Search for Active Galactic Nuclei using *AKARI* Mid-infrared All-Sky Survey

S. Oyabu,[1] Y. Toba,[2,3] D. Ishihara,[1] H. Matsuhara,[3] T. Wada,[3] Y. Ohyama,[4] and M. Malkan[5]
[1] Graduate School of Science, Nagoya University, Furo-cho,
Chikusa-ku, Nagoya, Aichi 464-8602 Japan
[2] Department of Space and Astronautical Science, the Graduate University for Advanced Studies (Soukendai),
3-1-1, Yoshinodai, Sagamihara, Kanagawa 252-5210 Japan
[3] Institute of Space and Astronautical Science,
Japan Aerospace Exploration Agency, 3-1-1, Yoshinodai, Sagamihara, Kanagawa 252-5210 Japan
[4] Academia Sinica, Instituted of Astronomy and Astrophysics, Taiwan
[5] Department of Physics and Astronomy, University of California, Los Angels, CA 90024, USA
E-mail(SO): oyabu@u.phys.nagoya-u.ac.jp

Abstract

AKARI, the Japanese infrared satellite launched at February 2006, have a primary mirror of 70cm diameter cooled with the combination of liquid helium and mechanical coolers. It had unique capabilities of near-infrared spectroscopy in the wavelength between 2um and 5um, allsky survey in the mid- and far-infrared as well as broadband filters consecutively covering the near-, mid- and far-infrared wavelengths. Using the point source catalog in the *AKARI* Mid-infrared All-Sky Survey, we are searching for Active Galactic Nuclei (AGNs), not only normal AGNs but also dusty AGNs, in the local Universe. *AKARI* provides remarkable improvement in sensitivity and spatial resolution upon the previous all-sky survey with IRAS. We are performing the follow-up observations of mid-infrared sources showing red-color in the near- and mid-infrared bands with the *AKARI* near-infrared spectroscopy and the ground-based optical spectroscopy. During the follow-up observations, we have started to detect hidden AGNs located in galaxies that were previously unrecognized to contain an AGN at other wavelengths.

Key words:

1. Introduction

Many observations imply the presence of a large number of heavily obscured active galactic nuclei (AGNs) in the local universe. It is found that a significant number of ultra luminous infrared galaxies (ULIRGs) contain AGNs in their centers (Sanders et al. 1996; Lutz et al. 1998; Imanishi et al 2008). Various hard X-ray and soft gamma-ray observations (Maiolino et al. 1998; Risaliti et al. 1999; Malizia et 2009) show that about 80 percent of the AGNs in the local Universe are obscured. AGN synthesis models of the X-ray background postulate their existence in order to explain the flat spectrum of the hard X-ray background (e.g. Ueda et al. 2003). They are potentially important contributors to the growth of super massive black holes in the history of the universe. These black holes also contribute to the local black hole mass density (Fabian et al. 1999) However, the nature of this population, even in the local universe, is only poorly understood, due to a strong selection bias at optical wavelengths.

Mid-infrared(MIR) searches for AGNs provide us with an ideal opportunity to overcome the obstacle by dust extinction and to identify most of the AGN population, including Type 2 and buried AGNs. The original IRAS 12μm active galaxy samples (Spinoglio et al. 1989; Rush et al. 1993) provide a unbiased sample of local active galaxies. Using the *ISOCAM parallel mode survey* of 10 square degrees at 6.7μm(LW2), Leipski et al. (2005,2007) succeeded in finding redder Type 1 AGNs as well as Type 2's. Several searches have also been performed using the near- and mid-infrared bands in the Spitzer Space Telescope (e.g. Lacy et al. 2004; Alonso-Herrero et al. 2006; Polletta et al. 2006). In this paper we search for buried AGNs in the new MIR all-sky survey data taken with *AKARI* (Murakami et al. 2007).

AKARI, the Japanese infrared satellite launched at February 2006, have a primary mirror of 70cm diameter cooled with the combination of liquid helium and mechanical coolers. It had unique capabilities of near-infrared spectroscopy in the wavelength between 2μm and 5μm, all-sky survey in the mid- and far-infrared as well as broadband filters consecutively covering the near-, mid- and far-infrared wavelengths (Murakami et al. 2007).

