, in other words, the BAT AGN FIR colors are statistically indistinguishable from those in normal galaxies. On the other hand, the FIR colors for the BAT AGNs are statistically different than those in the DGS sample with a K-S test null probability of 0.0%. The majority of the BAT AGNs and KINGFISH galaxies have $F_{70}/F_{160}$ corresponding to colder dust, whereas most of the dwarf galaxies peak at shorter wavelengths, $F_{70}/F_{160} > 1$, suggesting warmer dust due to the harder radiation field illuminating the environment surrounding young stars. Note that $F_{70}/F_{160}$ is also sensitive to metallicity in that the lower metallicity galaxies have warmer dust than is found in their metal-rich counterparts (Rémy-Ruyer et al. 2013).

8. CONCLUSIONS

We present FIR flux densities and maps for 313 hard X-ray selected AGNs from the low-redshift ($z < 0.05$) 58 month Swift-BAT survey in two PACS bands at 70 and 160 $\mu$m. Of the 313 sources, 94% and 83% are detected in the FIR by PACS at 70 and 160 $\mu$m, respectively. From our analysis, we find the following.

1. Using the K-S test the FIR luminosity distributions at 70 and 160 $\mu$m for the Seyfert 1 and Seyfert 2 galaxies are indistinguishable from one another. This result suggests that the FIR emission is isotropic, i.e., independent of orientation. We propose two different interpretations for the isotropic nature of the FIR emission: (1) SF, which is isotropic, and/or (2) some AGN torus models predict isotropy at FIR wave-lengths. Regarding the former scenario, if SF dominates the FIR emission, then it has to happen in a very compact nuclear region, suggesting a connection between the AGN and the nuclear cold molecular gas (see Mushotzky et al. 2014).

In the latter scenario, torus models predict a similar shape for the FIR part of the SED for both types of Seyferts (e.g., Kennicutt et al. 2003; Stalevski et al. 2012). However, some torus models predict an angle dependence on the FIR luminosity with Seyfert 1 galaxies having higher luminosities than Seyfert 2 galaxies. For these models, SF would also be needed (e.g., Fritz et al. 2006).

Using the two-sample test for censored data, the 160 $\mu$m luminosity distributions between Seyfert galaxies may be distinguishable at a weak but possibly statistically significant level. By including the non-detections, the Seyfert 2 galaxies are found to have a very slightly higher mean luminosity than the Seyfert 1 galaxies. If the FIR emission is a good probe of SF, then this result suggests that Seyfert 2 galaxies have a slightly higher SFR than Seyfert 1 galaxies, which could imply a time-dependent evolutionary scenario, where the AGNs are more obscured when the SFRs are at their higher values (see discussion in Section 5).

2. A K-S test on the present data shows that the 14–195 keV luminosity distributions are statistically different between Seyfert 1 (unabsorbed) and Seyfert 2 (absorbed) galaxies. Our analysis suggests that the statistical differences between AGN types are fundamental, with absorbed AGNs being intrinsically less luminous than unabsorbed AGNs. This scenario is supported by the difference in the luminosity function between the two types of Seyferts for the BAT sample, with absorbed AGNs having, on average, lower luminosities than unabsorbed AGNs (e.g., Cowie et al. 2003; Steffen et al. 2003; Ueda et al. 2003; Barger et al. 2005; Meléndez et al. 2014).
3. Using a non-parametric test for partial correlation with censored data, we find a statistically significant correlation between the AGN intrinsic power (BAT luminosity) and the FIR emission at 70 and 160 μm in Seyfert 1 galaxies. We find a better correlation between the BAT and PACS luminosities at 70 μm than at 160 μm. The correlation is also stronger for the most X-ray luminous objects. The observed correlations suggest two possible scenarios: (1) if we assume that the FIR luminosity is a good tracer of SF, then there is a connection between SF and the AGN at sub-kiloparsec scales, and/or (2) dust heated by the AGN has a statistically significant contribution to the FIR emission. Regarding the former scenario, and given the fact that the majority of the BAT sources have their FIR fluxes dominated by a point source located at the nucleus, one needs to consider that SF has to happen in a very compact, nuclear region (Mushotzky et al. 2014). In the latter, SFR indicators that rely on FIR emission, either through the individual infrared bands (Calzetti et al. 2010) or the total FIR emission (8–1000 μm; Kennicutt 1998), need to consider the AGN contribution in their predictions. However, all torus models studied in the present work underpredict the amount of cold dust (from the outer regions of the torus) needed to match the observations; thus, a stellar component may still be required.

