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Luminous buried AGNs in the local universe and the origin of galaxy downsizing

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Abstract. We present the results of our systematic infrared spectroscopy of ultraluminous infrared galaxies (ULIRGs). We detected signatures of optically-elusive, but intrinsically luminous, buried AGNs in a significant fraction of optically non-Seyfert ULIRGs. The buried AGN fraction increases with increasing infrared luminosities of galaxies, supporting the AGN feedback scenario as the origin of galaxy downsizing phenomena.

Key words. Galaxies: active – Galaxies: nuclei – Infrared: general

1. Introduction

Ultraluminous infrared galaxies (ULIRGs) radiate the bulk of their large luminosities (>$10^{12}L_{\odot}$) as infrared dust emission (Sanders & Mirabel 1996). This means that very luminous energy sources are present, but hidden behind dust. The energy source can be nuclear fusion inside rapidly formed stars (starburst) and/or active mass accretion onto a central supermassive black hole (AGN). Distinguishing the hidden energy sources of ULIRGs is indispensable not only to understand the true nature of the ULIRG population, but also to unveil the history of star-formation and supermassive black hole growth in the dust-obscured side of the universe.

If a luminous AGN is present hidden behind *torus*-shaped dust, the so-called narrow lines regions (NLRs), photo-ionized by AGN's radiation, should develop along the torus axis, above a torus scale height, and NLRs are visible from all directions. Such an AGN obscured by torus-shaped dust is classified optically as a "Seyfert 2" and so AGN signatures are easily detectable through optical spectroscopy. However, since the nuclear regions of ULIRGs are very dusty (Sanders & Mirabel 1996), AGNs resident in the majority of ULIRGs may be obscured by dust along *all sightlines*. It is fundamental to understand such optically elusive *buried* AGNs in ULIRG's nuclei.

Infrared 3–35 μm spectroscopy is an effective means to study buried AGNs, because dust extinction is small (<$0.05A_V$). More importantly, normal starburst and AGN emission are clearly distinguishable using infrared 3–35 μm spectra. First, in a normal starburst galaxy, large equivalent width polycyclic aromatic hydrocarbon (PAH) emission features are observed, regardless of dust extinction of the starburst, while a pure AGN emits a PAH-free continuum (Imanishi & Dudley 2000). Next, in a normal starburst, where the stellar energy sources and dust are spatially well mixed (Figure 1, left), there is an upper limit for

Send offprint requests to: M. Imanishi the optical depths of dust absorption features, while they can be arbitrarily large in a buried AGN, where the energy source is more centrally concentrated than the surrounding dust (Figure 1, right) (Imanishi & Maloney 2003).

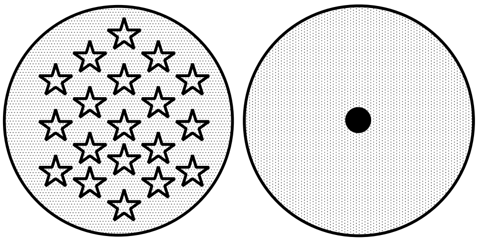

Fig. 1. Geometry of energy sources and dust. (*Left*): Normal starburst. Stellar energy sources (open stars) and dust are spatially well mixed. (*Right*): Buried AGN. The energy source (= a mass accreting supermassive black hole; filled circle) is spatially very compact and is more centrally concentrated than the surrounding dust.

In this manuscript, we present the results of ground-based Subaru IRCS infrared 3–4 μm spectroscopy, space-based Spitzer IRS 5–35 μm spectroscopy, and space-based AKARI IRC 2.5–5 μm spectroscopy of ULIRGs classified optically as non-Seyferts (i.e., LINERs and HII-regions), selected from the IRAS 1 Jy sample (Kim & Sanders 1998).