2. Search for AGN using *AKARI* Mid-Infrared All-Sky Survey

AKARI performed an all-sky survey at 9 and 18μm as well as at four far-infrared (FIR) bands (65, 90 140 and 160μm). It made improvements by about one order of magnitude compared to that of IRAS both in spatial resolutions and sensitivities at the mid-infrared bands. In the *AKARI* MIR All-Sky Survey catalogs, there are 870,972 point sources. The 5σ detection limits are 50 mJy and 90 mJy at 9 and 18μm, respectively. Ishihara et al. (2010) describe details of the *AKARI* MIR All-Sky Survey.

The initial identification of the *AKARI* MIR All-Sky Survey sources involves association with the Two Micron All Sky Survey (2MASS) catalog (Skrutskie et al. 2006). This search highlights *AKARI* MIR sources with $F(9\mu\mathrm{m})/\mathrm{F(Ks)} > 2$ as red sources in high galactic latitudes, $|b| > 30°$ after excluding those in the Large and Small Magellanic Clouds. The criterion $F(9\mu\mathrm{m})/\mathrm{F(Ks)} > 2$ excludes normal stars and quiescent galaxies from our sample as shown in Fig. 1. If we introduce a criterion $F(18\mu\mathrm{m})/\mathrm{F}(9\mu\mathrm{m}) > 1$, we will remove the contamination of very low-temperature stars. However, we do not use this criterion due to low sensitivity of 18μm. In order to examine the origin of the excess of $F(9\mu\mathrm{m})/\mathrm{F(Ks)} > 2$, we performed follow-up observations with the *AKARI* near-infrared(NIR) spectroscopy.

Using the *AKARI* NIR spectroscopy of the 2.5-5 μm wavelength range, AGNs can be distinguished by their red continuum emission, while strong Polycyclic Aromatic Hydrocarbons(PAH) emission and blue continuum characterize star-formation galaxies. In addition, we also collected the optical spectra from the Sloan Digital Sky Survey, NED and our observations with the 2.1m telescope in the Kitt Peak National Observatory and the 3m Shane telescope in the Lick Observatory in order to measure redshift and search optically for AGN or star-formation signatures.

Our *AKARI* NIR follow-up observations provide that 42 out of 80 MIR sources show the red continuum, which indicate the presence of AGN, 29 others show a strong PAH band that is a star-forming signature and 9 others are red stars. Our MIR sources sample spans a redshift range of 0.01-0.5 and the near infrared magnitude of 10.2-14.3 in the K_S-band.

3. Buried Active Galactic Nuclei

During these follow-up observations, we discovered two buried AGN candidates that have steep red NIR continuum from hot dust, but do not show any AGN features in optical spectra, such as strong high-ionization emission lines relative to Hα.

Table 1 summarizes the properties of our targets as well as the fluxes in the *AKARI* All-Sky MIR and FIR

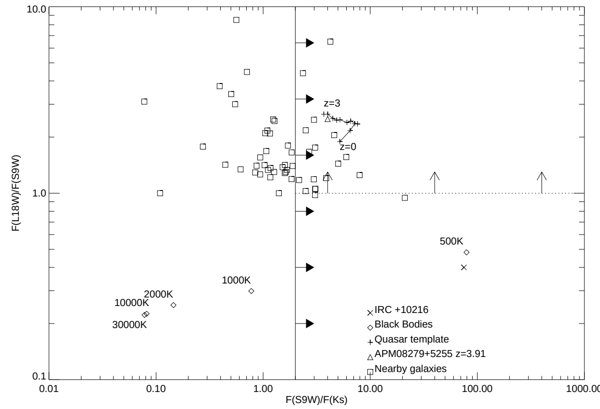

Fig. 1. The calculated F(S9W)/F(Ks) vs. F(L18W)/F(S9W). $\times$ represents a red C-rich star, IRC +10216. Diamonds shows the blackbodies with various temperatures. The + marks and lines indicate the track estimated with the quasar template (Elvis et al. 1994). The triangle shows the colors of a high-z quasar, APM 082789+5255, at z=3.91. Squares represent the colors that estimated from the ISO photometry of nearby galaxies (Dale et al. 2000).