4. A non-parametric test for partial correlation with censored data reveals that there is no statistically significant correlation between the 14–195 keV and FIR luminosities in Seyfert 2 galaxies when the influence of the distance is excluded. The results presented in this paper support a scenario in which Seyfert 2 galaxies are intrinsically less luminous than Seyfert 1 galaxies, suggesting that the FIR–X-ray connection is luminosity dependent. In other words, in low-luminosity AGNs (Seyfert 2 galaxies), the FIR may be dominated by dust heated primarily by the stellar activity in the host galaxy (e.g., Rosario et al. 2012), while at higher luminosities (Seyfert 1 galaxies) the contribution from dust heated by the AGN overwhelms the SF contribution, thereby creating the correlation between the intrinsic power of the AGN and the FIR.

5. Using a K-S test, the distributions of the $F_{70}/F_{160}$ ratios for the Seyfert 1 and 2 galaxies are indistinguishable from one another. They are also indistinguishable from those of normal star-forming galaxies. In general, we find that the vast majority of the BAT AGNs (74% of all sources with a detection in both FIR bands) have $F_{70}/F_{160}$ ratios less than unity. Assuming that the FIR is dominated by SF, these results are in agreement with the isotropic nature of the SF emission. However, one must consider that the weak but statistically significant correlation between the intrinsic power of the AGN and the FIR emission suggests that there must be an underlying population of BAT AGNs in which the FIR emission is dominated by the non-stellar contribution (the AGN torus). This population includes AGN-dominated sources with weak or no signatures of SF at other wavelengths, e.g., Mrk 3 (e.g., Sales et al. 2014). Nonetheless, when comparing with predictions from different torus models, we find that there is no region in parameter space (input parameters for the different models) that can reproduce $F_{70}/F_{160}$ ratios less than unity. All these models, on average, overpredict the $F_{70}/F_{160}$ ratios by at least a factor of two to three (Fritz et al. 2006; Höning & Kishimoto 2010) and by as much as a factor of ~20 (Fritz et al. 2006; Stalevski et al. 2012). Continuous models with a torus full-opening angle of $θ = 60°$ (covering factor, Fritz et al. 2006) can only reproduce the most extreme sources at the high end of the observed FIR colors distribution with $F_{70}/F_{160} > ~2.5$, namely Mrk 841, MCG−05-23-016 and ESO 103−035. Thus, current torus models may underpredict the AGN emission at 160 μm (colder dust) relative to 70 μm with a steeper FIR SED.

6. Using a Spearman rank-order analysis, the 14–195 keV luminosities for the Seyfert 1 and 2 galaxies are weakly statistically correlated with the $F_{70}/F_{160}$ ratios. This result suggests two possible interpretations: (1) a time-evolutionary sequence, as discussed in Section 5, where SFRs are higher in the more X-ray luminous sources, producing a trend of increasing AGN luminosity and FIR temperature; and/or (2) the existence of a dust grain distribution with a warm (nuclear) dust component, heated by the very energetic environment in the proximity of the AGN (with a strong contribution to the 70 μm continuum), and a colder dust component farther out in the outer regions of the AGN torus and/or the host galaxy (the primary contribution to the 160 μm continuum).

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Figure 10. PACS images for different types of morphologies for the BAT sample. The images were randomly selected to show an example of a point-like source (Mrk 766), a slightly extended source (Mrk 618), a fully resolved source with complex structures (NGC 5899), a dual system (IC4518 pair) and a source contaminated from Galactic cirrus (2MASXJ20183871+4041003). The images are displayed with an inverse hyperbolic sine scaling (Lupton et al. 1999). All the Scanamorphos images are presented in their native resolution and pixel size, 1.4 and 2.′′85 pixel$^{-1}$ at 70 and 160 μm, respectively. The beam size at each wavelength is indicated by a black filled circle at the bottom left of each panel. The angular size of each panel is 2.′2 × 2.′2. North is up, and east is left for all the images. (A color version and a complete figure set (105 images) of this figure is available in the online journal.)

APPENDIX

Herschel PACS IMAGES

Figure 10 shows the PACS Scanamorphos images for the BAT sample. The images are displayed with an inverse hyperbolic sine scaling (Lupton et al. 1999). All the images are presented in their native resolution and pixel size, 1.4 and 2.′85 pixel$^{-1}$ at 70 and 160 μm, respectively. The beam size at each wavelength is indicated by a black filled circle at the bottom left of each panel. The angular size of each panel is 2.′2 × 2.′2. North is up and east is left for all the images. Figures 10.1–10.105 are available in the online journal.

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