SPIRITZER INFRARED LOW-RESOLUTION SPECTROSCOPIC STUDY OF BURIED ACTIVE GALACTIC NUCLEI IN A COMPLETE SAMPLE OF NEARBY ULTRALUMINOUS INFRARED GALAXIES

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ABSTRACT
We present the results of Spitzer Infrared Spectrograph low-resolution infrared 5–35 μm spectroscopy of 17 nearby ultraluminous infrared galaxies (ULIRGs) at z < 0.2, optically classified as non-Seyferts. The presence of optically elusive, but intrinsically luminous, buried active galactic nuclei (AGNs) is investigated, based on the strengths of polycyclic aromatic hydrocarbon emission and silicate dust absorption features detected in the spectra. The signatures of luminous buried AGNs, whose intrinsic luminosities range up to ~10^{12} L_⊙, are found in eight sources. We combine these results with those of our previous research to investigate the energy function of buried AGNs in a complete sample of optically non-Seyfert ULIRGs in the local universe at z < 0.3 (85 sources). We confirm a trend that we previously discovered: that buried AGNs are more common in galaxies with higher infrared luminosities. Because optical Seyferts also show a similar trend, we argue more generally that the energetic importance of AGNs is intrinsically higher in more luminous galaxies, suggesting that the AGN–starburst connections are luminosity dependent. This may be related to the stronger AGN feedback scenario in currently more massive galaxy systems, as a possible origin of the galaxy downsizing phenomenon.

Key words: galaxies: active – galaxies: ISM – galaxies: nuclei – galaxies: Seyfert – galaxies: starburst – infrared: galaxies

1. INTRODUCTION

Ultraluminous infrared galaxies (ULIRGs) are characterized by a spectral energy distribution dominated by infrared emission, and an absolute infrared luminosity with L_IR > 10^{12} L_⊙ (Sanders et al. 1988a; Sanders & Mirabel 1996). This means that in ULIRGs, (1) very luminous energy sources with L > 10^{12} L_⊙ are present, (2) the energy sources are hidden by dust, which absorbs most of the primary radiation, and (3) the heated dust grains then radiate this energy as infrared dust emission. The dust-obscured energy sources are nuclear fusion occurring inside rapidly formed stars (starbursts) and/or the release of gravitational energy generated by spatially compact, mass-accreting, supermassive black holes (SMBHs; i.e., AGN activity). Because the ULIRG population becomes very important at z > 1, in terms of cosmic infrared radiation density (Caputi et al. 2007), understanding the hidden energy sources of ULIRGs is closely coupled with clarifying the connection between star formation and SMBH growth in the dust-obscured galaxy population of the early universe. Because distant ULIRGs are generally faint, detailed studies of nearby (z < 0.3) ULIRGs continue to play an important role in understanding the nature of the ULIRG population of the universe.

Nearby ULIRGs have two important observational properties. First, the fraction of optical Seyferts (optically identified AGNs) is known to be substantially greater in ULIRGs, compared with galaxies with lower infrared luminosities (L_IR < 10^{12} L_⊙) (Veilleux et al. 1999; Goto 2005). Second, although galaxies with L_IR < 10^{12} L_⊙ generally exhibit strong, spatially extended infrared emission originating from stars distributed inside them, the infrared dust emission of nearby ULIRGs is dominated by a spatially compact feature (Soifer et al. 2000, 2001), suggesting that a large amount of dust is concentrated in the nuclear regions of ULIRGs, and heated by spatially compact energy sources.

Because the nuclear dust concentration increases in ULIRGs (Sanders & Mirabel 1996; Soifer et al. 2000), the putative AGNs in ULIRG’s cores are surrounded by a large amount of gas and dust, and ionizing UV radiation from the AGN can be blocked at the inner part (<10 pc) in virtually all lines of sight (Hopkins et al. 2005; Imanishi et al. 2006, 2007). Such buried AGNs lack well-developed narrow-line regions (NLRs) at 10–1000 pc scale, the primary sources of forbidden emission lines, and so are elusive through the conventional optical and infrared spectroscopic classification, looking for high-excitation forbidden emission lines from the NLRs (Veilleux & Osterbrock 1987; Kewley et al. 2006; Armus et al. 2007; Farrah et al. 2007). Low-resolution infrared 2.5–35 μm spectroscopy is an effective tool for studying such elusive (Maiolino et al. 2003) buried AGNs for the following reasons. First, the effects of dust extinction are sufficiently small (<0.06 A_V; Nishiyama et al. 2008; 2009) that buried AGNs are detectable. Second, in a normal starburst with moderate metallicity (>0.3 solar), consisting of UV-emitting H II regions, molecular gas and dust, and photodissociation regions (PDRs), the polycyclic aromatic hydrocarbons (PAHs) in the PDRs are excited by far-UV photons from stars without being destroyed, so strong PAH emission is usually detected (Sellgren 1981; Wu et al. 2006). However, PAHs in close proximity to an AGN are destroyed by the high-energy X-ray radiation of the AGN (Voit 1992), so that PAH emission is virtually absent from a pure AGN, as demonstrated from observations (Moordwood 1986; Roche et al. 1991; Gniezal et al. 1998; Imanishi & Dudley 2000). In a galaxy hosting an AGN, strong PAH emission can be observed, if PAHs survive in the regions shielded from the high-energy radiation of the AGN, and PAH-exciting far-UV photons from local energy sources (i.e., stars) are available there. Finally, in a normal starburst, stellar energy sources and gas/dust are spatially well mixed (Puxley 1991; McLeod et al. 1993; Forster
Schreiber et al. 2001), so that the absolute optical depths of dust absorption features in the infrared spectra cannot exceed certain thresholds, whereas the optical depths can be arbitrarily large in a buried AGN, because the energy source (a compact mass-accreting SMBH) is more centrally concentrated than dust/gas (Imanishi & Maloney 2003; Imanishi et al. 2006, 2007). Thus, in principle, starbursts and buried AGNs are distinguishable on the basis of the strengths of PAH emission and dust absorption features in the infrared spectra.

From the low-resolution infrared 2.5–35 μm spectra of a large number of nearby ULIRGs, obtained with ISO, Spitzer, and AKARI infrared satellites, the detected AGN fraction has indeed been found to increase in ULIRGs, compared with galaxies with lower infrared luminosities (Tran et al. 2001; Imanishi et al. 2009). Infrared spectroscopic studies also indicate that AGNs are more centrally concentrated than dust absorption features in the infrared spectra. Thus, the detectable buried AGNs in the 85 optically non-Seyfert ULIRGs without published Spitzer IRS 5–35 μm low-resolution spectra in the IRAS 1 Jy sample. Because Spitzer IRS 5–35 μm low-resolution spectroscopy of one source (IRAS 08474+1813) was scheduled in Cycle 3, we observed the remaining 16 ULIRGs on our own, during Spitzer Cycle 5. Table 1 summarizes the properties of these 17 ULIRGs.

