Infrared colours and spectral energy distributions of hard X-ray selected obscured and Compton-thick active galactic nuclei

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ABSTRACT
We investigate the infrared colours and spectral energy distributions (SEDs) of 338 X-ray selected active galactic nuclei (AGNs) from the Swift/Burst Alert Telescope (BAT) 105-month survey catalogue, which have been detected using AKARI, in order to find new selection criteria for Compton-thick AGNs. By combining data from the Galaxy Evolution Explorer (GALEX), the Sloan Digital Sky Survey (SDSS) Data Release 14 (DR14), the Two-Micron All Sky Survey (2MASS), the Wide-field Infrared Survey Explorer (WISE), AKARI and Herschel for the first time, we perform ultraviolet (UV) to far-infrared (FIR) SEDs, fitting 158 Swift/BAT AGNs using CIGALE and constraining the AGN model parameters of obscured and Compton-thick AGNs. The comparison of average SEDs shows that while the mid-infrared (MIR) SEDs are similar for the three AGN populations, the optical/UV and FIR regions have differences. We measure the dust luminosity, the pure AGN luminosity and the total infrared luminosity. We examine the relationships between the measured infrared luminosities and the hard X-ray luminosity in the 14–195 keV band. We show that the average covering factor of Compton-thick AGNs is higher compared with the obscured and unobscured AGNs. We present new infrared selection criteria for Compton-thick AGNs based on MIR and FIR colours ([9–22 μm] > 3.0 and [22–90 μm] < 2.7) from WISE and AKARI. We find two known Compton-thick AGNs that are not included in the Swift/BAT sample. We conclude that MIR colours covering 9.7-μm silicate absorption and the MIR continuum could be promising new tools to identify Compton-thick AGNs.

Key words: galaxies: active – quasars: general – infrared: galaxies.

1 INTRODUCTION
Active galactic nuclei (AGNs) are mass-accreting supermassive black holes residing at the centres of nearly all massive galaxies. Recent studies have shown that AGNs that are obscured by gas and dust might make up a non-negligible fraction of the AGN population (e.g. Hickox et al. 2007; Treister et al. 2010; Assef et al. 2013, 2015; Mateos et al. 2017). Obscured AGNs are important for understanding the full growing black hole population and the influence of black holes on the host galaxy (e.g. Hopkins et al. 2008). These sources are important for understanding the accretion history of supermassive black holes via the cosmic X-ray background radiation (e.g. Ueda et al. 2014). It is still unknown how many obscured AGNs there are in the Universe. The number of low-luminosity or obscured AGNs is critical for our understanding of galaxies (e.g. Hickox & Alexander 2018). Therefore, it is important to find new techniques to identify obscured AGNs.

The structure of an AGN is mainly composed of a central supermassive black hole, an accretion disc (Shakura & Sunyaev 1973) and a corona (e.g. Czerny & Elvis 1987; Zheng et al. 1997; Telfer et al. 2002; Mehdipour et al. 2011, 2015; Done et al. 2012; Jin et al. 2012). The accretion disc and the corona in its immediate vicinity produce the primary optical–ultraviolet (UV) and X-ray continuum emission (e.g. Sanders et al. 1989; Marconi et al. 2004; Suganuma et al. 2006). This central engine is embedded within the infrared (IR) emitting dusty structure, the so-called torus (e.g. Lawrence 1991; Antonucci 1993; Simpson 2005; Höfner & Beckert 2007; García-Burillo et al. 2016). AGNs that can be identified by their blue continuum and broad and/or narrow emission lines in the optical are often referred to as Type 1 (e.g. Antonucci 1993). Once the AGN signatures cannot be detected in the optical spectrum, then they are referred to as ‘Type 2’ or obscured AGNs (e.g. Antonucci 1993). Obscured AGNs can show narrow line emission or no emission at all, depending on the degree of obscuration, which is dictated by the geometrical structure of the dusty torus or the strength of the host galaxy emission (e.g. Hickox & Alexander 2018). As they are mostly absorbed in the optical and soft X-
AGNs can be classified as (i) unobscured (log $N_H^{optical/UV/X-ray}$ radiation from the central engine. Therefore, it is common practice to use IR emission to separate AGNs from starburst/nuclear galaxies (e.g. Stern et al. 2012; Mateos et al. 2013; Lansbury et al. 2014; Huang et al. 2017; Ichikawa et al. 2019). The MIR dust emission of an AGN is in the form of power law with different slopes for Type 1 and Type 2 AGNs (Alonso-Herrero et al. 2006; Donley et al. 2007, 2008). IR power-law selection has been used to select AGNs with $WISE$ colours (3.4–4.6 $\mu$m versus 4.6–12 $\mu$m) for AGNs at low redshift ($z \leq 0.5$; Mateos et al. 2012, 2013). $Spitzer$ IRAC flux ratios (18–4.5 $\mu$m versus 5.8–3.6 $\mu$m) have been used as a reliable method to select AGNs at higher redshift ($z \sim 1, 2$; Lacy et al. 2004; Stern et al. 2005; Donley et al. 2008, 2012). Many AGN selection criteria have been shown and applied in other studies (Stern et al. 2012; Assef et al. 2013; Jarrett et al. 2013). Millions of AGNs have been selected from AllWISE using the criteria of Mateos et al. (2012). The completeness of IR colour AGN selection is highly complete for luminous Type 1 AGNs and moderately complete for Type 2 AGN (Mateos et al. 2012; Lansbury et al. 2017). It has been shown by Mateos et al. (2013) and Rovilos et al. (2014) that obscured AGNs and CT AGN candidates meet the MIR selection criteria of Stern et al. (2012), Mateos et al. (2013) and Lansbury et al. (2014). These colours mainly identify obscured AGNs, although this colour selection has been combined with $N_H$ classification in only a few studies (Mateos et al. 2013; Rovilos et al. 2014). In this work, we focus on selecting obscured AGNs with new IR colour criteria.

Because MIR and X-ray radiation originate from the AGN, the two types of radiation are expected to be correlated. The relation between the MIR and X-ray emission has been an important tool to gain information about AGN physics (e.g. Krabbe, Börker & Maiolino 2001; Lutz et al. 2004; Ramos Almeida et al. 2015; Horst et al. 2008; Fiore et al. 2009; Gandhi et al. 2009, 2017; Levenson et al. 2009; Asmus et al. 2011, 2015; Ichikawa et al. 2012, 2017, 2019; Mason et al. 2012; Matsuta et al. 2012; Sazonov et al. 2012; Mateos et al. 2015; García-Bernete et al. 2016; Chen et al. 2017). The relation between MIR and X-ray was initially established for the 2–10 keV X-ray band, because of the technical limitations of the former X-ray telescopes. Once hard X-ray telescopes such as $Swift$ and $INTEGRAL$ became available, the MIR and X-ray relation extended to the 14–195 keV ultra-hard X-ray regime (e.g. Mullaney et al. 2011; Matsuta et al. 2012; Ichikawa et al. 2012, 2017; Sazonov et al. 2012; Asmus et al. 2015). Ichikawa et al. (2012) investigated the MIR and far-infrared (FIR) properties of AGNs in the $Swift$/Burst Alert Telescope (BAT) nine-month catalogue (Tueler et al. 2008) and found a good correlation between the MIR and X-ray luminosities. Ichikawa et al. (2017, 2019) studied the IR properties of AGNs in the 70-month Swift/BAT sample in great detail. Ichikawa et al. (2019) have analysed IR SEDs and estimated the AGN contribution to the 12–$\mu$m, MIR and total IR luminosities. They show a significant luminosity correlation between the MIR and 14–150 keV bands. Although the IR colours and properties of the hard X-ray selected AGNs in the previous $Swift$/BAT samples have been extensively studied, these studies (Ichikawa et al. 2012, 2017, 2019) have not investigated a possible CT AGN selection based on the MIR and FIR colours, which is the main goal of this study.

In this work, we combine the IR colours with the measured $N_H$ of the X-ray selected AGNs and we present new CT AGN selection criteria that allowed us to select CT AGN candidates from the AKARI all-sky survey catalogue. We also aim to constrain the AGN model parameters of obscured and CT AGNs, within the limitations imposed by the model assumptions in CIGALE, the available broad-band photometry and the fitting procedure. The structure of this paper is as follows. In Sections 2 and 3, we present the sample selection and data, respectively. We describe the SED analysis of obscured and CT AGNs in our sample in Section 4. We compare the average SEDs of unobscured, obscured and CT AGNs in Section 5.1. In Section 5.2, we present the correlations between the hard X-ray luminosity and the pure AGN luminosity in the IR band and dust luminosity. We show the $N_H$ dependence of IR colours in Section 5.3. In Section 5.4, we present new IR colour selection criteria for CT AGNs. We summarize our conclusions in Section 6. We adopt a cosmology with $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.7$ and $\Omega_{\Lambda} = 0.3$ and we use the base 10 logarithm.