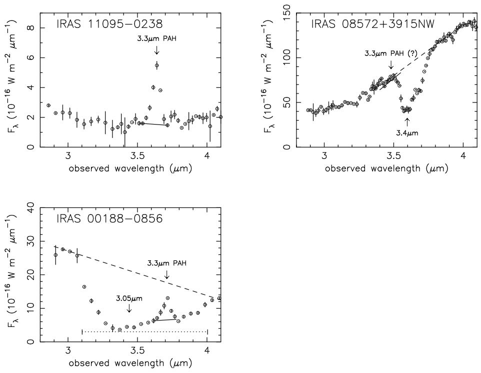

Fig. 2. Ground-based infrared 3–4 μm spectra of representative ULIRGs, obtained with Subaru IRCS (Imanishi et al. 2006). *Upper left :* Starburst-dominated ULIRG. 3.3 μm PAH emission is strong. *Upper right :* ULIRG dominated by a buried AGN. No 3.3 μm PAH emission and strong 3.4 μm bare carbonaceous dust absorption feature are detected. *Lower :* ULIRG with starburst and buried AGN composite. PAH emission is seen, but its equivalent width is low. The solid and dashed lines are the adopted continuum levels to measure the strengths of 3.3 μm PAH emission and dust absorption features, respectively. Broad 3.1 μm ice-covered dust absorption feature is detected in the range of dotted line inserted with two vertical lines.

2. Results and discussion

Figures 2 and 3 present Subaru infrared 3–4 μm and Spitzer 5–35 μm spectra of representative ULIRGs at $z < 0.15$.

2.1. Detected weakly-obscured starbursts

PAH emission, the probe of starbursts, is detected in almost all of the observed ULIRGs. It is likely that modestly-obscured ($A_V < 15$ mag) starbursts are responsible for the detected PAH emission. The observed PAH to infrared luminosity ratios are substantially smaller than those found in known starburst galaxies, suggesting that the detected modestly-obscured starbursts are energetically insignificant. The bulk of the ULIRG's infrared luminosities should come from non-PAH emitting AGNs and/or highly obscured ($A_V >> 15$ mag) starbursts. These two scenarios could be distinguished based on the equivalent widths of emission and absorption features in infrared spectra.

2.2. Luminous buried AGNs

Based on low PAH equivalent widths and strong dust absorption features (see §1), buried AGN signatures were found in roughly half of the observed ULIRGs at $z < 0.15$. The detected buried AGN fraction is substantially higher in optically LINER ULIRGs than HII-region ULIRGs.

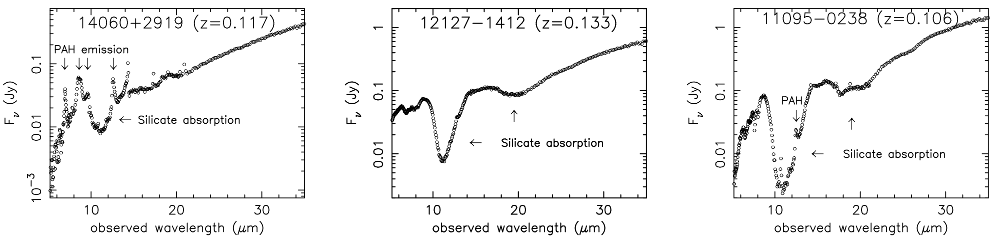

Fig. 3. Infrared 5–35 μm low-resolution (R < 100) spectra of ULIRGs obtained with Spitzer IRS (Imanishi et al. 2007). *Left :* Starburst-dominated ULIRG. PAH emission is strong. *Middle :* ULIRG dominated by a buried AGN. No PAH emission and strong silicate dust absorption are detected. The optical depth of the 9.7 μm silicate dust absorption feature exceeds the maximum value achieved by the mixed dust/source geometry (Fig.1, left). *Right :* ULIRG with starburst and buried AGN composite. PAH emission is seen, but its equivalent width is low. The silicate dust absorption feature is strong.

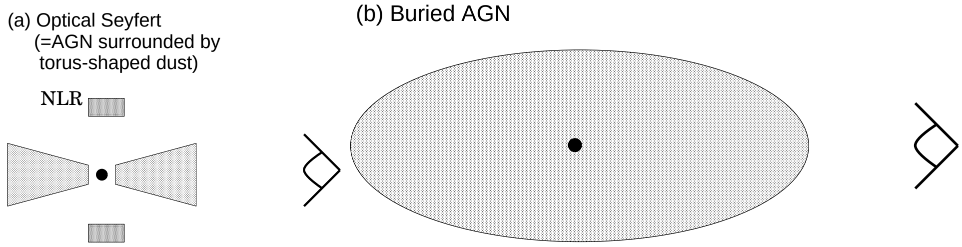

Fig. 4. Schematic diagram of nuclear dust distribution. *(a):* An AGN classified optically as a Seyfert. As the dust has angular momentum, dust distribution is axisymmetrical. When the total amount of nuclear dust is modest, dust along the direction of the lowest dust column density can be transparent to the AGN's ionizing radiation, producing the so-called narrow line regions (NLRs). *(b):* A buried AGN classified optically as a non-Seyfert. Since the total amount of nuclear dust is larger than that of a Seyfert-type AGN, even the direction of the lowest dust column density can be opaque to the AGN's radiation.