3. OBSERVATIONS AND DATA ANALYSIS

Observations of all 17 ULIRGs were performed with the IRS (Houck et al. 2004) on board the Spitzer Space Telescope (Werner et al. 2004). All four modules, Short-Low 2 (SL2; 5.2–7.7 μm) and 1 (SL1; 7.4–14.5 μm), and Long-Low 2 (LL2; 14.0–21.3 μm) and 1 (LL1; 19.5–38.0 μm) were used to obtain the full 5–35 μm low-resolution (R ~ 100) spectra. Table 2 contains details of the observation log. The slit width was 3.6 or 2 pixels for SL2 (1.8′′ pixel–1) and 3.7 or ~2 pixels for SL1 (1.8′′ pixel–1). For LL2 and LL1, the slit widths were 10.5′′ and 10.7′′, respectively, corresponding to ~2 pixels for both LL2 (5′′1 pixel–1) and LL1 (5′′1 pixel–1).

The latest pipeline-processed data products available at the time of our analysis were used. Frames taken at position A were subtracted from those taken at position B to remove background emission, consisting mostly of zodiacal light. The spectra were then extracted in the standard manner. Apertures with 4–6 pixels were employed for SL and LL data. All sources were dominated by spatially compact emission whose size is similar to the point-spread function (PSF) of SL and LL. The spectra extracted for the A and B positions were then summed. Wavelength and flux calibrations were made on the basis of the Spitzer pipeline-processed data. For the SL1 spectra, the data at λ_m > 14.5 μm in the observed frame are invalid (Infrared Spectrograph Data Handbook, version 1.0), and thus they were removed. For the LL1 spectra, the data at λ_m > 35 μm were not used because they are noisy and not necessary for our scientific discussions.

For the flux calibration, we did not re-calibrate our spectra using the IRS measurements at 12 μm and 25 μm, because the IRS 12 μm and/or 25 μm fluxes are upper limits in many sources (Table 1). In this case, the absolute flux calibration is dependent on the accuracy of the pipeline-processed data, which is taken to be better than 20% for SL and LL (Infrared Spectrograph Data Handbook). This level of flux uncertainty does not significantly affect our main conclusions. For ULIRGs with IRS 25 μm detection, we confirmed that the Spitzer IRS 25 μm flux agrees with the IRS 25 μm data within 30%. For ULIRGs with IRS 25 μm non-detection, the measured Spitzer IRS 25 μm flux is always smaller than the IRS 25 μm upper limits.

Among 33 ULIRGs at z > 0.15 optically classified as non-Seyferts in the IRAS 1 Jy sample, five LINER, six H ii regions, and two optically unclassified ULIRGs were not studied in Imanishi (2009). Additionally, four optically unclassified ULIRGs at z < 0.15 were not investigated by Imanishi et al. (2007). In total, there were 17 (20% of the total 85 sources) optically non-Seyfert ULIRGs without published Spitzer IRS 5–35 μm low-resolution spectroscopy of one source (IRAS 08474+1813) was scheduled in Cycle 3, we observed the remaining 16 ULIRGs on our own, during Spitzer Cycle 5. Table 1 summarizes the properties of these 17 ULIRGs.

2. TARGETS

The ULIRGs in the IRAS 1 Jy sample (Kim & Sanders 1998) are our targets. This sample consists of 118 ULIRGs at z < 0.3, whose IRAS 60 μm fluxes are larger than 1 Jy. Of these, 33 are optically classified as Seyferts, and 85 as non-Seyferts (Veilleux et al. 1999). The investigation of optically elusive, but intrinsically luminous, buried AGNs in the 85 optically non-Seyfert ULIRGs is our main objective. The 85 sources consist of 43 optically LINER, 32 optically H ii regions, and 10 optically unclassified ULIRGs (Veilleux et al. 1999).

Imanishi et al. (2007) investigated the buried AGN fraction in the complete sample of 48 ULIRGs at z < 0.15, classified optically as LINERs and H ii regions, in the IRAS 1 Jy sample, on the basis of Spitzer low-resolution infrared 5–35 μm spectra. These authors found strong signatures of luminous buried AGNs in a sizable fraction (16/48; 33%) of the observed ULIRGs. Four optically unclassified ULIRGs at z < 0.15 were not studied.

Imanishi (2009) extended the Spitzer IRS low-resolution infrared spectroscopic study to ULIRGs at z > 0.15, classified optically as non-Seyferts (LINERs, H ii regions, and unclassified), in the IRAS 1 Jy sample, by analyzing the spectra of 20 sources available at that time. As a result of this extension, a large number of ULIRGs with L_IR > 10^{12.3} L_☉ are now included, so that a meaningful investigation of the buried AGN fraction as a function of galaxy infrared luminosity has become possible, by dividing galaxies into different infrared luminosity classes. Specifically, the classes are defined by L_IR < 10^{12} L_☉, 10^{12} ≤ L_IR ≤ 10^{12.3} L_☉, and L_IR ≥ 10^{12.3} L_☉. Imanishi (2009) found a trend that the detectable buried AGN fraction systematically increases with increasing infrared galaxy luminosity. However, the ULIRG sample was not statistically complete, because unobserved, optically non-Seyfert ULIRGs remained in the IRAS 1 Jy sample.
the LL2 flux, to minimize missing PAH fluxes. Appropriate spectral binning with 2, 4, or 8 pixels was applied to reduce the scattering of data points particularly at SL2 (5.2–7.7 μm) and LL2 (14.0–21.3 μm) for faint ULIRGs, and at λ_{obs} ~ 10 μm for ULIRGs that show deep 9.7 μm silicate dust absorption features.
4. RESULTS

The infrared 5–35 μm low-resolution spectra of the 17 observed ULIRGs are shown in Figure 1. The full 5–35 μm spectra of these ULIRGs are published here for the first time. The spectra in Figure 1 are useful for observing the overall 5–35 μm spectral shapes and broad 9.7 μm and 18 μm silicate dust absorption features, but not for observing PAH emission. Following Imanishi et al. (2007) and Imanishi (2009), Figure 2 presents enlarged spectra at λ_{obs} = 5.2–14.5 μm to better exhibit the PAH emission properties.

4.1. PAH Emission

All ULIRGs in Figure 2 show clear signs of PAH emission at λ_{rest} = 6.2 μm, 7.7 μm, and 11.3 μm in the rest frame. To estimate the strengths of these PAH emission, we adopted a linear continuum, following Imanishi et al. (2007) and Imanishi (2009). Data points at slightly shorter and longer wavelengths than the 6.2 μm, 7.7 μm, and 11.3 μm PAH emission were used to determine linear continuum levels, which are shown as solid lines in Figure 2. PAH emission features above the adopted continuum levels were fitted with Gaussian profiles. The estimated rest-frame equivalent widths (EW_{PAH}) and luminosities of the 6.2 μm, 7.7 μm, and 11.3 μm PAH emission are summarized in Table 3.

As noted by Imanishi et al. (2007) and Imanishi (2009), we estimated the strength of the 7.7 μm PAH emission in such a way that the uncertainty caused by the strong, broad 9.7 μm silicate dust absorption feature is minimized. This definition of the 7.7 μm PAH emission strength is significantly different from that used in previous papers (e.g., Genzel et al. 1998). We will not use 7.7 μm PAH emission strengths in our main discussions, because of the difficulty of comparing our data with data in the literature, as well as possible large uncertainties in the 7.7 μm PAH strengths.

