Does AGN Fraction Depend on Redshift or Luminosity? An Extinction-Free Test by 18-band Mid-infrared SED Fitting in the AKARI NEP Wide Field

Chia-Ying CHIANG$^{1,2}$, Tomotsugu GOTO$^1$, Tetsuya HASHIMOTO$^1$, Seong-Jin KIM$^1$, Hideo MATSUHARA$^3$ and Nagisa OI$^4$

$^1$Institute of Astronomy, National Tsing Hua University, No. 101, Section 2, Kuang-Fu Road, Hsinchu City 30013, Taiwan
$^2$Department of Physics & Astronomy, Wayne State University, 666 W. Hancock, Detroit, MI 48202, USA
$^3$Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Yoshinodai 3-1-1, Sagamihara, Kanagawa 229-8510, Japan
$^4$Tokyo University of Science, 1-3 Kagurazaka, Shinjuku-ku, Tokyo 162-8601, Japan

*E-mail: ft8320@wayne.edu

Received 15-Jun-2018; Accepted 28-Jan-2019

Abstract

Revealing what fraction of galaxies harbor AGN is central in understanding black hole accretion history of the Universe. However, optical and soft X-ray surveys miss the most highly obscured AGNs. Infrared (IR), instead, is more robust against absorption. Previous IR photometric surveys, however, only had 4 or 5 filters in mid-IR. Our AKARI North Ecliptic Pole (NEP) wide field sample has 18 filters in mid-IR (9 from AKARI, 4 from WISE, and 5 from Spitzer), for the first time, allowing a sophisticated mid-IR SED fitting diagnosis for a statistical number of sources (89178 over 5.4 deg$^2$). By using a SED fitting technique, we investigate the evolution of AGN fraction as a function of redshift and IR (8-1000 µm) luminosity in an extinction-free way. We found that the AGN fraction ($F_{\text{AGN}}$) shows no sign of strong redshift evolution. Instead, $F_{\text{AGN}}$ increases with increasing IR luminosity in all redshifts bins (0 $< z <$ 2).

Key words: galaxies: active, galaxies: infrared

1 Introduction

Active Galactic Nuclei (AGNs) are powered by central accreting supermassive black holes, and cast impact on the environment via AGN feedback processes (Kauffmann & Haehnelt 2000; Di Matteo et al. 2005; Fabian 2012). It is essential to understand AGNs in order to probe cosmological evolution of supermassive black holes and the universe. In addition, AGN fraction is important when studying luminosity functions. Researchers have been investigating various surveys to study AGNs for decades. Although AGNs can be bright in a wide range of wavelengths, most surveys are severely biased towards unobscured (Type 1) AGNs. A large population of obscured (Type 2) AGNs are missed in optical and soft X-ray surveys due to obscuration caused by dust and gas. In this case, radio, hard X-ray, and mid-infrared (IR) selections are promising for detecting Type 2 AGNs. However, only ~10% of AGNs are radio-loud, and current hard X-ray satellites (i.e. Swift BAT, NuSTAR, etc.) have limited sensitivity. It is difficult for radio and hard X-ray surveys to reach a large sample size to overcome cosmic variance. As warm dust emission dominates the
mid-IR band (2-24 µm), and mid-IR satellites provide sensitive full-sky surveys, mid-IR selection is an effective, nearly free of extinction way to identify AGNs. In past few years there has been numerous studies using mid-IR colors to find AGNs in the local universe and at high-redshift (Lacy et al. 2004; Lacy et al. 2007; Stern et al. 2012).

