Discovery of Active Galactic Nuclei in Mid- and Far-Infrared Deep Surveys with ISO

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Abstract. We present a summary on the discovery of active galactic nuclei in mid- and far-infrared deep surveys with use of the Infrared Space Observatory.

1. Introduction

Active galactic nuclei (AGNs) such as quasars have been one of the important issues of modern astrophysics since the discovery of the quasar 3C 273 in 1963 (Schmidt 1963). Their central engines have been thought to be mass-accreting, supermassive single black holes around which gravitational energy is transformed into huge kinetic and radiation energy with the help of gaseous accretion disks (e.g., Rees 1984). Since AGNs are intrinsically bright in any frequency regime, various kinds of AGN surveys have been conducted by using radio through optical to X-ray telescope facilities (e.g., Peterson 1997).

Since current unified models for AGNs introduce a dusty torus around the central engine (see for reviews, Antonucci 1993; Urry & Padovani 1995), any infrared information is absolutely necessary to understand AGN phenomena because such dusty tori radiate anisotropic infrared emission (e.g., Pier & Krolik 1992; Clavel et al. 2000; Laurent et al. 2000; Murayama, Mouri, & Taniguchi 2000 and references therein). Another important issue related to infrared observations of AGNs seems to be possible starburst-AGN connections (Weedman 1983; Sanders et al. 1988; Heckman et al. 1989; Mouri & Taniguchi 1992, 2001; Cid Fernandes et al. 2001; Storchi-Bergmann et al. 2001). In particular, infrared emission properties are highly useful in investigating circumnuclear star formation and its relation to the nuclear activity in AGNs (e.g., Genzel et al. 1998; Tran et al. 2001).

Most Seyfert galaxies and a part of quasars were indeed detected at a wavelength range between 12 μm and 100 μm by the Infrared Astronomical Satellite, *IRAS*, launched in 1983 (see for a review, Soifer, Houck, & Neugebauer 1987). Although the *IRAS* all-sky survey covered over 96% of the sky, its completeness flux limit was 0.5 Jy at 12 μm, 25 μm, and 60 μm, and 1.5 Jy at 100 μm. Therefore, *IRAS* could probe infrared galaxies and AGNs up to redshift $\sim 0.2 - 0.3$ (e.g., Veilleux et al. 1999; Borne et al. 2000) except for some unusually bright (or gravitationally amplified) sources beyond redshift $z \sim 0.5$, e.g., IRAS F10214+4724 at $z = 2.28$ (Rowan-Robinson et al. 1991) and IRAS F15307+3252 at $z = 0.93$ (Cutri et al. 1994); see also Rowan-Robinson (2000).

More than 10 years after the launch of *IRAS*, the Infrared Space Observatory, *ISO*, was launched in 1994 (Kessler et al. 1996). The two infrared array detectors, ISOCAM (Cesarsky et al. 1996) and ISOPHOT (Lemke et al. 1996), were used to carry out mid-infrared (MIR) and far-infrared (FIR) deep surveys, respectively. In this paper, we will give a summary of the MIR and FIR deep surveys with *ISO* and then describe what kinds of AGNs are newly found in these surveys (see for a review, Genzel & Cesarsky 2000).

2.   MIR Deep Surveys with ISO

ISOCAM has two independent channels each containing a 32×32 pixel detector; 1) the short wavelength channel (2.5 μm to 5.5 μm) and the long wavelength one (4 μm to 18 μm) (Cesarsky et al. 1996). Since the short wavelengths can be accessible from ground-based telescope facilities, the long wavelength camera was used to carry out MIR deep surveys; i) at 7 μm (Taniguchi et al. 1997; Sato et al. 1999, 2001; Rowan-Robinson et al. 1997; Aussel et al. 1999; Oliver et al. 2000; Lémonon et al. 1998; Altieri et al. 1999; Fadda et al. 2000), ii) at 12 μm (Clements et al. 1999), and iii) 15 μm (Rowan-Robinson et al. 1997; Aussel et al. 1999; Oliver et al. 2000; Lémonon et al. 1998; Altieri et al. 1999; Fadda et al. 2000). A summary of these surveys is given in Table 1; note that the 12 μm survey by Clements et al. (1999) is not included in this table.