4.2. Silicate Absorption

To estimate the strengths of the silicate dust absorption features, we use τ_{9.7}^s and τ_{18}^s, defined by Imanishi et al. (2007). The value of τ_{9.7}^s is the optical depth of the 9.7 μm silicate absorption feature, relative to a power-law continuum, determined from data points at λ_{rest} = 7.1 μm and 14.2 μm, to minimize the effects of PAH emission. The value of τ_{18}^s is the optical depth of the 18 μm silicate absorption feature, relative to a power-law continuum determined from data points at λ_{rest} = 14.2 μm and 24 μm. These continua are shown as dotted lines in Figure 1. Because these continuum levels are determined using data points just outside the 9.7 μm and 18 μm features, and close to the absorption peaks, the measured optical depths are taken as true dips caused by the silicate dust absorption feature. The τ_{9.7}^s and τ_{18}^s values were estimated from several data points, close to the absorption peaks. The τ_{9.7}^s values for all the ULIRGs are shown in Table 4 (Column 2). The τ_{18}^s values are also shown in Table 4 (Column 3) for ULIRGs with clearly detected 18 μm silicate absorption features.

4.3. Ice Absorption

Many ULIRGs display dips on the shorter wavelength side of the 6.2 μm PAH emission, which we ascribe to the 6.0 μm H2O ice absorption feature (bending mode). Figure 3 presents enlarged spectra at λ_{obs} = 5.2–9 μm for ULIRGs with clearly detected ice absorption features. The spectrum of IRAS 14202+2615 is also included, as an example of non-detection. The observed optical depths (τ_{6.0}) are summarized in Table 5 for detected sources. The detection rate of this 6.0 μm ice absorption feature is substantially higher in optically LINER ULIRGs (5/5, 100%) than in H II-region ULIRGs (1/6; 17%).

5. DISCUSSION

For the sake of consistency, we use the criteria employed by Imanishi et al. (2007) and Imanishi (2009) to study buried AGNs in optically non-Seyfert ULIRGs. We first search for ULIRGs with luminous buried AGN signatures in infrared 5–35 μm spectra, and then estimate the extinction-corrected intrinsic luminosities of buried AGNs, based on the observed fluxes at ~10 μm and dust extinction toward the 10 μm continuum emitting regions (Imanishi et al. 2007; Imanishi 2009).

Several other methods of evaluating the energetic importance of buried AGNs, based on Spitzer IRS infrared low-resolution spectra, have been proposed in the literature (Veilleux et al. 2009; Nardini et al. 2009). In the methods of Veilleux et al. (2009), AGN and starburst zero points were derived from unobscured AGNs and starburst galaxies, respectively. Then, relative buried AGN contributions to the observed fluxes of continuum and line emission at infrared 5–35 μm were derived. No dust extinction correction was applied to estimate buried AGN luminosities. Even though dust extinction at 5–35 μm is smaller than that at shorter wavelengths, using the observed fluxes could underestimate the intrinsic buried AGN luminosities, because emission from buried AGNs is more highly flux attenuated than the surrounding starbursts in individual ULIRGs, as well as unobscured AGNs used to determine the AGN zero points.

Nardini et al. (2009) applied dust extinction correction to estimate the intrinsic buried AGN luminosities, but their modeling utilized only 5–8 μm spectra. Our methods use a wider-wavelength range (5–35 μm) of Spitzer IRS spectra, and dust extinction is also taken into account to estimate the buried AGN luminosities.

5.1. Detected Modestly Obscured Starbursts

Aside from the strong 9.7 μm silicate absorption peak, the flux attenuation of the continuum emission at λ_{rest} > 5 μm is small (<0.5 mag) for dust extinction with A_V < 20 mag (Nishiyama et al. 2008, 2009). Thus, the observed PAH emission luminosities at λ_{rest} > 5 μm can be used to roughly estimate the intrinsic luminosities of modestly obscured (A_V < 20 mag) PAH-emitting normal starbursts (with PDRs and modest metallicity), provided that the PAH emission and infrared luminosities proportionally correlate in the starbursts (Peeters et al. 2004; Soifer et al. 2002). Since the metallicity of ULIRGs is estimated to be solar or even higher (Rupke et al. 2008; Veilleux et al. 2009), the assumption of PAH-emitting starbursts is valid in ULIRGs (Wu et al. 2006; Madden et al. 2006; O’Halloran et al. 2006; Smith et al. 2007). Table 3 (Columns 8 and 9) lists the values of the 6.2 μm PAH to infrared luminosity ratio, L_{6.2PAH}/L_{IR}, and the 11.3 μm PAH to infrared luminosity ratio, L_{11.3PAH}/L_{IR}. In normal starburst galaxies with modest dust obscuration (A_V < 20 mag), the ratios are estimated to be L_{6.2PAH}/L_{IR} ∼ 3.4 × 10^{-3} (Peeters et al. 2004) and L_{11.3PAH}/L_{IR} ∼ 1.4 × 10^{-3} (Soifer et al. 2002).5

5 Smith et al. (2007) derived high PAH to infrared luminosity ratios, by including underlying plateau components as PAH fluxes. We employ the ratios obtained by Peeters et al. (2004) and Soifer et al. (2002), because of their similar continuum choices to ours.
Figure 1. Infrared 5–35 μm spectra of optically non-Seyfert ULIRGs, taken with Spitzer IRS. The abscissa and ordinate are, respectively, the observed wavelength in μm and the flux $F_\nu$ in Jy, both plotted in a decimal logarithmic scale. For all objects, the ratio of the uppermost to the lowermost scale in the ordinate is fixed as a factor of 1000, to illustrate the variation of the overall spectral energy distribution. Dotted line: power-law continuum determined from data points at $\lambda_{\text{rest}} = 7.1$ μm and 14.2 μm (in the rest frame) for the 9.7 μm silicate dust absorption feature, and at $\lambda_{\text{rest}} = 14.2$ μm and 24 μm for the 18 μm silicate dust absorption feature (see Section 4.2).
Figure 1. (Continued)