As star-forming galaxies (SFGs) are bright in mid-IR bands as well, it has been of great challenge to distinguish SFGs and AGNs. In mid-IR, a SFG has polycyclic aromatic hydrocarbon (PAH) broad emission line features at 3.3, 6.2, 7.7, 8.6, 11.2, and 12.7 µm (Puget et al. 1985; Allamandola et al. 1989), while an AGN presents a red power-law ($f_{\nu} \propto \nu^{-\alpha}$) spectrum with typical $\alpha \leq -0.5$ (Alonso-Herrero et al. 2006). Laurent et al. (2000) showed that the mid-IR Spectral Energy Distributions (SEDs) of SFGs and AGNs are distinct enough for separation, and some following work also confirmed that mid-IR photometry provides robust SFG-AGN diagnostics (Stern et al. 2005; Jarrett et al. 2011; Magdis et al. 2013). Survey data obtained by \textit{Spitzer} infrared telescope and Wide field Infrared Survey Explorer (\textit{WISE}) lead to an explosion of research to search and study AGNs (Lacy et al. 2004; Alonso-Herrero et al. 2006; Lacy et al. 2007; Lacy et al. 2013; Lacy et al. 2015; Eckart et al. 2010; Stern et al. 2005; Donley et al. 2012; Mateos et al. 2012; Stern et al. 2012; Assef et al. 2013). However, both \textit{WISE} and \textit{Spitzer} have limited available filters and gaps (between 12-22 µm in \textit{WISE} and 8-24 µm in \textit{Spitzer}) in the mid-IR wavelength range, which make SFG-AGN diagnostics difficult for sources at certain redshift ranges. PAH features of high redshift sources may fall into the wavelength gaps and make AGN selection difficult. For instance, the 8 to 24 µm gap is important for the diagnosis of AGN and SFG at 0.5 < z < 1.5. The infrared satellite \textit{AKARI} (Murakami et al. 2007) has 9-band mid-IR filters and does not suffer from the lack of continuous mid-IR data. The \textit{AKARI} North Ecliptic Pole (NEP) survey covers a field of 5.4 deg$^2$ and will remain the only survey with continuous mid-IR data until the James Webb Space Telescope (\textit{JWST}) performs a similar one.

Huang et al. (2017) (hereafter H17) used the AKARI NEP deep survey (Matsuhara et al. 2006) covering a field of 0.57 deg$^2$ catalogue (containing ∼5800 sources) to select AGNs using the SED fitting technique. By combining AKARI, \textit{WISE} and \textit{Spitzer} data with 18 bands in total and fitting 25 empirical models to the data, the authors recovered more X-ray detected AGNs than previous work by ∼20%. Previous research using \textit{WISE} or \textit{Spitzer} data performed SED fitting with limited models (Assef et al. 2008; Assef et al. 2010; Assef et al. 2013; Chung et al. 2014). Thanks to the continuous coverage of mid-IR band by AKARI, more detailed models can be used to help AGN selection at high redshift. In this work, we use the AKARI NEP wide field (covering 5.4 deg$^2$) catalogue for AGN selection. We will provide detailed information of the catalogue and data analysis in section 2, and present results in section 3. We will discuss the results compared with other work in section 4, and summarize the paper in section 5.

## 2 Data Analysis

### 2.1 Data

We used the catalogue from the NEP wide field survey (Kim et al. 2012) of AKARI in this work. The survey was carried out on a circular area of ∼5.4 deg$^2$ and is part of the large area survey programs of AKARI, which provides crucial FIR bands to measure SED accurately (Kim et al. 2015). The AKARI infrared camera (IRC; Onaka et al. 2007) offers coverage from near to mid-infrared (2-24 µm) wavelength bands. There are 9 filters (N2, N3, N4, S7, S9W, S11, L15, L18W, and L24) corresponding to 2.4, 3.4, 4.1, 7, 9, 11, 15, 18 and 24 µm effective wavelength. The instrument detection limits are 11, 9, 30, 34, 87, 93, and 256 µJy in the above 9 bands, respectively. The detection limits of the NEP survey are 20.9, 21.1, 21.1, 19.5, 19.4, 19.0, 18.6, 18.7 and 17.8 in AB magnitude (Kim et al. 2012). In this catalogue data of 4 mid-IR bands from \textit{WISE} (3.4, 4.6, 12 and 22 µm) and 5 mid-IR bands from \textit{Spitzer} (3.6, 4.5, 5.8, 8.0 and 24 µm) are included, forming a sample with 18 mid-IR bands in total.

The AKARI NEP survey detected a large number of IR sources, yet H17 only used sources in the deep field, which is a small part of it due to limited optical/UV coverage by the Galaxy Evolution Explorer (\textit{GALEX}) and the Canada France Hawaii Telescope (\textit{CFHT}). An optical survey covering the AKARI NEP wide field using Subaru’s Hyper Suprime-Cam (HSC; Miyazaki et al. 2012) has been carried out recently. The HSC coverage (Goto et al. 2017) increases the number of sources with optical data to 89178 in the catalogue, which is the largest sample to date. Photometric redshifts can be measured accurately from the data of the five HSC optical bands ($g, r, i, z$ and $y$; Oi et al., submitted to this volume). Fig. 1 shows the redshift distribution of the sample. In this work we only focus on galaxies, and after excluding stars in the catalogue, there are 57106 galaxies remaining in the sample.