Among the MIR imaging surveys tabulated, follow-up spectroscopy has been done for five surveys given in Table 2. Eleven AGNs (4 type 1 and 7 type 2 AGNs) were found among 78 sources in the CFRS-ISOCAM survey (Flores et al. 1999). However, only a few AGN were found in the remaining four surveys (Aussel et al. 1999; Taniguchi et al. 1997; Taniguchi 1999, 2000; Altieri et al. 1999; Fadda et al. 2000). In total, only 14 AGNs (7 type 1s and 7 type 2s) were found among 217 sources in the five surveys. This gives an AGN fraction, $f_{AGN} = N_{AGN}/N_{gal} \approx 7\%$. In Figure 1, we show an optical spectrum of a quasar at $z = 1.025$ found by Taniguchi et al. (1997) as an example.

Although the number of AGNs found in the MIR surveys with *ISO* is not so large, it seems interesting to compare the above observational result with some model predictions. Oliver et al. (1997) estimated expected numbers of AGNs for their MIR survey of the HDF (see also Rowan-Robinson et al. 1997; Aussel et al. 1999), adopting the following two models; 1) PRR models (Pearson & Rowan-Robinson 1996), and 2) AF models (Franceschini et al. 1994); in this article, we do not give the details of the PRR or AF models.

a) AGNs expected in the 7 μm survey: In the case of the PRR models, the expected number of AGNs in the ISO/HDF field is 1.26 (0.66 type 1 and 0.6 type 2 AGNs) if the 7 μm limiting flux is 38.6 μJy and the AGN fraction is $f_{AGN} \approx 22\%$. On the other hand, in the case of the AF models, they are 0.34 and 9%, respectively.

b) AGNs expected in the 15 μm survey: In the case of the PRR models, the expected number of AGNs in the ISO/HDF field is 1.51 (0.73 type 1 and 0.78 type 2 AGNs) if the 15 μm limiting flux is 255 μJy and the AGN fraction is $f_{AGN} \approx 21\%$. On the other hand, in the case of the AF models, they are 0.25 and 3.6%, respectively.

Table 1.   A Summary of the MIR Surveys with ISO

Field[a]	Area[b] (arcmin^2)	$F_{\lim}(7\mu m)$[c] (μJy)	$N(7\mu m)$[d]	$F_{\lim}(15\mu m)$[e] (μJy)	$N(15\mu m)$[f]
HDF-N[1]	5/9	65	7	200	45
LHNW[2]	9/—	32	27	—	—
SSA 13[3]	16/—	6	65	—	—
CFRS[4]	—/100	—	—	250	78
ELAIS[5]	11.7/22.8[g]	1000	~ 700	2000	~ 800
A2390C[6]	5.76/5.76	65	4	65	4
A2390[7]	6.76/6.76	25	31	40	34
A1689[8]	36/36	150	41	300	18

[a]HDF-N = Hubble Deep Field-North, LHNW = the NW field in the Lockman Hole, SSA 13 = Hawaii Small Selected Area No. 13, CFRS = Canada-France Redshift Survey Field, ELAIS = European Large Area ISO Survey field, A2390C = the central region of Abell 2390, A2390 = Abell 2390, & A1689 = Abell 1689. Their references are; 1. Aussel et al. 1999, 2. Taniguchi et al. 1997, 3. Sato et al. 1999, 2001, 4. Flores et al. 1999, 5. Oliver et al. 2000, & Serjeant et al. 2000, 6. Lémonon et al. 1998, 7. Altieri et al. 1999, & Fadda et al. 2000.
[b]Sky coverage. The first and second numbers means the sky coverage at 7μm and 15 μm, respectively.
[c]The 3 σ_{rms} flux limit at 7 μm in the survey.
[d]The number of objects detected at 7 μm in the survey.
[e]The 3 σ_{rms} flux limit at 15 μm in the survey.
[f]The number of objects detected at 15 μm in the survey.
[g]Note that the area for ELAIS is given in units of square degree.