Table 3

| Object                     | EW$_{6.2}$PAH (nm) | EW$_{7.7}$PAH (nm) | EW$_{11.3}$PAH (nm) | $L_{6.2}$PAH ($10^{42}$ erg s$^{-1}$) | $L_{7.7}$PAH ($10^{42}$ erg s$^{-1}$) | $L_{11.3}$PAH ($10^{42}$ erg s$^{-1}$) | $L_{6.2}$/L$_{IR}$ ($\times 10^{-3}$) | $L_{11.3}$/L$_{IR}$ ($\times 10^{-3}$) |
|----------------------------|--------------------|--------------------|--------------------|--------------------------------------|--------------------------------------|--------------------------------------|----------------------------------------|----------------------------------------|
| IRAS 04074$-$2801          | 60                 | 420                | 235                | 3.3                                  | 32.8                                 | 2.5                                  | 0.6                                    | 0.4                                    |
| IRAS 05020$-$2941          | 130                | 605                | 330                | 7.0                                  | 47.1                                 | 4.2                                  | 0.9                                    | 0.5                                    |
| IRAS 13106$-$0922          | 115                | 425                | 565                | 3.3                                  | 27.6                                 | 3.5                                  | 0.4                                    | 0.4                                    |
| IRAS 14121$-$0126          | 270                | 635                | 345                | 11.9                                 | 38.2                                 | 7.8                                  | 1.7                                    | 1.2                                    |
| IRAS 21477+0502            | 235                | 575                | 185                | 7.4                                  | 24.2                                 | 5.4                                  | 1.0                                    | 0.7                                    |
| IRAS 03209$-$0806          | 285                | 555                | 410                | 9.9                                  | 26.4                                 | 9.2                                  | 1.6                                    | 1.5                                    |
| IRAS 10594+3818            | 350                | 780                | 490                | 16.0                                 | 46.0                                 | 11.1                                 | 2.4                                    | 1.7                                    |
| IRAS 12447+3721            | 210                | 625                | 260                | 7.0                                  | 24.0                                 | 4.1                                  | 1.4                                    | 0.8                                    |
| IRAS 14202+2615            | 160                | 455                | 265                | 18.7                                 | 52.9                                 | 13.6                                 | 1.9                                    | 1.4                                    |
| IRAS 15043+5754            | 285                | 770                | 555                | 8.0                                  | 29.3                                 | 6.7                                  | 1.6                                    | 1.3                                    |
| IRAS 22088$-$1831          | 90                 | 455                | 195                | 3.0                                  | 23.6                                 | 2.3                                  | 0.3                                    | 0.3                                    |
| IRAS 02480$-$3745          | 325                | 915                | 535                | 7.3                                  | 25.6                                 | 5.0                                  | 1.2                                    | 0.8                                    |
| IRAS 08591+5248            | 310                | 695                | 535                | 9.7                                  | 30.7                                 | 9.7                                  | 1.8                                    | 1.8                                    |
| IRAS 02021$-$2103          | 285                | 490                | 275                | 5.5                                  | 13.0                                 | 4.2                                  | 1.4                                    | 1.0                                    |
| IRAS 08474+1813            | 170                | 985                | 285                | 2.2                                  | 13.1                                 | 1.4                                  | 0.4                                    | 0.3                                    |
| IRAS 14197+0813            | 305                | 565                | 325                | 3.8                                  | 11.4                                 | 3.7                                  | 0.9                                    | 0.9                                    |
| IRAS 14485$-$2434          | 150                | 495                | 295                | 6.8                                  | 26.2                                 | 6.8                                  | 1.6                                    | 1.6                                    |

Notes. Column 1: object name. Column 2: rest-frame equivalent width of the 6.2 $\mu$m PAH emission in nm. Column 3: rest-frame equivalent width of the 7.7 $\mu$m PAH emission in nm. Column 4: rest-frame equivalent width of the 11.3 $\mu$m PAH emission in nm. Column 5: luminosity of the 6.2 $\mu$m PAH emission in units of $10^{42}$ erg s$^{-1}$. Column 6: luminosity of the 7.7 $\mu$m PAH emission in units of $10^{42}$ erg s$^{-1}$. Column 7: luminosity of the 11.3 $\mu$m PAH emission in units of $10^{42}$ erg s$^{-1}$. Column 8: 6.2 $\mu$m PAH to infrared luminosity ratio in units of $10^{-3}$. The ratio for normal starbursts with modest dust obscuration ($A_V < 20$ mag) is $\sim 3.4 \times 10^{-3}$ (Peeters et al. 2004). Column 9: 11.3 $\mu$m PAH to infrared luminosity ratio in units of $10^{-3}$. The ratio for normal starbursts with modest dust obscuration ($A_V < 20$ mag) is $\sim 1.4 \times 10^{-3}$ (Soifer et al. 2002).

* We consider the flux excess at $\lambda_{rest} = 7.3$–$8.1 \mu$m above an adopted continuum level to be 7.7 $\mu$m PAH emission, to reduce the effects of the strong 9.7 $\mu$m silicate dust absorption feature. The 7.7 $\mu$m PAH emission strengths may be significantly different from those estimated by other authors.
Figure 2. Spitzer IRS spectra of ULIRGs at $\lambda_{\text{obs}} = 5.2-14.5 \, \mu\text{m}$, for investigating the PAH emission in detail. The abscissa and ordinate are, respectively, the observed wavelength in $\mu\text{m}$ and the flux in Jy, both plotted in a linear scale. The expected wavelengths of the 6.2 $\mu\text{m}$, 7.7 $\mu\text{m}$, and 11.3 $\mu\text{m}$ PAH emission features are indicated as down arrows with labels. The solid lines are the adopted linear continuum levels for estimating the strength of the PAH emission (see Section 4.1).
Figure 4 compares the 6.2 μm and 11.3 μm PAH luminosities with the observed infrared luminosities. The observed $L_{6.2\text{PAH}}/L_{\text{IR}}$ ratios are $(0.3–2.4) \times 10^{-3}$ (Table 3), or 9%–71% of $3.4 \times 10^{-3}$ for modestly obscured starburst galaxies. In the majority of the observed ULIRGs, the ratios are $<1.7 \times 10^{-3}$, or $<50\%$ of $3.4 \times 10^{-3}$ (see also Figure 4). Taken at face value, the modestly obscured starbursts detected in these ULIRGs account for 9%–71% (mostly <50%) of their infrared luminosities. The same argument can be applied to the observed $L_{11.3\text{PAH}}/L_{\text{IR}}$ ratios for the ULIRGs. The $L_{11.3\text{PAH}}/L_{\text{IR}}$ ratios are $(0.3–1.8) \times 10^{-3}$ (Table 3), or 21%–100% of $1.4 \times 10^{-3}$ for modestly obscured starburst galaxies. On the basis of the $L_{11.3\text{PAH}}/L_{\text{IR}}$ ratios, there are some ULIRGs whose infrared luminosities can be explained by the detected modestly obscured ($A_V < 20$ mag) starbursts. However, for ULIRGs with $<0.7 \times 10^{-3}$ ($<50\%$ of $1.4 \times 10^{-3}$), additional energy sources would be required. The 11.3 μm PAH emission tends to provide higher contributions from modestly obscured starbursts to the infrared luminosities of ULIRGs, than the 6.2 μm PAH emission (Figure 4), possibly because the 11.3 μm PAH emission originates in large-sized PAHs which may be less susceptible to destruction by the energetic radiation from AGNs and intense starbursts in ULIRGs (Smith et al. 2007). Luminosities that are not accounted for by the detected modestly obscured starbursts might originate from (1) highly obscured ($A_V \gg 20$ mag) starbursts, in which the PAH emission flux is substantially attenuated by dust extinction, and/or (2) buried AGNs that produce strong infrared radiation, but virtually no PAH emission.