Survey catalogs (Ishihara et al. 2010; Yamamura et al. 2009). LEDA 84274 is identified as the FIR source, IRAS 14416+6618. Previous optical spectroscopy of LEDA 84274 (Kim et al. 1995; Vielleux et al. 1995) reported that low-ionization spectrum with strong Balmer lines indicated an HII-region like or star-formation galaxy at z=0.0377 that is known to be photoionized by early-type stars. For IRAS 01250+2832, the *AKARI* accurate source position provided the identification with a galaxy at $z = 0.043$.

Figure 2 shows the *AKARI* NIR spectra. Both objects show steep red continuum. We find emission features of Polycyclic Aromatic Hydrocarbons(PAH) at 3.3μm and Brα at 4.05μm for LEDA 84274. For IRAS 01250+2832, the R-branch of CO ro-vibrational absorption is detected at 4.75μm.

The spectra of both LEDA 84274 and IRAS 01250+2832 are shown in Figure 3. We identify the strong emission lines in LEDA 84274 and IRAS 01250+2832. Based on these identifications, we determine the redshift of z=0.0377 for LEDA 84274, which is consistent with the redshift previously determined by Kim et al. (1995). Our measurements of the line ratios are consistent with previous ones in Kim et al. (1995). The spectrum of IRAS 01250+2832 shows a series of absorption lines in blue. We identify these absorption lines as CaII H+K, Hδ, CaI g-band, Hγ and Fe I as shown in Figure 3(b). Although Hα 6563Å and [N II] 6548,6583Å emission lines are detected, there are no other emission lines detected. Thus, we use absorption lines to estimate the redshift of $z = 0.043$. In order to examine the stellar population of the galaxies, we measured

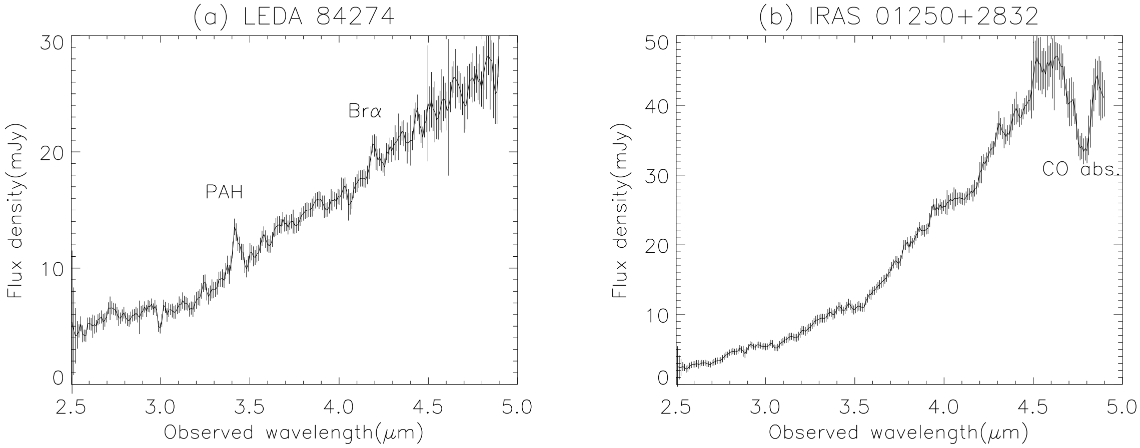

Fig. 2. *AKARI* NIR spectra of (a) LEDA 84274 and (b) IRAS 01250+2832 as a function of observed wavelength. Thin vertical lines represent 1σ error.