2 SAMPLE SELECTION

The $Swift$ observatory (Gehrels et al. 2004) scans the whole sky at 14–195 keV with the wide-field BAT (Barthelmy et al. 2005). With its continuous all-sky survey, $Swift$/BAT identified several hard-X-ray selected AGNs in the local Universe (e.g. Tuller et al. 2008; Baumgartner et al. 2013; Ricci et al. 2017a; Oh et al. 2018). The most recent data release of $Swift$/BAT (105-month; Oh et al. 2018) includes 947 hard X-ray selected non-beamed AGNs. To investigate the MIR and FIR colours of the hard X-ray selected obscured and CT AGNs, we select the 947 non-beamed AGNs from $Swift$/BAT 105-month survey catalogue (Oh et al. 2018). We cross-match these hard X-ray selected AGNs based on their optical counterpart coordinates within the AKARI/FIS all-sky survey bright source catalogue version 2.1 (Yamamura et al. 2018) within a radius of 20 arcsec. We find the AKARI 90-$\mu$m detection for 378 AGNs, which is near the peak of the FIR dust emission near 100 $\mu$m. In particular, the 140- and 160-$\mu$m bands are crucial to constrain the dust emission peak and to measure better IR luminosity. Among these AGNs, only 332 have been detected in three AKARI bands at 90, 140 and 160 $\mu$m. However, for our analysis when we need to use high-quality AKARI data with $\text{QUAL} = 3$, only 51 of these 332 AGNs have high-quality data in three AKARI bands. Therefore, we use additional FIR data when available, as described in Section 3.

The $Swift$/BAT Spectroscopic Survey (BASS; Koss et al. 2017) data release 1 provides multiband data of 836 local AGNs from the $Swift$/BAT 70-month catalogue (Baumgartner et al. 2013). The broad-band X-ray (between 0.3–150 keV) spectral analysis of the BASS AGN sample is completed by Ricci et al. (2017a). They combine $Swift$/XRT, XMM–Newton, ASCA, Chandra and Suzaku observations for the soft X-ray (0.3–10 keV) spectral analysis. They fit the AGN continuum with a simple power-law model with Galactic absorption and use different models (see their table 2), when necessary, to improve the fit. In order to measure the column density along the line of sight, Ricci et al. (2017a) take into account both photoelectric and Compton scattering with $ZPHABS$ and $CABS$ models, respectively. BASS includes 311 of the AGNs in our AKARI

http://www.ir.isas.jaxa.jp/AKARI/Archive/Catalogues/FISBSCv2/.
AN sample, so for these sources we adopt the $N_H$ values from BASS; except for ESO244-IG030 and ESO317-G041 for which we adopted the revised $N_H$ measurements from Marchesi et al. (2019). For 19 AGNs in our AKARI AGN sample, we take the published $N_H$ values from the literature (Maiolino et al. 1998; Fukazawa et al. 2001; Pappa et al. 2002; Zhang et al. 2006; Shu et al. 2007; Malizia et al. 2007, 2008, 2011, 2012; Pian et al. 2010; de Rosa et al. 2012; Matt et al. 2012; Baloković et al. 2014; Gandhi et al. 2015, 2017; Koss et al. 2016; Giustini et al. 2017; She, Ho & Feng 2017; Iwasawa et al. 2018; Marchesi et al. 2019), based on the soft X-ray spectral analysis. We take X-ray data of eight sources from public archives and perform the X-ray data analysis as described in Appendix A. In total, 338 AGNs in our sample have $N_H$ measurements.

We focus our study on the hard X-ray selected AKARI/BAT AGN sample that includes 338 sources with measured $N_H$ values. A flow chart describing the selection criteria of our final AKARI/BAT AGN sample is displayed in Fig. 1. We list several source properties in Table 1. Based on the listed $N_H$ values in Table 1, our sample includes 133 unobscured, 153 obscured and 52 CT AGNs. The redshift distribution of our sample of 338 AGNs is shown by the plus signs of the unobscured, obscured and CT AGNs. The median redshift of our sample is 0.023. The median redshifts (shown by the plus signs) of the unobscured, obscured and CT AGNs are 0.025, 0.023 and 0.014, respectively. For visual inspection, the distribution is shown up to $z = 0.60$; there are only two sources beyond this limit at $z = 0.51$ and $z = 0.60$. For 19 AGNs in our AKARI/BAT AGN sample, we take the published $N_H$ values from the literature (Maiolino et al. 1998; Fukazawa et al. 2001; Pappa et al. 2002; Zhang et al. 2006; Shu et al. 2007; Malizia et al. 2007, 2008, 2011, 2012; Pian et al. 2010; de Rosa et al. 2012; Matt et al. 2012; Baloković et al. 2014; Gandhi et al. 2015, 2017; Koss et al. 2016; Giustini et al. 2017; She, Ho & Feng 2017; Iwasawa et al. 2018; Marchesi et al. 2019), based on the soft X-ray spectral analysis. We take X-ray data of eight sources from public archives and perform the X-ray data analysis as described in Appendix A. In total, 338 AGNs in our sample have $N_H$ measurements.

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3 DATA

To gain insight into the nature of our hard X-ray selected AKARI/BAT AGN sample, we perform a comprehensive sky survey at near-UV (NUV) and far-UV (FUV) bands at $\lambda_{\text{eff}} = 2267 \text{Å}$ and $\lambda_{\text{eff}} = 1516 \text{Å}$, respectively. The revised catalogue of GALEX UV sources (Bianchi, Shiao & Thilker 2017) lists revised photometric measurements and eliminates any duplicate entries. We cross-match the optical counterpart positions of AGN in our sample with the revised catalogue of GALEX UV sources within a separation threshold of 5 arcsec and colours (Sections 5.3 and Section 5.4), we collect archival photometry from UV to FIR.

Figure 1. Flow chart with all applied selection criteria for our AKARI/BAT AGN sample.

Figure 2. Redshift distribution of the sample of 338 hard X-ray selected AKARI AGNs. The median redshift of our sample is 0.023. The median redshifts (shown by the plus signs) of the unobscured, obscured and CT AGNs are 0.025, 0.023 and 0.014, respectively. For visual inspection, the distribution is shown up to $z = 0.60$; there are only two sources beyond this limit at $z = 0.51$ and $z = 0.60$.

We find 205 UV counterparts. Because Bianchi et al. (2017) only include sources from All-Sky Imaging Survey (AIS) observations with both FUV and NUV detectors exposed, their catalogue does not include sources exposed only with a single FUV or NUV detector. To include such sources in our UV counterpart sample, the remaining 173 sources were cross-matched (using a search radius of 5 arcsec) with the GALEX source catalogue (Martin et al. 2005) Data Release 6 (DR6) from the MAST portal.2 After dropping matches with measurements with dichroic reflections (NUV = 0.0; V = 0.0) and keeping only the single photometric measurement with the longest duration for multiple observations of the same source, we find 56 more GALEX counterparts. In total, we find 261 GALEX counterparts. We correct the UV photometric measurements for Galactic foreground extinction using the listed $E(B-V)$ values (based on the extinction maps of Schlegel, Finkbeiner & Davis 1998) in the GALEX catalogues.

For the optical counterparts, we extract the Galactic extinction corrected $g$, $r$, $i$- and $z$-band magnitudes from the Sloan Digital Sky Survey (SDSS; York et al. 2000) Data Release 14 (Abolfathi et al. 2018) PhotoObjAll catalogue.3 We find we only 146 sources in the SDSS DR14 footprint. However, 67 galaxies whose photometric flags include CLEAN = 0 are not reliable and are therefore not included in our analysis. We visually inspected images of the remaining galaxies and discarded any suspicious photometry of: (i) very large (nearby) galaxies whose automated deblending is unreliable; (ii) too bright galaxies close to the $r$-band saturation magnitude limit at $r = 14.5$ (Strauss et al. 2002); (iii) galaxies contaminated by superposed stars. We use the near-infrared (NIR) Two-Micron All-Sky Survey (2MASS; Skrutskie et al. 2006) $J$, $H$- and $K_s$-band magnitudes from the 2MASS Extended Source Catalogue (XSC; Jarrett et al. 2000) and the 2MASS Point Source Catalogue (PSC; Cutri et al. 2003). For the 332 sources in the

2http://mast.stsci.edu.

3https://skyserver.sdss.org/dr14/.
In order to include AKARI and WISE MIR photometry at 3.4, 4.6, 9, 12, 18 and 22 μm, we cross-match AKARI/FIS coordinates of our hard X-ray selected AKARI AGN sample with the AKARI/IRC all-sky survey point source catalogue version 1 and the AllWISE source catalogue⁴ (Cutri et al. 2013) using a search radius of 20 arcsec.