| Object        | $r'_{9.7}$ | $r'_{18}$ | $r'_{18}/r'_{9.7}$ |
|---------------|------------|-----------|---------------------|
| IRAS 04074−2801 | 3.0        | 1.2       | 0.40                |
| IRAS 05020−2941 | 2.4        | 0.9       | 0.38                |
| IRAS 13106−0922 | 2.0        | 1.2       | 0.60                |
| IRAS 14121−0126 | 1.3        | ...       | ...                 |
| IRAS 21477+0502 | 0.8        | ...       | ...                 |
| IRAS 03209−0806 | 1.0        | ...       | ...                 |
| IRAS 10594+3818 | 1.0        | ...       | ...                 |
| IRAS 12447+3721 | 1.4        | 0.5       | 0.36                |
| IRAS 14202+2615 | 0.7        | ...       | ...                 |
| IRAS 15043+5754 | 1.4        | 0.7       | 0.50                |
| IRAS 22088−1831 | 2.6        | 1.0       | 0.38                |
| IRAS 02480−2941 | 2.8        | 1.5       | 0.43                |
| IRAS 06591+5248 | 1.0        | ...       | ...                 |
| IRAS 02021−2103 | 1.4        | 0.4       | 0.29                |
| IRAS 08474+1813 | 2.0        | 1.0       | 0.50                |
| IRAS 14197+0813 | 0.8        | ...       | ...                 |
| IRAS 14485−2434 | 1.2        | ...       | ...                 |

Notes. Column 1: object name. Column 2: $r'_{9.7}$ is the optical depth of the 9.7 μm silicate dust absorption feature, plotted against a power-law continuum, shown as dotted lines in Figure 1. Column 3: $r'_{18}$ is the optical depth of the 18 μm silicate dust absorption feature, plotted against a power-law continuum, shown as dotted lines in Figure 1. Column 4: $r'_{18}/r'_{9.7}$ ratio for ULIRGs with clearly detectable 18 μm silicate absorption. The uncertainty with ~10% may be present.
We note that emission from extreme starbursts, which consist of H II regions only, without PDRs and molecular gas, can be PAH free, because PAH molecules can be destroyed inside the H II regions themselves (Sellgren 1981). If starbursts are exceptionally more centrally concentrated than the surrounding molecular gas and dust (Figure 1(e) of Imanishi et al. 2007), such H II-region-only starbursts could happen. However, in the case of ULIRG’s cores, such extreme starbursts require extremely high-emission surface brightnesses, and so are unlikely (Imanishi et al. 2007), if not completely ruled out. We thus use the term “buried AGN signatures,” rather than “buried AGN evidence” throughout this paper.

Figure 3. Spitzer IRS spectra at $\lambda_{\text{obs}} = 5.2-9 \mu m$ for ULIRGs displaying clear $6.0 \mu m$ H$_2$O ice absorption features (marked with “6.0 $\mu m$ ice absorption” in the first nine plots). The spectrum of IRAS 14202+2615, marked “no 6.0 $\mu m$ ice absorption,” is shown as an example of undetected ice absorption. The abscissa is the observed wavelength in $\mu m$ plotted in a linear scale, and the ordinate is the flux in Jy plotted in a decimal logarithmic scale.
Figure 4. Comparison of the 6.2 μm (left) and 11.3 μm (right) PAH luminosities with the infrared luminosities. Optically non-Seyfert ULIRGs that were newly studied in this paper are plotted with “X” symbols. Open circles represent sources studied in previously published papers (Imanishi et al. 2007; Imanishi 2009). The solid lines indicate the canonical PAH to infrared luminosity ratios found in modestly obscured starburst galaxies (see Section 5.1). Specifically, on the solid lines, 100% of the infrared luminosity can be reproduced from the detected modestly obscured starburst activity. The dashed and dotted lines represent 50% and 10% of the ratios.

### Table 5

| Object             | τ_{6.0} | τ_{11.3} |
|--------------------|---------|----------|
| IRAS 04074−2801    | 0.3     |          |
| IRAS 05020−2941    | 0.4     |          |
| IRAS 13106−0922    | 1.0     |          |
| IRAS 14121−0126    | 0.8     |          |
| IRAS 21477+0502    | 0.6     |          |
| IRAS 22088−1831    | 0.5     |          |
| IRAS 02480−3745    | 0.9     |          |
| IRAS 08591+5248    | 0.5     |          |
| IRAS 14485−2434    | 0.3     |          |

**Notes.** Column 1: object name. Column 2: optical depth of the 6.0 μm H_2O ice absorption feature for clearly detected sources. The uncertainty with ∼0.1 may be present.

### Table 6

| Object             | EW_{6.2PAH} | EW_{11.3PAH} | τ_{1487} | Total |
|--------------------|--------------|---------------|----------|-------|
| IRAS 04074−2801    | X            | X             | X        | O     |
| IRAS 05020−2941    | X            | X             | X        | O     |
| IRAS 13106−0922    | X            | X             | X        | O     |
| IRAS 14121−0126    | X            | X             | X        | O     |
| IRAS 21477+0502    | X            | X             | X        | O     |
| IRAS 08591+5248    | X            | X             | X        | O     |
| IRAS 14485−2434    | X            | X             | X        | X     |

**Notes.** Column 1: object name. Column 2: buried AGN signatures based on the low equivalent width of the 6.2 μm PAH emission (EW_{6.2PAH} < 180 nm) (Section 5.2.1). □: present. X: none. Column 3: buried AGN signatures based on the low equivalent width of the 11.3 μm PAH emission (EW_{11.3PAH} < 200 nm) (Section 5.2.1). □: present. X: none. Column 4: buried AGN signatures based on the large τ_{1487} value (≥2) (Section 5.2.2).  □: present. X: none. Column 5: buried AGN signatures from combined methods in Columns 2–4. □: strong. X: none.

5.2. ULIRGs that Could Contain Luminous Buried AGNs

5.2.1. Low Equivalent Width PAH Emission

Highly obscured normal starbursts and buried AGNs are basically distinguishable, based on the equivalent width of the PAH emission. A PAH equivalent width (EW_{PAH}) must always be large in a normal starburst (with PDRs) with a mixed dust/source geometry, regardless of the amount of dust extinction, because both the PAH and nearby continuum emission are similarly flux attenuated. Thus, a small EW_{PAH} value suggests a contribution from a PAH-free continuum-emitting energy source, namely an AGN (Imanishi et al. 2007; Imanishi 2009).

Following Imanishi et al. (2007) and Imanishi (2009), we classify ULIRGs with EW_{6.2PAH} < 180 nm and EW_{11.3PAH} < 200 nm as sources displaying clear signatures of luminous AGNs, because a considerable contribution from a PAH-free continuum would be required for these sources. Figure 5 is a plot of the distribution of EW_{6.2PAH} and EW_{11.3PAH} values. Table 6 (Columns 2 and 3) records the detection or non-detection of buried AGN signatures in terms of the PAH equivalent width threshold. The EW_{6.2PAH} method provides a much larger buried AGN fraction (7/17; 41%) than the EW_{11.3PAH} method (2/17; 12%), as seen in Imanishi et al. (2007) and Imanishi (2009). An explanation for this is that the 11.3 μm PAH emission feature is inside the strong 9.7 μm silicate dust absorption feature. Thus, the buried AGN continuum emission at λ_{rest} ∼ 11.3 μm is severely attenuated, and has little effect on the equivalent widths of the 11.3 μm PAH emission from less obscured starburst regions outside the AGNs (Imanishi et al. 2007; Imanishi 2009).