### 2.2 SED Fitting

We performed SED fitting using the \textit{Le PHARE} \footnote{http://www.cfht.hawaii.edu/~arnouts/LEPHARE/lephare.html} (Arnouts et al. 1999; Ilbert et al. 2006) code. The Lagache et al. (2003) template was used to measure infrared luminosities in the catalogue. As galaxy types were not given by the Lagache template, we used the Polletta et al. (2007) templates, which contains 3 elliptical (type number 1-3), 7 spiral (type number 4-10), 6 starburst (type number 11-16), 7 AGN (type number 17-22 and 25), and 2 AGN- Starburst composite (type number 23-24) models and
3 Results

We plot the distribution of best-fitting models in Fig. 2. There are 6070 AGNs selected among the total 16464 galaxies, giving an overall AGN fraction of 36.9 ± 0.5%, which is mildly higher than the number of 29.6 ± 0.8% reported in H17 using the NEP deep field catalogue. Our sample size is ∼3.5 times larger than that used in H17. Surprisingly, a large number (3239 in total) of elliptical galaxies (type number 1–3) are detected as this class of galaxies are usually faint in the mid-IR. Type numbers 17–19 and 24–25 belong to Type 2 AGNs, and it seems mid-IR observations are good at selecting obscured AGNs as expected.

3.1 AGN Fraction as a Function of Redshift

We separate the SED sample into a few luminosity bins and plot the evolution of AGN fraction as a function of photometric redshift (see Fig. 3). It is clearly seen that all luminosity bins show a relatively constant or decreasing trend at z < 0.5 except the 10 < log $L_{\text{IR}}$ < 11 bin. In the regime of z > 0.5, the 10 < log $L_{\text{IR}}$ < 11 and log $L_{\text{IR}}$ > 12 bins show an increasing trend, while the 11 < log $L_{\text{IR}}$ < 12 bin displays a decreasing trend. Different luminosity bins show different behaviors, and from our results it seems that there may be no strong redshift dependence in AGN fraction evolution.

3.2 AGN Fraction as a Function of Luminosity

In order to check if AGN fraction has luminosity dependence, we divide the SED sample into a few groups of different redshift range, and plot the evolution of AGN fraction as a function of luminosity in Fig. 4. We find that all redshift bins show an increasing trend at log $L_{\text{IR}}$ > 10. Furthermore, all bins seem to

---

\[ \text{http://www.iasf-milano.inaf.it/~polletta/templates/swire_templates.html} \]
reach similar values of AGN fraction, which again reveals that there is no significant redshift dependence. Instead, the result implies that there is more luminosity dependence than redshift dependence in AGN fraction. Note that most luminosity bins reach a fraction of ~0.6 at high luminosities.

4 Discussion

4.1 AGN Fraction

We show that there is possible luminosity dependence in the evolution of AGN fraction, which is consistent with the results reported in previous literature. Goto (2005) investigated 4828 Infrared Astronomical Satellite (IRAS) galaxies and selected AGNs using the optical emission-line ratios, and found that the AGN fraction increases as a function of $L_{\text{IR}}$. Similar trends have been reported by Yuan et al. (2010), Kartaltepe et al. (2011), and Weigel et al. (2018) using various local samples. These results imply that luminous infrared galaxies (LIRGs; $11 < \log L_{\text{IR}} < 12$) and ultraluminous infrared galaxies (ULIRGs; $12 < \log L_{\text{IR}} < 13$) are more likely to be powered by AGNs. AGN fractions reported in previous literature also reach ~0.6, which is consistent with the result of the present work. Note that previous research only used samples in the local ($z < 0.3$) universe, and our work extends the study to trace behaviors of galaxies at higher redshifts and compares results between different branches of redshifts. We show that the luminosity dependence of AGN fraction may be global.