The Herschel Space Observatory (Pilbratt et al. 2010) mapped about a small fraction of the sky in FIR and submillimetre bands centred at 70, 100, 160, 250, 350 and 500 μm with the Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) and the Spectral and Photometric Receiver (SPIRE; Griffin et al. 2010) instruments. Meléndez et al. (2014) and Shimizu et al. (2016) present Herschel PACS and SPIRE photometric measurements for 313 AGN from the 58-month Swift/BAT catalogue (Baumgartner et al. 2013), respectively. By matching the optical counterpart names with the Herschel/BAT AGN sample of Meléndez et al. (2014) and Shimizu et al. (2016), we find Herschel PACS photometry for 155 AGNs and SPIRE photometry for 187 AGNs in our sample.

When photometric fluxes from AKARI, WISE and Herschel are combined for the SED analysis (Section 4), the spatial resolution differences among each band may cause discrepancies in the nuclear and host galaxy IR emission measurements (e.g. Clements et al. 2019). The beam size for the AKARI/FIS is (beam FWHM is ∼30–50 arcsec; Doi et al. 2015) larger than that of Herschel/PACS (beam FWHM is ∼6–11 arcsec; Poglitsch et al. 2010). As shown by Clements et al. (2019), when AKARI FIR fluxes are compared with IRAS fluxes, the ∼10 times better angular resolution of AKARI causes missing FIR emission for extended sources. Clements et al. (2019) derive beam corrections that should be applied to fluxes at 65 and 90 μm from the AKARI/FIS all-sky survey bright source catalogue, version 2. These corrections depend on the extendedness parameter measured as the J-band magnitude difference between the 2MASS PSC and 2MASS XSC. We apply this beam correction (see equation 2 of Clements et al. 2019) to the 65- and 90-μm AKARI/FIS fluxes in our sample. The applied beam correction results in an average of 4 and 20 per cent additional flux at 65 and 90 μm, respectively. Clements et al. (2019) also find that no beam corrections are needed for the moderately extended sources at 140- and 160-μm bands.

As reported by Mushotzky et al. (2014), the bulk of BAT sources are point-like with a compact host galaxy with Herschel spatial resolution. In the comparison of aperture correction applied (as described above), AKARI/FIS 65-μm ($S^F_{65}$) and Herschel/PACS 70-μm ($S^P_{70}$) fluxes for 61 sources in our sample show good agreement (Fig. 3), and the median difference between the two fluxes is 18 per cent with respect to $S^F_{65}$. A typical difference of 18 per cent between the two fluxes is added in quadrature to the flux uncertainties of the $S^F_{65}$ fluxes. As both $S^P_{70}$ and $S^F_{65}$ fluxes agree, we use both as independent photometric measurements in our SED analysis. There are 30 sources in our sample that have

Table 1. Hard X-ray selected AKARI AGN sample. The full table is available in the electronic version of the article. Column 1 gives the Swift/BAT 105-month survey catalogue. Column 5 is the redshift reference for the adopted log ($N \times F$) measurement. Column 6 is the base 10 logarithm of the intrinsic hydrogen column density in units of cm⁻². Column 7 is the X-ray spectral analysis 2. Column 8 is the base 10 logarithm of the pure AGN luminosity in the IR band measured from the SED fitting by CIGALE. Column 9 is the fractional AGN emission contribution to the total IR luminosity. Column 10 is the 14–195 keV luminosity adopted from the Swift/BAT catalogue. Column 11 is the WISE m(4) magnitude. Columns 12–15 give the 9-, 18-, 65- and 90-μm AKARI/FIS all-sky survey bright source catalogue version 2.

| Source name  | RA (2000.00) | Dec (2000.00) | Swift ID | m(4) | log(NXF) | log(n_H) | log(L_IR) | AGN fraction | 14–195 F_L | m(4) | 9μm | 18μm | 65μm | 90μm |
|--------------|-------------|-------------|----------|------|----------|----------|----------|-------------|------------|------|-----|-----|-----|-----|-----|
| J0002.5+0323 | 00 02 05.55 | +03 23 44  | 00025+0323 | 0.61 | -7.51 | 20.30 | 20.70 | 0.0255 | 20.0 | 0 | |
| J0002.5+0323 | 00 02 05.55 | +03 23 44  | 00025+0323 | 0.61 | -7.51 | 20.30 | 20.70 | 0.0255 | 20.0 | 0 | |
| J0002.5+0323 | 00 02 05.55 | +03 23 44  | 00025+0323 | 0.61 | -7.51 | 20.30 | 20.70 | 0.0255 | 20.0 | 0 | |
| J0002.5+0323 | 00 02 05.55 | +03 23 44  | 00025+0323 | 0.61 | -7.51 | 20.30 | 20.70 | 0.0255 | 20.0 | 0 | |
| J0002.5+0323 | 00 02 05.55 | +03 23 44  | 00025+0323 | 0.61 | -7.51 | 20.30 | 20.70 | 0.0255 | 20.0 | 0 | |

⁴http://www.ir.isas.jaxa.jp/AKARI/Observation/PSC/Public/RN/AKARI-IRC_PSC_V1_RN.pdf.

⁵http://wise2.ipac.caltech.edu/docs/release/allwise.
both high-quality AKARI and PACS fluxes at the 160-μm band. As shown in Fig. 3, the median percentage difference between AKARI and PACS 160-μm fluxes is 32 per cent with respect to the AKARI fluxes. As reported by Mushotzky et al. (2014), the FIR radiation of most BAT sources is point-like at the spatial resolution of Herschel. Additionally, Meléndez et al. (2014) and Shimizu et al. (2016) present PACS measurements for an appropriate aperture for each source, so we prefer to use PACS 160 μm fluxes for these 30 AGNs. If Herschel/PACS 160-μm band photometry is not available, then we use AKARI/FIS 160-μm flux measurements for the rest of our sample. Because both AKARI/FIS 140- and 160-μm bands are similar, to be conservative we add a 52 per cent flux uncertainty in quadrature to the photometric uncertainties of the 140- and 160-μm fluxes.

The 9-arcsec beam size of AKARI/IRC is (Ishihara et al. 2010) similar to the beam size of WISE, which is between 6 and 12 arcsec (Wright et al. 2010). We only use WISE measurements with zero cc_flags values (cc_flags = '0000') to avoid contaminated measurements (i.e., by diffraction spikes, bright sources). For extended WISE sources (with ext_flg > 0) we use elliptical aperture magnitudes ('wngmag', n is the band number). For AKARI/IRC photometry, we only include measurements with high quality: FQUAL(9 μm) = 3, FQUAL(18 μm) = 3, AKARI/IRC 9- and 18-μm and WISE 12- and 22-μm bands have close but slightly different central wavelengths. In our sample, 112 sources have both AKARI/IRC 9-μm and WISE 12-μm fluxes. Additionally, 139 sources have both AKARI/IRC 18-μm and WISE 22-μm measurements. For these sources, the comparison of AKARI/IRC and WISE fluxes agree (the mean percentage difference is ~20 per cent) without any systematic differences. Therefore, we do not apply any aperture correction at these bands and we use each photometric measurement separately in our SED analysis. However, to be conservative, we add the typical flux difference of ~20 per cent in quadrature to the photometric uncertainties of the 9-, 12-, 18- and 22-μm fluxes.

**Figure 3.** Comparison between the PACS and AKARI fluxes at 70–65 μm (a) and 160–160 μm (b). The dashed lines represent y = x.

CIGALE\(^6\) is a modern galaxy SED modelling code that applies the energy conservation principle between the NIR/optical/UV emission that is absorbed by dust and the re-emitted MIR and FIR emission. CIGALE models host galaxy emission and AGN components separately, and it combines several built models based on the given input parameters for stellar, dust and AGN components. As a result, it generates the probability distribution function of the model parameters. The mean value of the probability distribution function is the output value of a parameter. The standard deviation measured from the probability distribution function is the associated error of the parameter.

Stellar component models include the stellar population, initial mass function (IMF) and star formation history. Here we adopt the stellar population models of Maraston (2005) with Salpeter IMF (Salpeter 1955) and a double exponential star formation history. For the dust component, we use the dust models of Draine et al. (2014) and for the dust attenuation we use a modified Charlot & Fall (2000) attenuation law. We model the AGN component with the models from Fritz, Franceschini & Hatziminaoglou (2006). These AGN models are composed of the isotropic central source emission in the form of power laws between 0.001 and 20 μm and the dust emission of the toroidal obscurer. In these models, the central AGN emission can be partly absorbed by the dust and re-emitted at 1–1000 μm or scattered by the dust. Table 2 lists the adopted parameters used for the SED fitting and includes 17 parameters, but we note that some of the parameters and data are correlated and interconnected. As a result, the number of degrees of freedom is not 17. CIGALE compares one data set (with N observed data points) to every single model. So the Bayesian method used in CIGALE does not estimate each parameter separately but measures the likelihood of each model (built from a set of parameters) to match the data set. From these likelihoods, the probability is evaluated and the probability distribution functions are built.