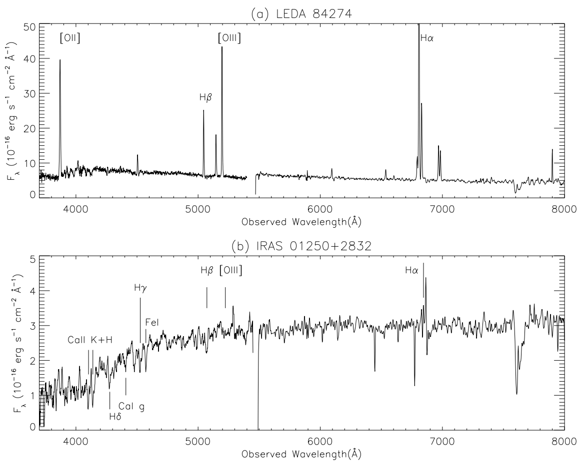

Fig. 3. Optical spectra of (a) LEDA 84274 and (b) IRAS 01250+2832. In (b), the positions of the Hβ4861Å and [O III] 5007Å lines are denoted.

$D_{\rm n}(4000)$ (Bruzual 1983; Balogh et al. 1999). Their resultant $D_{\rm n}(4000)$ indexes are 1.10 ± 0.02 and 1.63 ± 0.08 for LEDA 84274 and IRAS 01250+2832, respectively. Based on the indexes, LEDA 84274 has a spectrum of a late-type galaxy, and IRAS 01250+2832 is like an elliptical galaxy.

In Figure 4, the spectral energy distributions (SEDs) of LEDA 84274 and IRAS 01250+2832 are shown. An M82 template (Takagi et al. 2003) and an elliptical galaxy's template (Silva et al. 1998) are overplotted on the figures. In addition, we must add a single blackbody component with the temperature of 500K in order to explain the *AKARI* NIR spectrum. Fits of the hot dust with the temperature of 500K to the observed SEDs provide that the luminosities of this component are 2.8×10^{10} $L_\odot$ and 6.8×10^{10} $L_\odot$ for LEDA 84274 and IRAS 01250+2832, respectively. If we assume an optically thick spherical emitting region, the size of emitting regions is 1.0 pc and 1.6 pc in diameters for LEDA 84274 and IRAS 01250+2832, respectively. One possible situation is that an OB star cluster has huge luminosities of $L_{\rm IR} > 10^{10} L_\odot$ in such a compact volume that is as small as a cubic parsec, and it heats up the surrounding dust to 500K. However, the relaxation time of the dynamically bound system is calculated at $10^6 - 10^7$ years. Thus, this situation is expected to be very rare.

A likely possibility is a compact central engine that consists of a hot accretion disk surrounding a supermassive black hole. However, in both optical spectra there is no evidence that indicates AGN's existence in these galaxies. The various emission lines ratios of LEDA 84274 in the optical band show that it is an HII-like galaxy as Kim et al. (1995) showed. IRAS 01250+2832 shows no emission lines except for Hα and [NII] lines. The weak- and non-detection of PAH 3.3μm emission may support the idea of AGN existence. If PAH-free AGN emission contributes significantly to the observed 2.5-5μm spectra, the equivalent width of PAH 3.3 μm emission feature should decrease. The equivalent widths of the PAH 3.3 μm emission feature are 0.018 μm and < 0.003 μm for LEDA 84274 and IRAS 01250+2832, respectively. Observations of starbursts show equivalent widths of PAH 3.3 μm with an average value of 0.1μm, and they are never lower than 0.04μm(Moorwood 1986; Imanishi et al. 2008). Clearly the PAH equivalent width is heavily diluted by strong featureless NIR continuum.

The hot dust is likely to be associated with AGNs, but the possibility that the hot dust is heated by multiple dusty star clusters with massive stars can not be ruled out with our current data. If they are AGNs, their activities would be buried because present AGN activities are seen in only NIR and MIR, regardless of no

AGN clues in their optical spectra. If they have AGNs, the black hole masses of $\sim 8-20\times10^7$M$_\odot$ are estimated from the hot dust luminosity and the assumption of radiative efficiency of 0.1. The masses of host galaxy of $\sim 4-6\times10^9$M$_\odot$ are also estimated from the K_S−magnitude with $M_{\rm host}/L_{K_S}\sim 1$. The blackhole and host galaxy's masses indicate less massive population in optical selected AGNs (Kauffman et al. , 2003). These objects were eluded in previous surveys, demonstrating the power of *AKARI* MIR All-Sky Surveys to acquire a deeper understanding of the whole AGN populations (Oyabu et al. submitted to A&A).