The reason that the AGN fraction is high among LIRGs can be explained by one of the merger scenarios for LIRGs (Sanders et al. 1988; Dasyra et al. 2006). When two galaxies merge, they lose orbital energy and angular momentum to tidal features and/or shocks, which trigger star formation (Kennicutt et al. 1987; Liu & Kennicutt 1995; Barnes 2004). These activities heat surrounding dust and produce strong far-infrared (FIR) radiation. It then reaches an ultraluminous IR stage which is powered by starburst or AGNs. The merger finally evolves into an optically bright QSO when star formation activities decline. In this scenario AGNs dominate luminous IR sources during final merger stages. We plot the fraction of SFGs in the top panel of Fig. 5. It can be seen that fractions of SFGs of all redshift bins show mild decreasing trends at high luminosities. Bottom: $N_{\text{SFG}}/N_{\text{AGN}}$ ratio as a function of luminosity. It can be seen that AGN dominates at high luminosities.
4.2 Other SED Fitting Templates

H17 performed SED fitting of the NEP deep field sample using the templates provided by Brown et al. (2014) as well, and found that the results are consistent with those given by the Polletta’s template set. The Brown’s template set contains 100 models in total, and provides a set of 37 SFG, 11 AGN and 22 AGN-Starburst composite models which allow more detailed classifications. The LePHARE code determined types for 16417 sources in the catalogue, which is comparable to the number obtained using the Polletta’s template set and all of them are included in the SED sample. There are 5427 SFGs, 2083 AGNs and 3890 AGN-Starburst composites classified by the Brown’s template set. Note that 3097 galaxies are classified as elliptical galaxies, which is comparable with the large number of elliptical galaxies classified by the Polletta’s template set. Around 77 % of Polletta elliptical galaxies are also classified as elliptical galaxies by the Brown’s template set. Only 33 % of SFGs, AGNs and AGN-Starburst composites have the same classification in both Polletta’s and Brown’s template sets. However, the overall AGN fraction (including AGNs and composites) is 36.4 ± 0.5%, which is remarkably similar to the number obtained using the Polletta’s template set. It is not surprising that the Brown’s template set is capable of more detailed classification because there are a lot more models than those of the Polletta’s template set. Note that the Brown’s template set does not determine types for more galaxies than the Polletta’s template set, indicating that both template sets perform similarly on the AKARI survey data. Given that not all sources in the SED sample are detected by every of the 18 mid-IR band, increasing models of SED fitting does not necessarily lead to more information. In this sense, results obtained using different templates should not differ significantly and the Polletta’s template set remains reliable in our sample. Future development is expected when JWST data are available.

Fig. 6 shows results obtained using the Brown’s template set. It can be seen that the AGN fraction still shows no significant redshift dependence. The luminosity dependence is not as strong as that showed in the Polletta results, but most bins do show significant increase at high luminosities.

5 Conclusions

We used the unique AKARI NEP wide field survey sample with 18 mid-IR bands of data to perform SED fitting and select AGNs. Our results indicate that AGN fraction seems to show stronger luminosity dependence than redshift dependence. This is consistent with results reported in previous literature and the theoretical model of ULIRGs. We also examined the fractions of SFGs and found mild decreasing trends at high luminosities, which is in agreement with theoretical predictions. The major improvement from previous research is that our sample contains
both local and high-redshift galaxies, the other work only used local samples. Although further improvement is expected with the coming launch of JWST, AKARI NEP survey will remain the best sample to study luminosity function, AGN fractions, etc., in decades.

Acknowledgements
We acknowledge the support by the Ministry of Science and Technology (MoST) of Taiwan through grant105-2112-M-007-003-MY3. CYC thanks the support by the MoST Leaders in Future Trends (LiFT) program.