In CIGALE, the quality of the parameter estimation process depends on the provided data points at different regions over the SED. For example, CIGALE uses UV–optical and NIR data to model stellar components. Additionally, MIR and FIR data are needed to model the dust components. To estimate reliable luminosities from the SED fitting, we need to have at least one detection at each UV–

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\(^6\)http://cigale.lam.fr/.
optical, NIR, MIR and FIR region. For the FIR part, to accurately constrain the dust SED, we need to have at least one detection at shorter wavelengths than the peak of the dust SED near 100 μm and at least one detection at longer wavelengths. Table 3 list the broadband filters included in our SEDs, the detection rate of our sample of 338 AGNs at each band and the number of sources detected at different wavelength regions of the SED. The data requirement for the SEDs needs all of the SEDs to have at least five data points. As a result of the applied wavelength coverage criteria, we perform SED fitting analysis for 158 AGNs in our sample. Among those, 68 are unobscured, 65 are obscured and 25 are CT AGNs.

Fritz et al. (2006) model the AGN emission by considering the radiative transfer model of three main emission components: (i) the central illuminating source; (ii) the scattered emission by dust in the torus; (iii) the thermal dust emission from the torus. These models depend on seven parameters. The size of the torus, $r$, is defined by ratio of the maximum outer radius to the minimum innermost radius of the dust torus. According to the model, $r_{ratio}$ can have the values of 10, 30, 60, 100 and 150. The main dust components are silicate and graphite grains. Silicate grains are responsible for the absorption feature at 9.7 μm, and $\tau$ is the optical depth at 9.7 μm. In these models, $\tau$ can be 0.1, 0.3, 0.6, 1.0, 2.0, 3.0, 6.0 and 10.0.

The dust density distribution is determined by $r^{\beta} e^{-\gamma/\cos\theta}$. Here, the $\beta$ parameter is related to the radial dust distribution in the torus and can have the values of $-1.00$, $-0.75$, $-0.50$, $-0.25$ and 0.00. The $\gamma$ parameter is related to the angular dust distribution in the torus and can have the values of 0.0, 2.0, 4.0 and 6.0. $\theta$ is the opening angle of the torus, and it can have the values of 60°, 100° and 140°. The angle between the equatorial axis and line of sight, $\psi$, can have values between 0.001 and 89.990 in steps of 10 deg. $\psi = 90°$ for Type 1 AGNs and $\psi = 0°$ for Type 2 AGNs.

In this work, our main interest is to constrain the parameters of the AGN component and to measure the AGN and dust luminosities. We obtain statistically good fits ($\chi^2_{\text{reduced}} \leq 5.0$) for most sources except for four unobserved AGNs (i.e. M81 and NGC 4579, 4235 and 5273). We show examples of SED fitting for one CT AGN and one obscured AGN with good photometric coverage from UV to FIR including optical and NIR bands, in Fig. 4.

We obtain several physical quantities as a result of the SED analysis by CIGALE: (i) the host galaxy dust luminosity, $L_{\text{host}}$, measured from the best-fitting dust emission model (the red component in Fig. 4) from the models of Draine et al. (2014); (ii) the pure AGN luminosity in the IR band, $L_{\text{IR}}$, based on the Fritz et al. (2006) AGN model (the green component in Fig. 4), where $L_{\text{IR}}$ is the sum of three AGN luminosity components (the direct emission from the central engine, the thermal emission from the torus and the scattered emission from the torus); (iii) the total IR luminosity $L_{\text{IR}}$, which can be measured as the sum of $L_{\text{host}}$ and $L_{\text{IR}}$. The physical origin of $L_{\text{host}}$ is the host galaxy dust grains heated by the interstellar radiation (Draine et al. 2014).

Based on the analysis of the SEDs of the 68 unobscured, 65 obscured and 25 CT AGNs, we find that the fractional AGN emission contribution to the total IR luminosity ($\text{frac}_{\text{AGN}}$) is between 10 and 80 per cent. Based on the $\text{frac}_{\text{AGN}}$ values listed in Table 1, we identify 7 unobscured, 2 obscured and 18 CT AGNs with high (≥40 per cent) AGN contribution to the total IR luminosity. These sources represent IR SEDs with strong AGN luminosity and weak star formation activity from the host galaxy. We have also checked whether there is a correlation between the $\text{frac}_{\text{AGN}}$ value and $N_{\text{H}}$. We find that while unobscured and obscured AGNs have a similar $\text{frac}_{\text{AGN}}$ distribution between 10 and 60 per cent, CT AGNs have higher $\text{frac}_{\text{AGN}}$ values within the 10 and 80 per cent range. Unobserved and obscured AGNs do not show a correlation between $\text{frac}_{\text{AGN}}$ and $N_{\text{H}}$, and CT-AGNs tend to have higher $\text{frac}_{\text{AGN}}$.

As a result of the SED analysis of 68 unobscured, 65 obscured and 25 CT AGNs, we find that while unobscured AGNs can have $\psi$ values between 30.10 and 89.990, all obscured and CT AGNs have $\psi$ values of 0.001 or 20.0, as expected. Our analysis confirms that the angle between the equatorial axis and the line of sight is an important parameter to separate obscured and unobscured AGNs based on the SED fitting using this model. We find that CT and obscured AGNs have $\theta$ values of 140° (52 percent), 100°...
Table 3. Photometric filters used in the SEDs and the detection rate out of 338 AGNs in our sample at each band. Columns give the following: (1) telescope/survey name; (2) filter name; (3) efficient wavelength of the filter; (4) number of detections of the 338 AGNs in our sample at each band; (5) number of sources that have at least one detection at each region, where region A is UV–optical (covering the FUV, NUV, u, g, r, i and z bands), B is NIR (covering J, H and Ks bands), C is MIR (covering w1, w2, w3, w4, S9W and L18W bands) and D is FIR (covering N60, WIDE-S, WIDE-L, N160, PACS blue and PACS red bands). Each region is separated by a horizontal line.

| Telescope/survey | Filter | $\lambda_{\text{eff}}$ (\(\mu\)m) | Detection rate at each band | Number of sources with at least one detection in each region |
|------------------|--------|-------------------------------|-----------------------------|----------------------------------------------------------|
| GALEX            | FUV    | 0.15                          | 173                         |                                                          |
|                  | NUV    | 0.23                          | 222                         |                                                          |
| SDSS             | u      | 0.36                          | 75                          |                                                          |
|                  | g      | 0.46                          | 75                          | A = 244                                                  |
|                  | r      | 0.61                          | 75                          |                                                          |
|                  | i      | 0.74                          | 75                          |                                                          |
|                  | z      | 0.89                          | 75                          |                                                          |
| 2MASS            | J      | 1.24                          | 335                         |                                                          |
|                  | H      | 1.66                          | 335                         | B = 335                                                  |
|                  | $K_s$  | 2.16                          | 335                         |                                                          |
| WISE             | w1     | 2.25                          | 256                         |                                                          |
|                  | w2     | 4.60                          | 256                         |                                                          |
|                  | w3     | 11.56                         | 255                         |                                                          |
|                  | w4     | 22.09                         | 255                         | C = 305                                                  |
| AKARI            | S9W    | 9                             | 149                         |                                                          |
|                  | L18W   | 18                            | 186                         |                                                          |
| AKARI            | N60    | 65                            | 92                          |                                                          |
|                  | WIDE-S | 90                            | 333                         |                                                          |
|                  | WIDE-L | 140                           | 120                         |                                                          |
|                  | N160   | 160                           | 23                          | D = 338                                                  |
| Herschel         | PACS blue | 68.927                       | 155                         |                                                          |
|                  | PACS red | 153.95                        | 155                         |                                                          |
| Herschel         | PSW    | 242.82                        | 187                         |                                                          |
|                  | PMW    | 340.89                        | 187                         |                                                          |
|                  | PLW    | 482.25                        | 187                         |                                                          |

Best model for Mrk1066 at $z = 0.012$. Reduced $\chi^2 = 1.07$

Best model for IC0486 at $z = 0.027$. Reduced $\chi^2 = 0.62$

Figure 4. Examples of best-fitting models of one CT AGN (left) and one obscured AGN (right) obtained with CIGALE. These SEDs are representative of SEDs with full photometric coverage data from UV to FIR. Blue squares are the measured flux densities (from GALEX, SDSS, 2MASS, WISE, AKARI and Herschel) of the AGNs. Red circles are best-fitting model fluxes. The black solid lines are the best fits given by CIGALE. The dashed blue lines, the solid red lines and the solid green lines show the unattenuated stellar emission, the dust emission and the total AGN emission, respectively.
(32 per cent) or 60° (15 per cent). Unobscured AGNs can have θ values of 140° (53 per cent), 100° (32 per cent) or 60° (14 per cent). We find that unobscured, obscured and CT AGNs mostly have β = −0.5 or β = −1.0. Unobscured, obscured and CT AGNs mostly have γ = 4.0 and γ = 6.0. Models with r\_ratio equal to 150 are favoured for unobscured, obscured and CT AGNs. Models with τ equal to 10.0 provide good fits for most of the unobscured, obscured and CT AGNs.