References

Alonso-Herrero, A., et al. 2006, ApJ, 640, 167
Balogh, M., L., et al. 1999, ApJ, 527, 54
Bruzual, A., G. 1983, ApJ, 273, 105
Dale, H et al. 2000, AJ 120, 583
Elvis, M. et al. 1994, ApJS, 95, 1
Fabian, A. C., & Iwasawa, K. 1999, MNRAS, 303, L34
Imanishi, M., Nakagawa, T., Ohyama, Y., Shirahata, M., Wada, T., Onaka, T., & Oi, N. 2008, PASJ, 60, 489
Ishihara, D., et al. 2010, A&A, 514, A1
Kauffmann, G., et al. 2003, MNRAS, 346, 1055
Kim, D.-C., Sanders, D. B., Veilleux, S., Mazzarella, J. M., & Soifer, B. T. 1995, ApJS, 98, 129
Lacy, M., et al. 2004, ApJS, 154, 166
Leipski, C., et al. 2005, A&A, 440, L5
Leipski, C., et al. 2007, A&A, 464, 895
Lutz, D., Spoon, H. W. W., Rigopoulou, D., Moorwood, A. F. M., & Genzel, R. 1998, ApJL, 505, L103
Maiolino, R., Salvati, M., Bassani, L., Dadina, M., della Ceca, R., Matt, G., Risaliti, G., & Zamorani, G. 1998, A&A, 338, 781
Malizia, A., Stephen, J. B., Bassani, L., Bird, A. J., Panessa, F., & Ubertini, P. 2009, MNRAS, 399, 944
Moorwood A. F. M., 1986, A&A, 166, 4
Murakami, H., et al. 2007, PASJ, 59, 369
Polletta, M. d. C., et al. 2006, ApJ, 642, 673
Risaliti, G., Maiolino, R., & Salvati, M. 1999, ApJ, 522, 157
Rush, B., Malkan, M. A., & Spinoglio, L. 1993, ApJS, 89, 1
Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., & Scoville, N. Z. 1988, ApJ, 325, 74
Silva, L., Granato, G. L., Bressan, A., & Danese, L. 1998, ApJ, 509, 103
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Spinoglio, L., & Malkan, M. A. 1989, ApJ, 342, 83
Takagi, T., Vansevicius, V., & Arimoto, N. 2003, PASJ, 55, 385
Ueda, Y., Akiyama, M., Ohta, K., & Miyaji, T. 2003, ApJ, 598, 886

Table 1. Properties of LEDA 84274 and IRAS 01250+2832

Property	LEDA 84274	IRAS 01250+2832
R.A.(J2000)[a]	14 42 34.88	01 27 53.95
Dec.(J2000)[a]	+66 06 04.3	+28 47 51.0
Redshift	0.0377	0.043
J(mag)[b]	13.756 ± 0.054	14.774 ± 0.117
H(mag)[b]	13.293 ± 0.090	13.941 ± 0.131
Ks(mag)[b]	12.744 ± 0.083	13.462 ± 0.169
IRAS 12μm(Jy)[c]	0.10 ± 0.03 (2)	<0.11 (1)
IRAS 25μm(Jy)[c]	0.56 ± 0.03(3)	0.28 ± 0.05(2)
IRAS 60μm(Jy)[c]	2.19 ± 0.20(3)	0.52 ± 0.03(3)
IRAS 100μm(Jy)[c]	1.80 ± 0.14(2)	<0.76 (1)
AKARI 9μm(Jy)[d]	0.084 ± 0.007	0.105 ± 0.010
AKARI 18μm(Jy)[d]	0.344 ± 0.016	0.182 ± 0.017
AKARI 65μm(Jy)[e]	1.89 ± 0.22(1)	<3.2[h]
AKARI 90μm(Jy)[e]	1.51 ± 0.04(3)	<0.55[h]
AKARI 140μm(Jy)[e]	1.79 ± 0.26(1)	<3.8[h]
AKARI 160μm(Jy)[e]	<7.5[h]	<7.5[h]
$L_{\rm IR}$(L$_\odot$)[f]	1.8×10^{11}	1.0×10^{11}
$D_{\rm n}$(4000)[g]	1.10 ± 0.02	1.63 ± 0.08

[a] The 2MASS coordinates. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[b] The 2MASS magnitudes in All-Sky Extended Source Catalog

[c] The flux information comes from the IRAS Faint Source (Moshir et al. 1992). The number in parentheses indicates the flux qualities.