References
Allamandola, L. J., Tielens, A. G. G. M., & Barker, J. R. 1989, ApJS, 71, 733
Alonso-Herrero, A., Pérez-González, P. G., Alexander, D. M., et al. 2006, ApJ, 640, 167
Arnouts, S., Cristiani, S., Moscardini, L., et al. 1999, MNRAS, 310, 540
Assef, R. J., Kochanek, C. S., Brodwin, M., et al. 2008, ApJ, 676, 286
—. 2010, ApJ, 713, 970
Assef, R. J., Stern, D., Kochanek, C. S., et al. 2013, ApJ, 772, 26
Barnes, J. E. 2004, MNRAS, 350, 798
Brown, M. J. I., Moustakas, J., Smith, J.-D. T., et al. 2014, ApJS, 212, 18
Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682
Chung, S. M., Kochanek, C. S., Assef, R., et al. 2014, ApJ, 790, 54
Dasyra, K. M., Tacconi, L. J., Davies, R. I., et al. 2006, ApJ, 651, 835
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Nature, 433, 604
Donley, J. L., Koekemoer, A. M., Brusa, M., et al. 2012, ApJ, 748, 142
Eckart, M. E., McGreer, I. D., Stern, D., Harrison, F. A., & Helfand, D. J. 2010, ApJ, 708, 584
Fabian, A. C. 2012, ARA& A, 50, 455
Goto, T. 2005, MNRAS, 360, 322
Goto, T., Arnouts, S., Malkan, M., et al. 2011, MNRAS, 414, 1903
Goto, T., Toba, Y., Utsumi, Y., et al. 2017, Publication of Korean Astronomical Society, 32, 225
Huang, T.-C., Goto, T., Hashimoto, T., Oi, N., & Matsuhara, H. 2017, MNRAS, 471, 4239
Ilbert, O., Arnouts, S., McCracken, H. J., et al. 2006, A&A, 457, 841
Jarrett, T. H., Cohen, M., Masci, F., et al. 2011, ApJ, 735, 112
Kartaltepe, J. S., Sanders, D. B., Le Floc’h, E., et al. 2010, ApJ, 709, 572
Kauffmann, G., & Haehnelt, M. 2000, MNRAS, 311, 576
Kennicutt, Jr., R. C., Keel, W. C., van der Hulst, J. M., Hummel, E., & Roettiger, K. A. 1987, AJ, 93, 1011
Kim, S. J., Lee, H. M., Matsuhara, H., et al. 2012, A&A, 548, A29
Kim, S. J., Lee, H. M., Jeong, W.-S., et al. 2015, MNRAS, 454, 1573
Lacy, M., Petric, A. O., Sajina, A., et al. 2007, AJ, 133, 186
Lacy, M., Ridgway, S. E., Sajina, A., et al. 2015, ApJ, 802, 102
Lacy, M., Storrie-Lombardi, L. J., Sajina, A., et al. 2004, ApJS, 154, 166
Lacy, M., Ridgway, S. E., Gates, E. L., et al. 2013, ApJS, 208, 24
Lagache, G., Dole, H., & Puget, J.-L. 2003, MNRAS, 338, 555
Laurent, O., Mirabel, I. F., Charmandaris, V., et al. 2000, A&A, 359, 887
Liu, C. T., & Kennicutt, Jr., R. C. 1995, ApJ, 450, 547
Magdis, G. E., Rigopoulou, D., Helou, G., et al. 2013, A&A, 558, A136
Mateos, S., Alonso-Herrero, A., Carrera, F. J., et al. 2012, MNRAS, 426, 3271
Matsuhara, H., Wada, T., Matsuura, S., et al. 2006, PASJ, 58, 673
Miyazaki, S., Komiyama, Y., Nakaya, H., et al. 2012, in Proc. SPIE, Vol. 8446, Ground-based and Airborne Instrumentation for Astronomy IV, 84460Z
Murakami, H., Baba, H., Barthel, P., et al. 2007, PASJ, 59, S369
Onaka, T., Matsuhara, H., Wada, T., et al. 2007, PASJ, 59, S401
Polletta, M., Tajer, M., Maraschi, L., et al. 2007, ApJ, 663, 81
Puget, J. L., Leger, A., & Boulanger, F. 1985, A&A, 142, L19
Sanders, D. B., Soifer, B. T., Elias, J. H., Neugebauer, G., & Matthews, K. 1988, ApJ, 328, L35
Stern, D., Eisenhardt, P., Gorenstein, V., et al. 2005, ApJ, 631, 163
Stern, D., Assef, R. J., Benford, D. J., et al. 2012, ApJ, 753, 30
Weigel, A. K., Schawinski, K., Treister, E., Trakhtenbrot, B., & Sanders, D. B. 2018, MNRAS, 476, 2308
Yuan, T.-T., Kewley, L. J., & Sanders, D. B. 2010, ApJ, 709, 884