5.2.2. Optical Depths of Dust Absorption Features

Based on the low EW_{PAH} method, a buried AGN with very weak starbursts is easily detectable. If strong starburst activity is present, AGN detection becomes difficult, but a weakly obscured AGN is still detectable, because dilution of the PAH emission by the AGN’s PAH-free continuum can be significant. However, a deeply buried AGN with strong starbursts is very difficult to detect. Even if the intrinsic luminosity of a buried AGN is large, the AGN flux will be more highly attenuated by dust extinction than the surrounding starburst emission, keeping the observed EW_{PAH} value quite large.
To determine the presence of a deeply buried AGN with strong starbursts, we use the optical depths of the silicate dust absorption features. Specifically, these values can be used to distinguish whether the energy sources are spatially well mixed with dust (a normal starburst), or are more centrally concentrated than the dust (a buried AGN; Section 1). Imanishi et al. (2007) obtained a maximum value of $\tau_{9.7} = 1.7$ for a normal starburst with a mixed dust/source geometry. Considering the possible uncertainties of the $\tau_{9.7}$ estimate, coming from continuum determination ambiguities and statistical errors of individual data points, we classify ULIRGs with $\tau_{9.7} \geq 2$ as potential locations of luminous, but deeply buried AGNs with centrally concentrated energy source geometries. Five ULIRGs have $\tau_{9.7} \geq 2$ (Tables 4 and 6).

As noted by Imanishi (2009), although this large $\tau_{9.7}$ method is sensitive to deeply buried AGNs, it is obviously insensitive to weakly obscured AGNs, which are better probed with the low EW$_{PAH}$ method. Thus, the low EW$_{PAH}$ and large $\tau_{9.7}$ methods are complementary to each other. At the same time, a normal starburst nucleus with a mixed dust/source geometry and a large amount of foreground screen dust in an edge-on host galaxy (Figure 1(d) of Imanishi et al. 2007), and an exceptionally centrally concentrated starburst (Figure 1(e) of Imanishi et al. 2007), are capable of producing large $\tau_{9.7}$ values. However, it is unlikely that the majority of the ULIRGs with $\tau_{9.7} \geq 2$ fit these non-AGN cases (Imanishi et al. 2007; Imanishi 2009).

5.2.3. Strong Dust Temperature Gradients

As explained by Imanishi et al. (2007), a buried AGN with a centrally concentrated energy source geometry should have a strong dust temperature gradient, because the inner dust (close to the central energy source) has a higher temperature than the outer dust, whereas a normal starburst nucleus with a mixed dust/source geometry does not exhibit this behavior. The presence of a strong dust temperature gradient could be detected by comparing the optical depths of the 9.7 $\mu$m and 18 $\mu$m silicate dust absorption features, as long as the contaminations from weakly obscured starbursts to observed infrared fluxes are not severe. $\tau_{18}/\tau_{9.7} < 0.3$ could be taken as the signature of a strong dust temperature gradient (Imanishi et al. 2007; Imanishi 2009). This could provide an additional signature for a buried AGN. Although this was the case for 12 sources studied by Imanishi et al. (2007) and Imanishi (2009), no such case was found among the 17 newly observed ULIRGs (Table 4, Column 4). Because of the contamination from weakly obscured starburst activity, as well as other possible ambiguities (Imanishi et al. 2007), not all buried AGNs actually satisfy $\tau_{18}/\tau_{9.7} < 0.3$. The criterion $\tau_{18}/\tau_{9.7} < 0.3$ is a sufficient condition for an additional signature of a buried AGN, but it is not a necessary condition.

5.2.4. Combination of Energy Diagnostic Methods

Table 6 (Column 5) summarizes the strengths of the detected buried AGN signatures in the Spitzer IRS 5–35 $\mu$m spectra,
infrared luminosity can be fully accounted for with a buried AGN. The dashed AGN luminosity equals the infrared luminosity. In other words, the observed luminosities for selected ULIRGs with strong buried AGN signatures in their spectra (i.e., PAH equivalent widths are particularly low and the intrinsic AGN luminosities can be estimated with small ambiguities). Optically non-Seyfert ULIRGs that were newly studied in this paper are plotted with "X" symbols. Open circles represent sources studied in previously published papers (Imanishi et al. 2007; Imanishi 2009). The solid line indicates that the buried AGN luminosity equals the infrared luminosity. In other words, the observed infrared luminosity can be fully accounted for with a buried AGN. The dashed and dotted lines, respectively, indicate that 50% and 10% of the infrared luminosity can be explained by a buried AGN.

The detection rate of luminous buried AGNs in the newly observed optically non-Seyfert ULIRGs (8/17; 47%) is significantly smaller than the rate obtained by Imanishi (2009) (14/20; 70%). This may be partly due to the smaller fraction of ULIRGs with $L_{\text{IR}} > 10^{12.3} L_{\odot}$ (6/17; 35%) in this sample, compared with Imanishi (2009; 17/20, 85%).

5.2.5 Extinction-corrected Intrinsic Buried AGN Luminosities

For ULIRGs with very low EWPAH, the observed fluxes are taken to be mostly the result of AGN-heated, PAH-free dust continuum emission. We can estimate the extinction-corrected intrinsic dust emission luminosity at $\sim 10 \mu m (\nu F_{\nu})$, heated by the AGN, on the basis of the observed fluxes at $\lambda_{\text{rest}} \sim 10 \mu m$ and dust extinction toward the $10 \mu m$ continuum emitting regions inferred from $\tau_{6.7}$ (Imanishi et al. 2007; Imanishi 2009). As argued by Imanishi et al. (2007) and Imanishi (2009), in a pure AGN with a simple spherical dust distribution, dust emission luminosity is conserved at each temperature from hot inside regions to cool outside regions (Figure 2 of Imanishi et al. 2007). The extinction-corrected $10 \mu m$ luminosity ($\nu F_{\nu}$) should be comparable to the intrinsic luminosity of the AGN’s primary radiation.

To obtain the estimate, we followed Imanishi et al. (2007) and Imanishi (2009). The flux attenuation of the 8 or $13 \mu m$ continuum outside the $9.7 \mu m$ silicate feature is $10^{\tau_{6.7}/2.3}$ (Rieke & Lebofsky 1985), and ranges from a factor of 1.3 ($\tau_{6.7} \sim 0.7$) to 3.3 (IRAS 04074–2801; $\tau_{6.7} \sim 3.0$). We found that the extinction-corrected intrinsic buried AGN luminosities for selected ULIRGs with very low EWPAH values are a few $\times 10^{45}$ erg s$^{-1}$, or $\sim 10^{12} L_{\odot}$ in the maximum case (Table 7). Figure 6 compares the intrinsic buried AGN luminosity and the infrared luminosity. The detected buried AGNs could explain a significant, but not dominant fraction (6%–33%), of the luminosities of these ULIRGs. In Table 7, the luminosities of the detected modestly obscured starbursts, estimated from the $L_{6.2\text{PAH}}$ and $L_{11.3\text{PAH}}$ values, are also listed for the sake of comparison.