[d] *AKARI*/IRC Mid-infrared All-Sky Survey Point Source Catalog Ver. 1 (Ishihara et al. 2010).

[e] *AKARI*/FIS FIR All-Sky Survey Bright Source Catalog Ver. 1 (Yamamura et al. 2009). The number in parentheses indicates the flux qualities. (3) is a clear detection, and (1) is the flux in the position.

[f] The 8-1000 μm infrared luminosity $L_{\rm IR}=4\pi D_L^2F_{\rm IR}$ are computed using IRAS fluxes, $F_{\rm IR}=(1.8\times10^{-14})(13.56\times F_{12}+5.26\times F_{25}+2.54\times F_{60}+1.0\times F_{100})$ W m^{-2}(Kim et al. 1995). We used IRAS upper limits when IRAS did not detect it.

[g] $D_{\rm n}$(4000) is the discontinuity of the spectrum around 4000Å. See text for details.

[h] The detection limits in Yamamura et al. (2010) are estimated with the confirmed sources, the flux qualities of which is (3).

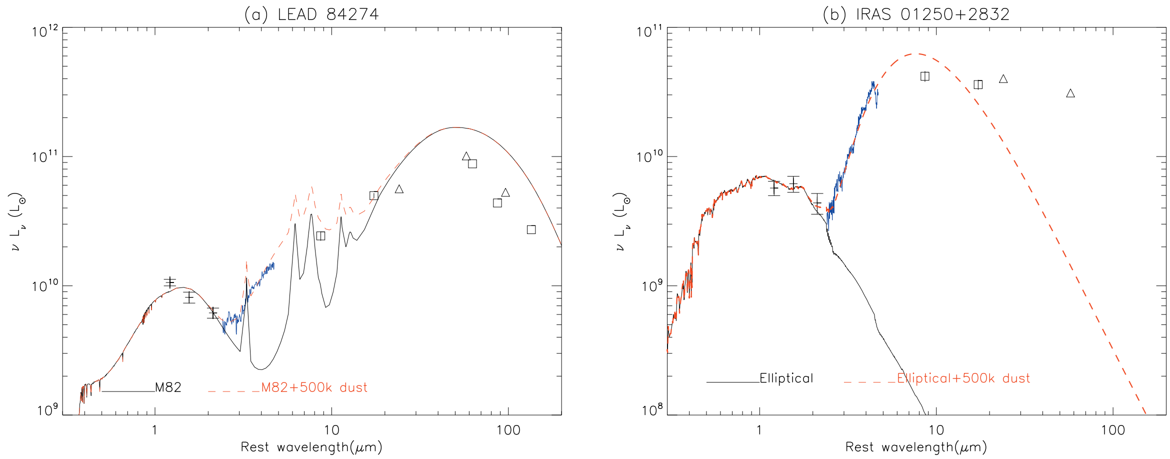

Fig. 4. The spectra energy distributions of (a) LEDA 84274 and (b) IRAS 01250+2832. The Blue line shows the *AKARI* NIR spectroscopy. Squares and triangles present the detections of *AKARI* All-Sky Survey and IRAS, respectively. Crosses show the 2MASS photometry. A solid line(black) and a dashed line(red) represent a model template and the model plus a blackbody component of hot dust with 500K, respectively. The adapted models are M82 (Takagi et al. 2003) and a elliptical galaxy (Silva et al. 1998) for LEDA 84274 and IRAS 01250+2832, respectively.

Veilleux, S., Kim, D.-C., Sanders, D. B., Mazzarella, J. M., & Soifer, B. T. 1995, ApJS, 98, 171

Yamamura et al. 2009, Astronomical Society of the Pacific Conference Series, 418, 3

Yamamure et al. 2010, AKARI/FIS All-Sky Survey Bright Source Catalogue Version 1.0 Release Note.