Table 2.   AGNs Found in the MIR Surveys with ISO

Field[a]	N_{gal}[b]	N_{AGN}[c]	f_{AGN}[d] (%)	N_{Type1}[e]	N_{Type2}[f]
HDF-N	49	1	2	1	0
LHNW	13	1	8	1	0
CFRS	78	11	14	4	7
A2390	32	0	0	0	0
A1689	45	1	2	1	0
Total	217	14	7	7	7

[a]The same as those in Table 1.
[b]The number of galaxies detected in the survey.
[c]The number of AGNs detected in the survey.
[d]The fraction of AGNs = N_{AGN}/N_{gal}.
[e]The number of Type 1 AGNs detected in the survey.
[f]The number of Type 2 AGNs detected in the survey.

It seems difficult to draw any firm conclusions from the above comparisons between the observations and models because of small-number statistics, although we do not see significant inconsistency between them. Future MIR surveys will give us firmer answers.

Among the *ISO* MIR deep surveys, it has been found that there are a number of MIR (either 7 μm or 15 μm) sources without optical/NIR counterparts (Taniguchi et al. 1997; Aussel et al. 1999; Flores et al. 1999). These results are summarized in Table 3. It is shown that $\approx 18\%$ of the MIR sources found in the three MIR surveys have no optical/NIR counterparts and $\approx 10\%$ of them above 5σ detection have no counterparts.

We cannot exclude the possibility that some of such sources may be attributed to unexpected noise. However, if a starburst galaxy with a mass of $10^{11} M_\odot$ at $z \sim 3$ is heavily reddened (e.g., $A_V \sim 10$), this galaxy could be detected in the MIR but not at 2 μm (Taniguchi 2000). Recent submillimeter deep surveys have been finding such dust-enshrouded high-z galaxies (Hughes et al 1998; Barger et al. 1998; Smail et al. 1999). Therefore, we also cannot exclude the possibility that deep NIR surveys may miss a certain part of reddened populations, causing an underestimate of either star formation density or nonthermal energy density or both in the universe. It seems important to keep in mind the presence of such MIR sources without counterparts in future investigations.

Table 3.   MIR sources without optical/NIR counterparts

Field[a]	S/N	$N_{\rm gal}$[b]	$N_{\rm no}$[c]	$f_{\rm no}$[d] (%)
HDF-N	$> 5\sigma$	49	7	14
	$> 4\sigma$	51	16	31
LHNW	$> 5\sigma$	13	2	15
CFRS	$> 4\sigma$	40	4	10
	$> 3\sigma$	34	4	15
Total			187 34	18

[a]The same as those in Table 1.
[b]The number of galaxies detected in the survey.
[c]The number of galaxies without optical/NIR counterparts.
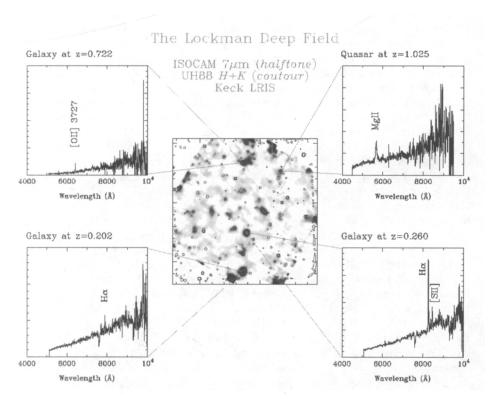[d]The fraction of no-counterparts = $N_{\rm no}/N_{\rm gal}$.

Figure 1. Optical spectra of four 7 μm sources found in the MIR deep survey by Taniguchi et al. (1997). The spectroscopic observations were made with LRIS on the W. M. Keck 1 telescope (Cowie et al. in preparation). One quasar at $z = 1.025$ was found in their survey (see also Taniguchi 1999). The middle panel shows the 7 μm image of the LHNW field (halftone; darker is brighter). The contours show the NIR (HK) image taken with the University of Hawaii 2.2 m telescope. Although the seeing size in the NIR image is good (FWHM$\simeq$0.8 arcsec), the image is blurred in order to make the comparison between the 7 μm and NIR images easier.