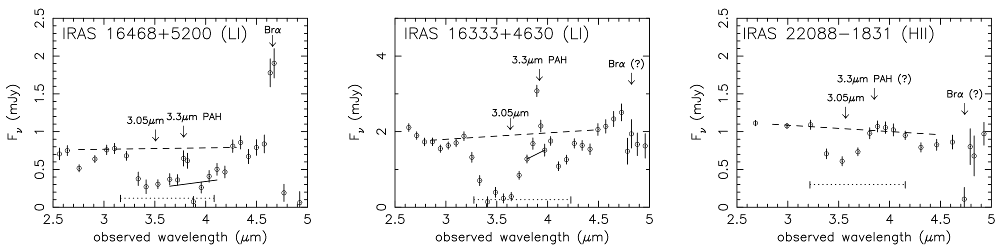

Fig. 5. Examples of AKARI 2.5–5 μm spectra of ULIRGs with $L_{IR} > 10^{12.3}L_\odot$ at $z > 0.15$ (Imanishi et al. 2008). All sources show signatures of luminous buried AGNs. Symbols are the same as Figure 2.

2.3. Our line-of-sight dust column

The optical depths of dust absorption features are generally larger in buried AGNs in optically non-Seyfert ULIRGs than in ULIRGs classified optically as Seyfert 2s (= obscured by torus-shaped dust). These results suggest that dust obscuration along our line-of-sight is larger in buried AGNs. Since dust covering factor is also larger in buried AGNs (= obscured by dust in virtually all directions) than Seyfert-type AGNs surrounded by torus shaped dust, we can safely conclude that the total amount of nuclear dust is substantially larger in buried AGNs in optically non-Seyfert ULIRGs than Seyfert AGNs surrounded by torus-shaped dust (Figure 4).

2.4. Buried AGNs in cool ULIRGs

Evidence for buried AGNs is found in non-Seyfert ULIRGs with both warm (IRAS 25 μm to 60 μm flux ratio >0.2) and cool (< 0.2) far-infrared colors. Although Seyfert AGNs usually display warm far-infrared colors, the cooler far-infrared colors of buried AGNs are naturally explained by a larger amount of nuclear dust, where contribution from outer, cooler dust component to infrared radiation becomes more important.

2.5. Buried AGNs as a function of infrared luminosity

Our energy diagnostic method based on ground-based Subaru observations was restricted to ULIRGs at $z < 0.15$, because above this redshift, parts of spectral features fall outside the Earth's atmospheric window. For this reason, our complementary Spitzer study was also focused to ULIRGs at $z < 0.15$.

Thanks to the AKARI's spectroscopic capability at 2.5–5 μm, unaffected by Earth's atmosphere, we extended our method to more distant ULIRGs at $z > 0.15$. By extending the redshift range, many ULIRGs with higher infrared luminosities ($L_{IR} > 10^{12.3} L_{\odot}$) are included. We have found that the detected buried AGN fraction increases with increasing infrared luminosities of galaxies. In fact, AKARI infrared spectra of the bulk of highly-infrared-luminous ULIRGs at $z > 0.15$ are buried AGN type (Figure 5). Recently, the so-called galaxy downsizing phenomena have been found, where galaxies with currently larger stellar mass have finished their major star-formation in earlier cosmic age. AGN feedbacks are proposed to be responsible for the galaxy downsizing phenomena. Namely, in more massive galaxies, AGN feedbacks have been stronger in the past, and gas has been expelled in a shorter time scale. Buried AGNs can have particularly strong feedbacks, because the AGNs are surrounded by a large amount of nuclear gas and dust. If we reasonably assume that galaxies with currently larger stellar mass have previously been more infrared luminous, then the higher buried AGN fraction in more infrared luminous galaxies may support the AGN feedback scenario as the origin of the galaxy downsizing phenomena.

3. Conclusions

Our infrared spectroscopy reveals the presence of optically elusive *buried* AGNs in many optically non-Seyfert ULIRGs. The detected buried AGN fraction increases with increasing infrared luminosities of galaxies, which may support the AGN feedback scenario as the origin of the galaxy downsizing phenomena.

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