Our SED analysis with CIGALE shows that obscured and CT AGNs can be identified based on the parameters of the Fritz et al. (2006) model. The most critical parameters are the angle between the equatorial axis and line of sight ψ, and the angular opening angle of the torus θ. Once the best-fitting SED given by CIGALE has ψ = 0.001 or ψ = 10.0, and θ = 140°, then it is very likely that the source is an obscured/CT AGN.

5 RESULTS AND DISCUSSION

5.1 Average SEDs of unobscured, obscured and CT AGNs

As a result of our SED analysis across the UV to FIR wavelength region, we make average SEDs of unobscured, obscured and CT AGNs. We build the mean best-fitting SEDs by CIGALE as follows. The flux densities at each frequency are converted to luminosity. Then, we calculate the mean SED at each log ν grid point (Δlog ν = 0.0007), and we normalize each SED at 1 μm. Figs 5(a), (b) and (c) show the mean SEDs of unobscured, obscured and CT AGNs, respectively. Fig. 5(d) shows the mean SEDs of each population together. As seen in Fig. 5(d) in the optical–UV region, unobscured AGNs have a strong contribution compared with the obscured/CT AGNs. This is consistent with the adopted AGN model of Fritz et al. (2006) because the emission from the inner torus is completely absorbed due to the optically thick torus. Therefore, the mean SEDs of the obscured/CT AGNs are dominated by the stellar population emission in the optical–UV region. Near the rest frame 10 μm, the mean AGN continuum is slightly stronger for unobscured AGNs compared with that of obscured/CT AGNs. This can be understood as a result of the relatively stronger silicate absorption feature seen in the obscured/CT AGNs. The mean SEDs are very similar in the 1–20 μm MIR range. The obtained mean SED properties of obscured, unobscured and CT AGNs in the optical to MIR range agree with previously obtained composite SEDs of Type 1 and Type 2 AGNs (e.g. Hickox et al. 2017). In the MIR region, PAH emission from host galaxy star-light is stronger in the mean SED of the CT AGN. The mean SED of the CT AGN shows a stronger FIR bump compared with the unobscured/obscured mean SEDs. This is consistent with more FIR emission observed in type 2 quasars (e.g. Hiner et al. 2009; Chen et al. 2015). The FIR emission is expected to be formed by the cold-dust emission heated by star formation. However, as suggested by Hiner et al. (2009), dust heated by AGNs can have a significant contribution to the FIR emission. The stronger FIR emission of CT AGNs supports a connection between the AGN obscuration and host galaxy dust emission.

5.2 Relations between the infrared luminosities and ultra-hard X-ray luminosity

As a result of the SED fitting analysis in Section 4, we measure the dust luminosity, L\_dust, the pure AGN luminosity in the IR band, L\_AGN\_IR, and the total IR luminosity L\_TOTAL\_IR, which is the sum of the L\_dust and L\_AGN\_IR. Here we quantify the relationships between L\_dust, L\_AGN\_IR, L\_TOTAL\_IR and the ultra-hard X-ray luminosity in the 14–195 keV band. Fig. 6 shows the relations between L\_dust, L\_AGN\_IR, L\_TOTAL\_IR and L\_X\_14–195 for unobscured, obscured and CT AGNs in our sample. Clear, positive correlations are seen for L\_dust–L\_X\_14–195 (left panel), L\_AGN\_IR–L\_X\_14–195 (middle panel) and L\_TOTAL\_IR–L\_X\_14–195 (right panel). We determine the significance of the correlations using the Pearson correlation coefficient, r (Pearson 1896). We measure r = 0.6 with a p-value equal to zero, which indicates a moderately strong correlation for all luminosities.

To characterize the L\_dust–L\_X\_14–195, L\_AGN\_IR–L\_X\_14–195 and L\_TOTAL\_IR–L\_X\_14–195 relationships, we adopt the following parametrization,

\[ \log(L_{\text{dust}}) = A_{\text{dust}} + \alpha_{\text{dust}} \log(L_{14–195}) + \epsilon_{\text{dust}}, \]

\[ \log[L(\text{IR})_{\text{AGN}}] = A_{\text{AGN}} + \alpha_{\text{AGN}} \log(L_{14–195}) + \epsilon_{\text{AGN}}, \]

\[ \log[L(\text{IR})_{\text{TOTAL}}] = A_{\text{TOTAL}} + \alpha_{\text{TOTAL}} \log(L_{14–195}) + \epsilon_{\text{TOTAL}}. \]

where A is the zero-point, α is the slope and ϵ is the estimated scatter. We establish the best-fitting relationships for both luminosities using the Bayesian regression method of Kelly (2007) that accounts for scatter (ϵ) and computes the posterior probability distributions of the parameters.

For the L\_dust–L\_X\_14–195 relationship, the best-fitting parameters are \( A_{\text{dust}} = 22.08 \pm 3.27, \alpha_{\text{dust}} = 0.51 \pm 0.07 \) and \( \epsilon_{\text{dust}} = 0.43 \pm 0.03 \). The best-fitting relationship for all sources is shown as the solid line. The dashed line, which is very similar to the solid line, shows the best-fitting relationship of obscured and CT AGNs. Best-fitting parameters for the L\_AGN\_IR–L\_X\_14–195 relationship are \( A_{\text{AGN}} = 15.50 \pm 2.91, \alpha_{\text{AGN}} = 0.66 \pm 0.07 \) and \( \epsilon_{\text{AGN}} = 0.53 \pm 0.03 \). The best-fitting relationship is shown as the solid black line for the unobscured, obscured and CT AGNs. When we only consider the obscured and CT AGNs, we find a slightly shallower slope of \( \alpha_{\text{AGN}} = 0.58 \pm 0.10 \), as shown by the dashed black line. Best-fitting parameters for the L\_TOTAL\_IR–L\_X\_14–195 relationship are \( A_{\text{TOTAL}} = 19.35 \pm 2.23, \alpha_{\text{TOTAL}} = 0.57 \pm 0.05 \) and \( \epsilon_{\text{TOTAL}} = 0.40 \pm 0.02 \). The best-fitting relationship (dashed line) for obscured and CT AGNs is slightly shallower than that of all sources (solid line). The slope of the dashed line is \( \alpha_{\text{TOTAL}} = 0.52 \pm 0.08 \). The obtained scatter values around the best-fitting relationships are similar (between 0.4 and 0.5) for all panels. The L\_dust–L\_X\_14–195 relationship slope is shallower compared with that of L\_AGN\_IR–L\_X\_14–195. As L\_TOTAL\_IR is the pure AGN luminosity and L\_dust originates from starburst radiation, we expect to have different slopes for these relationships.

The relationship between the AGN MIR luminosity and X-ray luminosity has been investigated previously (e.g. Asmus et al. 2015; Ichikawa et al. 2017, 2019). Ichikawa et al. (2019) decomposed the IR SED of the 587 AGNs in the 70-month Swift/BAT sample into starburst and AGN components. They quantified the relationship between the 12–2 μm MIR luminosities and the ultra-hard X-ray luminosity in the 14–195 keV for Swift/BAT 70-month AGNs. When we compare the L\_AGN\_IR–L\_X\_14–195 relationship slope with the MIR AGN luminosity L\_14–195 relationship slope values between 0.96 and 1.06 obtained by Asmus et al. (2015) andIchikawa et al. (2017, 2019), we obtain a much shallower slope. The obtained shallower slope in this work might be related to the sample difference. First of all, our AGN sample (158) is much smaller compared with that of Ichikawa et al. (2017, 2019) and therefore it does not expand to low- and high-luminosity ranges in both axes. Especially, our sample does not have any AGNs with log L\_14–195 > 45.0 and L\_AGN\_IR < 41.5, so we obtain a shallower slope compared with other studies (e.g. Asmus et al. 2015; Ichikawa et al. 2017, 2019) whose sam-
Figure 5. Obtained mean SEDs of unobscured (panel a), obscured (panel b) and CT (panel c) AGN populations as a result of SED analysis by CIGALE. In panel (d), the mean SEDs are shown on top of each other. All SEDs are normalized at rest frame 1 μm.