3. FIR Deep Surveys with ISO

ISOPHOT is an imaging photopolarimeter covering a wavelength range between 2.5 μm and 240 μm (Lemke et al. 1996). Among the several detectors, two detectors, C100 and C200, were used to carry out FIR deep surveys; i) FIRINDIV-DEEP&DEEP[1] (Kawara et al. 1998; Matsuhara et al. 2000), ii) FIRBACK-ELAIS; the 90 μm survey (Efstathiou et al. 2000; Serjeant et al. 2001), and the 170 μm survey (Puget et al. 1999; Lagache & Dole 2001; Dole et al. 2001). A summary of these survey is given in Table 4; note that we do not include another ISOPHOT survey at 60μm and 90 μm by Linden-Vornle et al. (2000) because no follow-up observation is available.

Although optical follow-up spectroscopy has not yet been completed for the two surveys, some preliminary results were reported recently. Serjeant et al. (2001) made optical spectroscopy for 20 sources detected in the FIRBACK-ELAIS survey with $f(90\mu m) > 100$ mJy, which are also detected either at 15 μm or at 1.4 GHz. Among them, they found two Seyfert galaxies at $z = 0.149$ and $z = 0.225$; the remaining 18 sources are either starbursts (16 sources) or early-type galaxies (2 sources). This gives an AGN fraction, $f_{AGN} = 2/20 = 10\%$. On the other hand, Kakazu et al. (2001a, 2001b; see also Murayama et al. 2001) made optical identification of 35 sources found in the FIRINDIV-DEEP&DEEP survey with $f(170\mu m) > 100$ mJy, using the W. M. Keck, Subaru, UH88, and VLA facilities. They identified two AGNs: a Seyfert 1.5 galaxy at $z = 0.206$ and a quasar at $z = 1.60$. The remaining 33 sources are classified as starbursts (21 sources), LINERs (10 sources), and early-type galaxies (2 sources). Since infrared-selected LINERs may be shock-heated galaxies (Taniguchi et al. 1999; Lutz, Veilleux, & Genzel 1999; cf. Imanishi, Dudley, & Maloney 2001), they are not genuine AGNs but starburst-related (i.e., superwind) galaxies. Therefore, their survey gives an AGN fraction, $f_{AGN} = 2/36 \approx 6\%$.

The above AGN fractions are considered to be tentative values because the number of observed galaxies are still small. We hope that future follow-up observations will give us firmer statistics. It seems worthwhile noting that Franceschini et al. (1989) estimated an AGN fraction in such FIR deep surveys; i.e., $f_{AGN} \sim 10\%$, being similar to the observed values.

Finally, we mention that 10 ultraluminous infrared galaxies (ULIGs) and 1 hyperluminous infrared galaxy (HyLIG) were identified as counterparts of 170 μm sources found in Kawara et al.'s (1998) survey (Kakazu et al. 2001a, 2001b; Murayama et al. 2001). Although the HyLIG[2] is a quasar at $z = 1.6$, the ULIGs are located at $z \simeq 0.3 - 0.8$. Such intermediate-z ULIGs had not yet been found by *IRAS*. It is also remarkable that the observed surface density of ULIGs is $\simeq 10$ degree^{-2}. Note that only ~ 120 ULIGs with $z < 0.3$ were found by *IRAS*

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[1] In contrast to the FIRBACK-ELAIS program (acronym for Far Infrared Background), in this article, we call the Japanese-IfA/UH program FIRINDIV-DEEP&DEEP where INDIV means individual sources found in the FIR survey and DEEP&DEEP means a *deep* survey for *dust-enshrouded extragalactic populations (deep)*. Please make sure to note that DEEP&DEEP is different from the famous DEEP (Deep Extragalactic Evolutionary Probe) survey program promoted by David Koo at UCO/Lick Observatory, University of California (http://www.ucolick.org/ deep/home.html).

[2] See for discovery of a HyLIG in the ELAIS survey, Morel et al. (2001).