5.3 Buried AGN Fraction as a Function of Galaxy Infrared Luminosity

Imanishi et al. (2007) investigated the presence of luminous buried AGNs in 48 ULIRGs at $z < 0.15$, classified optically as non-Seyferts (28 LINER and 20 H II-region ULIRGs). Imanishi (2009) did the same in 20 ULIRGs at $z > 0.15$, classified optically as non-Seyferts (10 LINER, six H II-region, four unclassified ULIRGs). In the present research, we have continued this work in 13 optically non-Seyfert ULIRGs at $z > 0.15$ (five LINER, six H II-region, two unclassified ULIRGs) and four optically unclassified ULIRGs at $z < 0.15$. Taken together, these 85 observed sources comprise a complete sample of optically non-Seyfert ULIRGs in the IRAS 1 Jy sample.

Following Imanishi (2009), we divide the observed ULIRGs into those with $10^{12} L_{\odot} \lesssim L_{\text{IR}} < 10^{12.3} L_{\odot}$ and those with $L_{\text{IR}} \geq 10^{12.3} L_{\odot}$. After combining the results of Imanishi et al. (2007), Imanishi (2009) and this paper, we summarize the detectable buried AGN fraction in Table 8. Using this complete sample, we confirm the previously discovered trend (Imanishi et al. 2008; Imanishi 2009; Veilleux et al. 2009; Nardini et al. 2009) that the detectable buried AGN fraction is significantly higher in ULIRGs with $L_{\text{IR}} \geq 10^{12.3} L_{\odot}$ (22/31, 71%) than in those with $10^{12.3} L_{\odot} \leq L_{\text{IR}} < 10^{12.3} L_{\odot}$ (15/54, 28%). Figure 7 illustrates this trend by including galaxies with $L_{\text{IR}} < 10^{12} L_{\odot}$. Figure 5 displays the distributions of EW$_{6.2\text{PAH}}$, EW$_{11.3\text{PAH}}$, and...
Buried AGNs in a Complete Sample of Nearby ULIRGs

Table 7
Luminosities of Buried AGNs After Extinction Correction and Modestly Obscured Starbursts

| Object            | L(AGN) 10^45 (erg s^-1) | L(SB-6.2PAH) 10^45 (erg s^-1) | L(SB-11.3PAH) 10^45 (erg s^-1) | L_IR 10^45 (erg s^-1) |
|-------------------|--------------------------|-------------------------------|--------------------------------|-----------------------|
|                   | (1)                      | (2)                           | (3)                            | (4)                   |
| IRAS 04074−2801   | 2                        | 1                             | 2                              | 6                     |
| IRAS 05020−2941   | 1.5                      | 2                             | 3                              | 8                     |
| IRAS 13106−0922   | 1                        | 1                             | 2.5                            | 8                     |
| IRAS 14202+2615   | 1                        | 5.5                           | 9.5                            | 10                    |
| IRAS 22088−1831   | 1.5                      | 1                             | 1.5                            | 10                    |
| IRAS 08474+1813   | 0.3                      | 0.7                           | 1                              | 5                     |
| IRAS 14485−2434   | 1                        | 2                             | 5                              | 5                     |

Notes. Column 1: object name. Column 2: extinction-corrected intrinsic luminosity of a buried AGN in units of 10^45 erg s^-1. Column 3: infrared (8–1000 μm) luminosity of modestly obscured (A_V < 20 mag) starbursts, estimated from the 6.2 μm PAH emission luminosity (L_{SB-6.2PAH}) and L_{SB-6.2PAH}/L_{IR} = 3.4 × 10^{-3} (Peeters et al. 2004), in units of 10^45 erg s^-1. Column 4: infrared (8–1000 μm) luminosity of modestly obscured (A_V < 20 mag) starbursts, estimated from the 11.3 μm PAH emission luminosity (L_{11.3PAH}) and L_{11.3PAH}/L_{IR} = 1.4 × 10^{-3} (Soifer et al. 2002), in units of 10^45 erg s^-1. Column 5: observed infrared luminosity in units of 10^45 erg s^-1.

Table 8
Buried AGN Fraction in ULIRGs

| Optical Classification | Sub-category | Number of Sources | Buried AGNs |
|------------------------|--------------|------------------|-------------|
|                        |              |                  |             |
| Non-Seyfert            | Total        | 37               | 21 (49%)    |
|                        | L_{IR} < 10^{12.3} L_⊙ | 54               | 15 (28%)    |
|                        | L_{IR} ≥ 10^{12.3} L_⊙ | 31               | 22 (71%)    |
|                        | z ≤ 0.15     | 52               | 18 (35%)    |
|                        | z > 0.15     | 33               | 19 (58%)    |
| LINER                  | Total        | 43               | 21 (49%)    |
|                        | L_{IR} < 10^{12.3} L_⊙ | 25               | 9 (36%)     |
|                        | L_{IR} ≥ 10^{12.3} L_⊙ | 18               | 12 (67%)    |
|                        | z ≤ 0.15     | 28               | 10 (36%)    |
|                        | z > 0.15     | 15               | 11 (73%)    |
| H II region            | Total        | 32               | 12 (38%)    |
|                        | L_{IR} < 10^{12.3} L_⊙ | 22               | 4 (18%)     |
|                        | L_{IR} ≥ 10^{12.3} L_⊙ | 10               | 8 (80%)     |
|                        | z ≤ 0.15     | 20               | 6 (30%)     |
|                        | z > 0.15     | 12               | 6 (50%)     |
| Unclassified           | Total        | 10               | 4 (40%)     |
|                        | L_{IR} < 10^{12.3} L_⊙ | 7                | 2 (29%)     |
|                        | L_{IR} ≥ 10^{12.3} L_⊙ | 3                | 2 (67%)     |
|                        | z ≤ 0.15     | 4                | 2 (50%)     |
|                        | z > 0.15     | 6                | 2 (33%)     |

Notes. Column 1: optical classification. Column 2: sub-category of ULIRGs, whether 10^{12} L_⊙ ≤ L_{IR} < 10^{12.3} L_⊙ or L_{IR} ≥ 10^{12.3} L_⊙, and whether z ≤ 0.15 or z > 0.15. Column 3: number of sources in each sub-category. Column 4: number and fraction of ULIRGs with strong buried AGN signatures in each sub-category (Imanishi et al. 2007; Imanishi 2009, this paper).

For an AGN surrounded by dust with a torus–shaped distribution, the visibility of the central AGN is expected to increase with increasing AGN luminosity, because the innermost dust sublimation radius of the torus is proportional to the square root of the central AGN luminosity, and thus (assuming a constant torus scale height) the opening angle of the AGN is greater in luminous AGNs (the so-called receding torus model: Lawrence 1991; Simpson 2005; Arshakian 2005). In this scenario, the fraction of optically elusive buried AGNs is not large in luminous AGNs. However, this model is applicable only if the total amount of dust surrounding the central AGN does not vary significantly, depending on the galaxy and AGN luminosity. ULIRGs are driven by mergers of gas-rich galaxies, and gas/dust is quickly transported to the nuclear regions by the gravitational torques, producing a highly concentrated nuclear gas/dust distribution (Hopkins et al. 2006). AGNs can be easily buried by the increasing amount of nuclear gas/dust surrounding the central AGNs, and thus we believe that a high buried AGN fraction is a natural state of affairs in ULIRGs.