Samples include higher $L_{14-195}$ and lower $L_{\text{IR}}$ objects. Another difference that may result in different slope values is the difference between the measured IR luminosities; while we have the AGN luminosity in the total IR range, previous works (e.g. Asmus et al. 2015; Ichikawa et al. 2017, 2019) only consider the MIR luminosity. We also note that slope values of $\sim 0.65$ (e.g. Netzer 2009; Matsumura & Woo 2015) and $\sim 0.8$ (Ichikawa et al. 2017) are obtained for the relationship between the FIR luminosity and the bolometric AGN luminosity. The obtained $\alpha_{\text{dust}} = 0.51 \pm 0.07$ slope in this work is close to the slope values obtained in these previous studies.

As shown in Fig. 7, we also check the ratio of the pure AGN luminosity to the hard X-ray luminosity as a function of $L_{\text{IR}}$ (left panel) and $L_{14-195}$ (right panel). As seen in both panels, the fraction of pure AGN luminosity to hard X-ray luminosity of obscured and CT AGNs does not show a clear separation from the unobscured AGNs.
Figure 6. Relations between the 14–195 keV hard X-ray luminosity and \(L_{\text{dust}}\) (left panel), the pure AGN luminosity in the IR band, \(L_{\text{IR}}\)\(_{\text{AGN}}\) (middle panel) and the total IR luminosity (right panel) \(L_{\text{IR}}\)\(_{\text{TOTAL}}\). Triangles, squares and circles represent the unobscured, obscured and CT AGNs, respectively. The black solid lines show the best-fitting relationships for all sources. The dashed lines represent the best-fitting relationships for only obscured and CT AGNs.

Figure 7. Ratio of \(L_{\text{IR}}\)\(_{\text{AGN}}\) to \(L_{\text{14–195}}\) as a function of \(L_{\text{IR}}\)\(_{\text{AGN}}\) (left panel) and \(L_{\text{14–195}}\) (right panel). See Fig. 6 for a description of the symbols.

The measured \(L_{\text{IR}}\)\(_{\text{AGN}}\) as a result of the SED fitting can be used to calculate \(R = L_{\text{IR}}\)\(_{\text{AGN}}\)/\(L_{\text{BOL}}\)\(_{\text{AGN}}\), which is a good indicator of the dust covering factor (e.g. Elitzur 2012). For comparison, we follow Ichikawa et al. (2019) and use a constant bolometric factor of 8.47 (Ricci et al. 2017b) to obtain \(L_{\text{BOL}}\)\(_{\text{AGN}}\). In Fig. 8, we show \(R\) versus \(N_{\text{H}}\) in order to see the differences of covering factors among unobscured, obscured and CT AGNs. We find that the median covering factor of CT AGNs, \(\log (R_{\text{ct}}) = 0.21\), is larger than the median covering factor of the obscured AGNs, \(\log (R_{\text{obscured}}) = -0.71\), and the median covering factor of the unobscured AGNs, \(\log (R_{\text{unobscured}}) = -0.34\). For our sample, we see that the median covering factor of the unobscured AGNs is larger than that of the obscured AGNs, although we note that the majority of obscured and unobscured AGNs have \(R\) values in a similar range. For a larger sample of Swift/BAT AGNs, Ichikawa et al. (2019) found that obscured AGNs have a larger covering factor compared with unobscured AGNs. The higher covering factor values of the CT AGNs are consistent with the results of Ichikawa et al. (2019).

5.3 Infrared colours and luminosities versus \(N_{\text{H}}\)

Here we investigate whether the IR colours depend on \(N_{\text{H}}\). NIR photometry is a good tracer of the direct stellar component, the MIR photometry is a good tracer of the AGN torus and the FIR photometry is a good tracer of host galaxy dust emission. Therefore, NIR–FIR and MIR–FIR colours have physically different origins. NIR–FIR colours represent the energy balance between the direct stellar component versus dust emission from the host galaxy, while the MIR–FIR colours compare the AGN torus versus host dust emission. We show the observed 1.25–65 \(\mu\)m, 1.25–90 \(\mu\)m, 18–65 \(\mu\)m, 18–90 \(\mu\)m, 22–65 \(\mu\)m and 22–90 \(\mu\)m colours versus \(N_{\text{H}}\) in Fig. 9. Because the median redshift of our sample is 0.02, we do not expect to have a significant redshift effect in the observed colours. As seen in Fig. 9, although there is a large scatter for individual colours, the median 1.25–65 \(\mu\)m, 1.25–90 \(\mu\)m, 18–65 \(\mu\)m, 18–90 \(\mu\)m, 22–65 \(\mu\)m and 22–90 \(\mu\)m colours of the unobscured, obscured and CT AGNs show a slightly
increasing trend with $N_H$. We note that we have checked other colour combinations and see a similar trend for $H$–65 $\mu$m, $H$–90 $\mu$m, $K_s$–65 $\mu$m, $K_s$–90 $\mu$m, 12–65 $\mu$m and 12–90 $\mu$m. This positive trend indicates that the MIR–FIR colours become slightly redder (or cooler) with increasing $N_H$ values.

We have also investigated the $L(\text{IR})_\text{AGN}$ dependence on the $N_H$ value. As seen in the left panel of Fig. 10, while unobscured and obscured AGNs have a similar distribution, CT AGNs have higher $L(\text{IR})_\text{AGN}$ values. The right panel of Fig. 10 shows that the IR luminosity produced by the torus, $L(\text{IR})_\text{AGN(torus)}$, is higher for CT AGNs.

5.4 Obscured/CT AGN selection by IR colours

We check many different colour–colour combinations including optical, NIR, MIR and FIR, but we mostly find that CT AGNs distribute over a wide colour range similar to obscured and unobscured AGNs. In one particular colour–colour diagram with 9–22 $\mu$m versus 22–90 $\mu$m colours (Fig. 11), we find a distinct colour region that is mostly occupied by CT AGNs. This region is shown by the black dashed lines in Fig. 11. In this figure, the unobscured, obscured and CT AGNs are shown as the grey triangles, black squares and red circles, respectively. The blue contours are the 699 IR galaxies selected from the AKARI IR Galaxy catalogue of Kilerci Eser & Goto (2018) that have a similar redshift range of $z < 0.13$. We first define $[9–22\,\mu m] > 2.0$ and $[22–90\,\mu m] < 2.7$ as new selection criteria for CT AGNs. The $[22–90\,\mu m]$ colour separates AGNs from IR galaxies, as AGNs have blue 22–90 $\mu$m colours. This is expected from the shallower slope of the $L_{\text{dust}}$ and $L(\text{IR})_\text{AGN}$ relationship (Section 5.2.), considering that the AGN IR emission traced by 22 $\mu$m and dust luminosity traced by 90 $\mu$m luminous AGNs should give bluer $[22–90\,\mu m]$ colours. The AKARI/IRC S9W band covers the silicate absorption feature at 9.7 $\mu$m. As shown by Shi et al. (2006), the strength of 9.7–$\mu$m absorption increases with higher $N_H$. Therefore, the [9–22 $\mu$m] colour is expected to be related to the deep silicate absorption feature seen in heavily obscured AGNs. 22 $\mu$m is a measure of the MIR continuum. Once a source has a deep silicate absorption, it will have a fainter 9 $\mu$m and a larger difference in the [22–90 $\mu$m] colour. In Fig. 11, we have four CT AGNs (NGC 6240, 7479, 6552 and 5643) that are used to define the [9–22 $\mu$m] > 2.0 colour range. Stierwalt et al. (2013) represent Spitzer Infrared Spectrograph (IRS; Houck et al. 2004) spectra covering 5–38 $\mu$m of NGC 6240. According to their silicate depth and MIR slope measurements, NGC 6240 shows a strong silicate absorption with a steep MIR slope. Stone et al. (2016) measure the strength of the 9.7–$\mu$m silicate feature of NGC 7479 from Spitzer MIR spectra. According to their measurements, NGC 7479 has a strong silicate absorption feature. Shi et al. (2006) present the Spitzer IRS spectrum of NGC 5643, measuring a deep silicate absorption feature. The Spitzer low-resolution IRS-LL spectrum of NGC 6552 shows a rising MIR continuum between 15 and 35 $\mu$m (Jarrett et al. 2011). The Spitzer spectrum of NGC 6552 does not cover the 9-$\mu$m range, so we do not have a measure for its silicate absorption strength. The MIR spectral measurements of NGC 6240, 7479 and 5643 show evidence for relatively faint 9 $\mu$m and relatively bright 22 $\mu$m, giving higher [9–22 $\mu$m] colours.

We apply these criteria to the AKARI IR galaxy catalogue of Kilerci Eser & Goto (2018) and find three new CT AGN candidates. These candidates are shown as cyan diamonds in Fig. 11. As a first step, we justify the nature of the CT AGN candidates based on the available public data sets and previous studies. The properties of the CT AGN candidates selected from the AKARI IR galaxy catalogue of Kilerci Eser & Goto (2018) are summarized in Table 4.