(Veilleux et al. 1999; Borne et al. 2000; see for a review Sanders & Mirabel 1996), giving a surface density of ~ 0.003 degree^{-2}. Therefore, it is suggested that the surface density of intermediate-z ULIGs is much higher by a factor of 3000 than that of low-z ULIGs. Since it has been often argued that ULIGs may be precursors of quasars (Sanders et al. 1988; Sanders & Mirabel 1996; Taniguchi, Ikeuchi, & Shioya 1999), it is interesting to investigate the nature of intermediate-z ULIGs found in the *ISO* FIR deep surveys. Future wide-field FIR deep surveys and their follow-up observations will be also very important to find new populations of intermediate-z and high-z ULIGs and HyLIGs.

Table 4.   A Summary of the FIR Surveys with ISO

Program	Field[a]	$F_{\lim}(90\mu m)$[b] (mJy)	$N(90\mu m)$[c]	$F_{\lim}(170\mu m)$[d] (mJy)	$N(170\mu m)$[e]
FIRINDIV-DEEP&DEEP	LH 1.1 deg^2/ 1.1 deg^2	45	36	45	45
FIRBACK-ELAIS	Several 11.6 deg^2/ 3.89 deg^2	100(?)	120(?)	135	106

[a]LH = Lockman H$\textsc{i}$ Hole. As for the FIRBACK survey fields, see http://wwwfirback.ias.u-psud.fr. The first sky coverage is for the 90 μm survey and the second one is for the 170 μm one.

[b]$3\sigma_{\rm rms}$.

[c]The number of galaxies detected in the survey. The galaxies detected in FIRINDIV have $F(90\mu m) > 150$ mJy.

[d]$3\sigma_{\rm rms}$.

[e]The number of galaxies detected in the survey. The numbers given in this column are that of galaxies with $F(170\mu m) > 150$ mJy for FIRINDIV and that of galaxies with $F(170\mu m) > 180$ mJy for FIRBACK.

4.   Discussion and Summary

As summarized in this article, *ISO* enabled us to perform a number of MIR and FIR deep surveys (see also Genzel & Cesarsky 2000). We give a summary of the main points of this article below.

1) As for the MIR surveys, the *ISO* deep surveys at 7 μm and 15 μm are sensitive enough to detect sources down to 10 μJy (Taniguchi et al. 1997; Aussel et al. 1999; Sato et al. 2001b). Approximately, 10% of the detected sources appear to be AGNs, from low-z Seyfert galaxies to a high-z quasar at z 1 – 2 (Taniguchi 1999; Aussel 1999; Flores et al. 1999). Since the sky areas observed by the surveys are so small, it seems hard to make statistical arguments about AGN populations. However, the number counts of the

MIR sources show significantly stronger evolution than what is expected from no-evolution models (e.g., Elbaz et al. 1999). This may be attributed mainly to intense star formation in galaxies at intermediate- and/or high-z galaxies (e.g., Takeuchi et al. 2000; Chary & Elbaz 2001). Since dusty starburst galaxies sometimes harbor hidden AGNs (e.g., Sanders et al. 1988; Ivison et al. 2000; Willott et al. 2001), future follow-up observations will be important to understand what faint MIR sources are.

2) The *ISO* FIR deep surveys have also shown that approximately, 10% of the detected sources appear to be AGNs (Serjeant et al. 2001; Kakazu et al. 2001a, 2001b; Murayama et al. 2001). Although the total sky area surveyed by the FIR surveys exceeds 10 deg^2, optical follow-up observations have not yet been fully done. Therefore, future follow-up observations will be important to understand the nature of faint FIR sources. The most remarkable finding of the *ISO* FIR deep surveys is the discovery of numerous ULIGs at intermediate redshift between $z \simeq 0.3$ and $z \simeq 0.8$ (Kakazu et al. 2001a), because such populations had not yet been known from the *IRAS* survey. It seems quite likely that these populations contribute to the observed excess number count in the FIR (e.g., Elbaz et al. 1999; Takeuchi et al. 2000).

3) The exciting results above urge us to conduct new MIR and FIR surveys. Indeed, new space infrared telescope facilities will be launched soon; SIRTF[3] and IRIS (ASTRO-F[4]). We hope that these facilities will give us much more information on AGN populations in the infrared universe.

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[3]http://sirtf.caltech.edu

[4]http://www.ir.isas.ac.jp/ASTRO-F/index-j.html

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