The higher fractions of buried AGNs (found in this work) and optical Seyferts (Veilleux et al. 1999; Goto 2005) indicate that AGNs become intrinsically more important with increasing galaxy infrared luminosity. Namely, the AGN-starburst connections depend on galaxy luminosity. This is the primary consequence of our results.

Figure 6 suggests that AGN’s energetic contributions are generally 10%–50%, or ~30% in median value, in ULIRGs with buried AGN signatures, which roughly agree with other independent estimates (Veilleux et al. 2009; Nardini et al. 2009) in overall ULIRG sample. If 30% of the infrared luminosity comes from a buried AGN in a ULIRG with L_{IR} = 10^{12.3} L_⊙ (= 2 × 10^{12} L_⊙), then the remaining infrared luminosity, originating in starbursts (including highly obscured A_V > 20 mag ones), is 1.4 × 10^{12} L_⊙. In the meanwhile, buried AGN contribution is generally insignificant in galaxies with L_{IR} = 10^{11.3} L_⊙ (= 2 × 10^{11} L_⊙) (Figure 7), and in this case, the starburst-originating luminosity is ~2 × 10^{11} L_⊙. Namely, in ULIRGs, the relative energetic importance of buried AGN is higher, but the absolute luminosities of starbursts, and thereby the star-formation rates, are also higher than galaxies with lower infrared luminosities. Unless the starburst duration time is drastically different, ULIRGs will produce more stars in the future, and evolve into more massive galaxies with larger stellar masses, than less infrared luminous galaxies.
Galaxies with higher infrared luminosities, the energetic importance of buried AGNs is relatively higher, and higher SFRs suggest that these galaxies will evolve into more massive galaxies with larger stellar masses. The higher AGN contributions in ULIRGs suggest that SMBHs in ULIRGs (progenitors of massive galaxies) are actively mass-accreting, and consequently, can have stronger radiation feedbacks to the surrounding gas and dust than mildly mass accreting SMBHs in less infrared luminous galaxies. A related phenomenon may be galaxy downsizing, where the more massive galaxies (with currently larger stellar masses) completed their major star formation during an earlier cosmic age (Cowie et al. 1996; Bundy et al. 2005). It has been suggested that in these more massive galaxies, AGN feedback was stronger in the past, heating or expelling gas and suppressing further star formation over a shorter timescale (Granato et al. 2004; Bower et al. 2006; Sijacki et al. 2007). Buried AGNs surrounded by a large amount of gas and dust may have particularly strong feedback, compared to already visible AGNs with a relatively thin dust covering, and thus are the important population for determining the interplay between AGNs and host galaxies.

Figure 8 illustrates our findings that buried AGNs are relatively more important energetically in galaxies that are currently more infrared luminous, and in the future, these galaxies will evolve into more massive galaxies with larger stellar masses. The energetic contributions from buried AGNs become discernible in ULIRGs, which are thought to evolve into galaxies with stellar masses of several $\times 10^{10} M_\odot$, based on infrared velocity dispersion measurements of ULIRG’s host galaxies (Dasyra et al. 2006). A similar eventual spheroidal stellar mass is derived for ULIRGs with detectable buried AGN signatures, from the intrinsic buried AGN luminosities (Imanishi 2009), if we assume that AGN luminosities are Eddington limits and if the widely accepted mass correlation between SMBHs and spheroidal stellar components holds (Magorrian et al. 1998; Ferrarese & Merritt 2000). This mass with several $\times 10^{10} M_\odot$ roughly corresponds to the stellar mass that separates red, massive galaxies with low-current star-formation rates (major star formation has already been completed) and blue, less massive galaxies with ongoing active star formation in the local universe (Kauffmann et al. 2003). Thus, our results may offer support to the AGN feedback scenario as the origin of the galaxy downsizing phenomenon.

6. SUMMARY

We have presented the results of Spitzer IRS infrared 5–35 μm low-resolution ($R \sim 100$) spectroscopy of 17 nearby ULIRGs at $z < 0.2$, optically classified as non-Seyferts (LINERs, H\textsc{ii} regions, and unclassified, i.e., no optical AGN signatures). Optically elusive, but intrinsically luminous buried AGNs were searched for in these optically non-Seyfert ULIRGs, on the basis of the strengths of PAH emission and silicate dust absorption features. We then combined these results with those of our previous studies of nearby ULIRGs, using Spitzer IRS, to investigate the energetic importance of buried AGNs in a complete sample of optically non-Seyfert ULIRGs in the local universe at $z < 0.3$ (85 sources altogether). We arrived at the following primary conclusions.

1. Among the 17 newly observed optically non-Seyfert ULIRGs, the signatures of important energy contributions from buried AGNs were found in eight sources. In these sources, the extinction-corrected intrinsic buried AGN luminosities were estimated at up to $\sim 10^{12} L_\odot$, accounting for a significant fraction (6%–33%) of the observed infrared luminosities of these ULIRGs.

2. By combining our new results with those of our previous studies (Imanishi et al. 2007; Imanishi 2009), we found that buried AGNs are energetically important in 37 sources of the complete ULIRG sample of 85 (37/85 = 44%), confirming previous suggestion that optically elusive, luminous buried AGNs are common in the ULIRGs of the local universe.

3. We investigated the fraction of detectable luminous buried AGNs by separating ULIRGs with $10^{12} L_\odot \leq L_{IR} < 10^{12.3} L_\odot$ (54 sources) and $L_{IR} \geq 10^{12.3} L_\odot$ (31 sources). We found that luminous buried AGNs were much more common in the latter ULIRGs (22/31 = 71%) than in the former ULIRGs (15/54 = 28%), confirming the previous arguments that buried AGNs become more energetically important with increasing galaxy infrared luminosity.

4. Given the higher fraction of optical Seyferts (optically identified AGNs) in ULIRGs with higher infrared luminosities, luminous AGNs are more common in ULIRGs with $L_{IR} \geq 10^{12.3} L_\odot$ than in ULIRGs with $10^{12} L_\odot \leq L_{IR} < 10^{12.3} L_\odot$. Because the detection rate of both optically identified Seyfert AGNs and optically elusive buried AGNs is substantially lower in galaxies with lower infrared luminosities ($L_{IR} < 10^{12} L_\odot$), we can conclude that the energetic importance of AGNs increases with increasing galaxy infrared luminosity, suggesting that the AGN-starburst connections are luminosity dependent. This may be related to the widely proposed AGN feedback scenario for the galaxy downsizing phenomenon.

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REFERENCES

Arumus, L., et al. 2007, ApJ, 656, 148
Arshakian, T. G. 2005, A&A, 436, 817