NGC 1614 is a well-observed local LIRG. Its earlier X-ray observations with ASCA suggest the presence of an AGN based on the well-fitted power law in the 2–10 keV band (Risaliti et al. 2000). Although the weak hard X-ray emission indicates a CT AGN at the first place, the multiwavelength observations in submillimetre (Xu et al. 2015), radio (Herrero-Illana et al. 2017) and X-rays (Pereira-Santaella et al. 2011; Herrero-Illana et al. 2014) do not support this. Xu et al. (2015) found that the amount of nuclear molecular gas and dust is much lower than that predicted for CT AGNs. According to Pereira-Santaella et al. (2011) and Herrero-Illana et al. (2014), the hard and soft X-ray emission of this source can be explained by star formation. As pointed out by Pereira-Santaella et al. (2015), in the case of a CT AGN the predicted 14–195 keV flux would be above the Swift/BAT survey sensitivity limit. Therefore, the non-detection of this source in the Swift/BAT survey (Oh et al. 2018) supports that it is not a CT AGN. Based on the current multiwavelength available data, we consider it as an unlikely/uncertain CT AGN candidate. However, we caution that NGC 1614 has not been observed with NuSTAR yet, and its high-energy nature is still a subject for investigation.

NGC 4418 is a luminous infrared galaxy with a known dust embedded nuclear CT source. The nature of this source has been subject to many observations at different wavelengths and the presence of a CT AGN is highly favoured. Infrared observations (Roche et al. 1986; Spoon et al. 2001; Roche, Alonso-Herrero & Gonzalez-Martín 2015) of NGC 4418 show a deep silicate absorption at 10 $\mu$m and indicate a very heavily obscured CT AGN. Submillimetre observations of NGC 4418 at high spatial resolution are also consistent with the presence of a CT AGN (Sakamoto et al. 2013). Observations from the Chandra/Advanced CCD Imaging Spectrometer (ACIS) show a flat hard X-ray spectrum and imply...
Figure 9. Infrared colour dependence on $N_H$. The black symbols represent the median colours in each $N_H$ bin. Median 1.25–65 μm, 1.25–90 μm, 18–65 μm, 18–90 μm, 22–65 μm and 22–90 μm colours show an increasing trend with $N_H$.

the presence of a CT AGN, but because of the limited photon statistics, this identification is considered as tentative (Maiolino et al. 2003). As pointed out by Roche et al. (2015), the non-detection of NGC 4418 by the Swift/BAT survey (Baumgartner et al. 2013; Koss et al. 2013) is probably due to the extremely high levels of obscuration.

NGC 7714 is a well-observed galaxy with a compact starburst nuclei (e.g. Gonzalez-Delgado et al. 1995; Smith et al. 2005). Smith
et al. (2005) studied the X-ray emission from NGC 7714 with the Chandra/ACIS. They report that the spectrum of the nuclear region can be fitted to a MEKAL function or an absorbed power-law function with a column density of \(N_{\text{H}} = 2.2 \times 10^{21}\) cm\(^{-2}\). Therefore, NGC 7714 possibly hosts an unobscured AGN.

This investigation shows us that our new colour selection criteria are successful to find at least one confirmed CT AGN. As the 9–22 µm colour of NGC 4418 is 3.32, we consider taking [9–22 µm] > 3.0 as a more reliable region that would avoid unobscured AGN selection. When we apply [9–22 µm] > 3.0 and [22–90 µm] < 2.7 as criteria for a larger sample of combined AKARI and WISE sources without any selection criteria, we find 341 candidates. These candidates are shown as the grey dots in Fig. 11. We investigate the nature of these 341 candidates in astronomical data bases such as the High Energy Astrophysics Science Archive Research Center (HEASARC\(^7\)) which is a service of the Astrophysics Science Division at NASA/GSFC, the NASA/IPAC Extragalactic Database\(^8\) (NED) and SIMBAD\(^9\) (Wenger et al. 2000). We find that most of these sources are Galactic IR sources such as young stellar objects (YSOs), asymptotic giant branch (AGB) stars, planetary nebulae (PNe) and H II and star-forming regions. Among these 341 sources only three (IRAS06190+1040, IRAS21144+5430, Mrk34) are classified as a galaxy in the searched data bases. Mrk34 is found to be an already known CT AGN in the literature (Gandhi et al. 2014). However, while IRAS06190+1040 is classified as a galaxy in the NED it is classified as a Galactic star cluster by Froebrich (2017). IRAS21144+5430 is also classified as a galaxy in the

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**Figure 10.** \(L(\text{IR})_{\text{AGN}}\) (left) and \(L(\text{IR})_{\text{AGN(\text{torus})}}\) (right) versus \(N_{\text{H}}\). Compared with the unobscured and obscured AGNs, median \(L(\text{IR})_{\text{AGN}}\) and \(L(\text{IR})_{\text{AGN(\text{torus})}}\) luminosities are higher for CT AGNs (black circle).

**Figure 11.** AKARI–WISE colours of X-ray selected AGNs with 9-, 22- and 90-µm detections. The grey triangles are unobscured AGNs, the black squares are obscured AGNs and the red circles are CT AGNs. The blue contours represent 699 IR galaxies from the AKARI IR Galaxy catalogue of Kilerci Eser & Goto (2018) within the \(z \leq 0.13\) limit that have detections at 9-, 22- and 90-µm bands. Cyan diamonds represent the three CT AGN candidates selected from the AKARI IR galaxy catalogue of Kilerci Eser & Goto (2018) based on the [9–22 µm] > 2.0 and [22–90 µm] < 2.7 selection criteria.

\(^7\)https://heasarc.gsfc.nasa.gov/cgi-bin/W3Browse/w3browse.pl.

\(^8\)http://nedwww.ipac.caltech.edu/. The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

\(^9\)http://simbad.u-strasbg.fr/simbad/.
NGC 7714 354.058 2.155 0.009 2.06 1.83 10.72 21.34 Smith, Struck & Nowak (2005) Unobscured AGN survey catalogue.

NGC 4418 186.727 − 0.877 0.007 3.32 2.08 (v) We compare the average covering factor \( R = \frac{L(\text{IR})_{\text{AGN}}}{L(\text{Bol})_{\text{AGN}}} \) for unobscured, obscured and CT AGNs. We show that CT AGNs have larger covering factors compared with the obscured and unobscured AGNs.

(vi) We show that the median 1.25–65 μm, 1.25–90 μm, 18–65 μm, 18–90 μm, 22–65 μm and 22–90 μm colours of the unobscured, obscured and CT AGNs have an increasing trend with \( N_H \). We show that MIR–FIR colours have a tendency to become redder (or cooler) with increasing \( N_H \).

(vii) We find that CT AGNs have higher \( L(\text{IR})_{\text{AGN}} \) and \( L(\text{IR})_{\text{AGN}(\text{non})} \) compared with obscured and unobscured AGNs.

(viii) We present new CT AGN selection criteria as [9–22 μm] > 3.0 and [22–90 μm] < 2.7. As a result of these criteria, we find two known CT AGNs (NGC 4418 and Mrk34) that are not included in the Swift/BAT sample. Due to the limited number of sources detected in 9 μm, we could not find any new CT AGNs. We conclude that MIR photometric bands covering 9.7-μm silicate absorption and MIR continuum can be used as a new tool to select the most heavily obscured CT AGNs.

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6 CONCLUSIONS
We have analysed the broad-band SEDs of 68 unobscured, 65 obscured and 25 CT AGNs from the UV to the FIR by combining data from the GALEX, SDSS, 2MASS, WISE, AKARI and Herschel surveys. We have constrained the parameters of the AGN component based on the AGN model (Fritz et al. 2006). We have investigated possible IR colour selection criteria for CT AGNs based on AKARI and WISE photometric magnitudes and found new promising colour selection criteria. The results of this work can be summarized as follows.

(i) The most important parameters to identify obscured/CT AGNs from the SED analysis with CIGALE are the angle between the equatorial axis and line of sight \( \psi \), and the angular opening angle of the torus, \( \theta \). SED models with \( \psi = 0.001 \) or \( \psi = 10.0 \), and \( \theta = 140^\circ \), are very likely to indicate an obscured AGN or a CT AGN.

(ii) The comparison of average SEDs of the three AGN populations show that the MIR SEDs are similar, the optical/UV region of the obscured/CT AGNs is dominated by the host galaxy emission, and in the FIR region CT AGNs show a stronger emission.

(iii) We identify 27 strong AGN luminosity dominated sources among the unobscured, obscured and CT AGNs based on the \( f_{\text{frac}}_{\text{AGN}} \) obtained by the SED fitting. These represent AGN luminosity dominated UV to FIR SEDs. We find that while unobscured and obscured AGNs have a similar \( f_{\text{frac}}_{\text{AGN}} \) distribution, CT AGNs have higher \( f_{\text{frac}}_{\text{AGN}} \) values.

(iv) We find moderately strong correlation luminosity correlations between \( L_{\text{dual}}-L_{14-195} \), \( L(\text{IR})_{\text{AGN}}-L_{14-195} \) and \( L(\text{IR})_{\text{AGN}}-L_{14-195} \). We quantify the relationships between these separated IR luminosities and the ultra-hard X-ray luminosity for the hard X-ray selected AGNs from the Swift/BAT 105-month survey catalogue.

SDSS, but it is also classified as a H II region in SIMBAD. We also note that IRAS06190+1040 and IRAS21144+5430 do not have archived X-ray observations for further investigation. We find three sources that are classified as IR sources with X-ray observations: WISEA J162015.92–505621.8, 2MASS J16344841–732432 and Allwise J181724.72–170628.1. X-ray observations of WISEA J162015.92–505621.8 show a weak X-ray source, but the quality of the available data does not allow for a reliable spectral analysis to measure \( N_H \). The available X-ray data of 2MASS J16344841–4732432 do not show an X-ray source. In the X-ray observation of Allwise J181724.72–170628.1 we identify a very weak X-ray source, but the low signal-to-noise ratio of the data does not allow us to obtain a spectral fit. Based on the available X-ray data, we cannot confirm if these sources are CT AGNs. However, all three sources are close to the Galactic plane, and therefore they could also be Galactic IR sources.

Table 4. Properties of the CT AGN candidates. The columns give the following: (1) object name; (2) RA of the optical counterpart; (3) Dec. of the optical counterpart; (4) spectroscopic redshift of the optical counterpart; (5) [9–22 μm] colour; (6) [22–90 μm] colour; (7) base 10 logarithm of the total IR luminosity between 8 and 1000 μm; (8) base 10 logarithm of the intrinsic hydrogen column density in units of cm\(^{-2}\); (9) X-ray reference for the adopted \( N_H \) value in column 8; (10) our comment about the CT AGN candidate.

| Name       | RA (J2000.0) | Dec. (J2000.0) | z   | [9–22 μm] [AB] | [22–90 μm] [AB] | log(\(L_{\text{IR}}/L_{\odot}\)) | log(\(N_H\)) | X-ray Ref. | Comment                  |
|------------|--------------|---------------|-----|---------------|----------------|----------------------|--------------|-------------|--------------------------|
| NGC 1614   | 68.500       | − 8.379       | 0.016 | 2.04          | 2.03           | 11.60                 | 21.58        | Pereira-Santaella et al. (2011) | Unconfirmed AGN          |
| NGC 4418   | 186.727      | − 0.877       | 0.007 | 3.32          | 2.08           | 10.72                 | 21.34        | Smith, Struck & Nowak (2008)   | Unobscured AGN            |
| NGC 7714   | 354.058      | − 1.171       | 0.009 | 2.06          | 1.83           | 10.72                 | 21.34        | Unconfirmed AGN                  | Unconfirmed AGN            |

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For **XMM–Newton** (Jansen et al. 2001), we mostly used EPIC-pn camera data. Only for ESO450-16 we used both EPIC-pn and EPIC-MOS data. We calibrated the data using SAS v15.0.0 (Gabriel et al. 2004) and the calibration files as of 2019/01/01 using the `eproc` package. We extracted source spectra using a circular region with a radius of about 32 arcsec. We extracted the background spectra from a nearby (located on the same CCD) uncontaminated larger circular region. Response and ancillary response files are generated using the `rmfgen` and `arfgen` tools.

For one source, we used **Chandra/ACIS** (Weisskopf et al. 2000; Garmire et al. 2003) data. **Chandra** data were reduced using CIAO v4.9 (Fruscione et al. 2006) following standard procedures. We used the `chandra_repro` task to reprocess the data. The spectra were extracted using the `specextract` tool from a circular aperture of 10-arcsec radius. Background spectra were extracted using a larger source-free nearby circular region.

We performed X-ray spectral fitting using the XSPEC version 12.10.1 software (Arnaud 1996). We adopted Verner cross-section (Verner et al. 1996) and Wilm abundance (Wilms, Allen & McCray 2000) in the TBABS model to account for the Galactic absorption. Intrinsic absorption was also modelled with TBABS. We grouped all spectra to have at least 50 counts per channel (only for 2MASX J08384815+0407340 we used 40 counts) and used χ² statistics. We fit the X-ray spectra in the 0.4–9.0 keV energy range, but in a few cases we had to narrow the energy range due to the source brightness, as shown in Fig. A1. In order to measure the intrinsic $N_{\text{H}}$ value, the spectra are fitted using a single power law modified by Galactic absorption plus an intrinsic absorption at the redshift of each source. During the spectral fitting process, the power-law normalization and the intrinsic column density were always left as free parameters. For 2MASXJ16510578–0129258, CGCG081–001 and MCG+00-58-028 the slope of the power law was left as a free parameter. As shown by Marchesi et al. (2018), fixing the photon index to the typical AGN value of $\Gamma \sim 1.7$ in low-quality 2–10 keV spectra gives better intrinsic $N_{\text{H}}$ measurements. Therefore, for 2MASXJ08384815+0407340, IC-588, ESO439-G009 and NGC 5940 we fixed the photon index to $\Gamma = 1.7$ or $\Gamma = 1.8$. For ESO450-16, we limited the slope of the power law between 1.0 and 2.0; for this source, fixing $\Gamma$ to be 1.7 does not give a statistically acceptable fit. For these sources when necessary, we also added a Gaussian line to the power-law model in order to obtain a better fit result. For IC-588, ESO439-G009 and NGC 5940, we used the additional MEKAL model (Mewe, Gronenschild & van den Oord 1985) to model the soft X-rays below 1 keV. The obtained spectral parameters from the spectral fitting are listed in Table A1. We show the best-fitting Chandra and XMM–Newton X-ray spectra in Fig. A1. As a result of our analysis, we classify 2MASXJ08384815+0407340, IC-588, 2MASXJ16510578–0129258, MCG+00-58-028 as obscured AGNs and ESO439-G009, NGC 5940, ESO450-16, CGCG081-001 as unobscured AGNs.
Figure A1. The best-fitting spectra of AGNs observed with XMM–Newton and Chandra. For seven sources, we use XMM–Newton EPIC-pn data and only for ESO450-16 we used both EPIC-pn and EPIC-MOS (shown in red) data.
Table A1. X-ray spectral analysis results. The columns give the following: (1) object name; (2) X-ray facility; (3) Galactic $N_H$; (4) measured intrinsic $N_H$; (5) temperature $kT$ in keV of the MEKAL component; (6) line energy of the simple Gaussian profile in keV; (7) power-law photon index; (8) reduced chi-squared (degrees of freedom).

| Source name | Facility   | $N_{H,Gal}$ (10$^{20}$ cm$^{-2}$) | $N_{H,Int}$ (10$^{22}$ cm$^{-2}$) | $kT$ (keV) | Line energy (keV) | $\Gamma$ | $\chi^2$ (d.o.f.) |
|-------------|------------|----------------------------------|----------------------------------|------------|-------------------|---------|------------------|
| 2MASXJ08384815+0407340 | Chandra | 2.68 | 5.09 $^{+0.61}_{-0.60}$ | 0.20 $^{+0.00}_{-0.45}$ | 1.7 | 1.20 (12) |
| IC-588 | XMM–Newton | 1.71 | 2.88 $^{+0.5}_{-0.90}$ | 0.08 $^{+0.01}_{-0.08}$ | 1.7 | 4.34 (51) |
| ES0439-G009 | XMM–Newton | 5.44 | $\leq$0.01 | 0.68 $^{+0.07}_{-0.05}$ | 6.40 $^{+0.17}_{-0.15}$ | 1.7 | 1.88 (21) |
| NGC 5940 | XMM–Newton | 3.95 | $\leq$0.01 | 0.23 $^{+0.01}_{-0.03}$ | 1.8 | 1.70 (555) |
| ESO450-16 | XMM–Newton | 7.46 | $\leq$0.01 | 6.40 $^{+0.15}_{-0.21}$ | 2.0 $^{+0.02}_{-0.03}$ | 1.65 (558) |
| CGCG081-001 | XMM–Newton | 4.43 | $\leq$0.01 | 1.83 $^{+0.16}_{-0.15}$ | 1.14 (171) |
| 2MASXJ16510578–0129258 | XMM–Newton | 7.80 | 5.39 $^{+0.10}_{-0.06}$ | 1.50 $^{+0.23}_{-0.22}$ | 0.93 (38) |
| MCG+00-58-028 | XMM–Newton | 3.92 | 3.29 $^{+0.12}_{-0.12}$ | 1.59 $^{+0.04}_{-0.04}$ | 1.63 (327) |

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