Comparison of AGN and Nuclear Starburst Activity in Seyfert 1 and 2 Galaxies over a Wide Luminosity Range Based on Near-Infrared 2–4 μm Spectroscopy

Nagisa Oi,* Masatoshi IMANISHI,* and Keisuke IMASE

Department of Astronomical Science, The Graduate University for Advanced Studies (Sokendai), 2-21-1 Osawa, Mitaka, Tokyo 181-8588
National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588

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Abstract

We present near-infrared K- (1.9–2.5 μm) and L- (2.8–4.2 μm) band spectroscopy of 22 Seyfert nuclei. We used two methods to investigate the presence of nuclear starbursts: (1) the Polycyclic Aromatic Hydrocarbon (PAH) emission feature at λ_{rest} = 3.3 μm in the rest frame of the L-band spectrum (a starburst indicator) and (2) the CO absorption feature at λ_{rest} = 2.3–2.4 μm in the rest frame of the K-band spectrum, originating in the CO molecule. We clearly detected the 3.3 μm PAH emission features in five objects and the CO absorption features in 17 objects. Seyfert 2 galaxies tend to show bluer K – L colors compared with Seyfert 1 galaxies. We interpret the discrepancy as resulting from the relative strength of stellar emission because AGN emission is affected by dust extinction. The 3.3 μm PAH emission luminosity (L_{3.3PAH}) distributions for the Seyfert 1s and Seyfert 2s are very similar when normalized to the AGN power. The star-formation rates estimated from L_{3.3PAH} could be large enough to inflate the dusty torus by a supernova explosion. We find that L_{3.3PAH} positively correlates with the N-band luminosity with small aperture over a wide AGN luminosity range, and is independent of the physical area we probed. The results suggest that the nuclear region has a concentration of star formation and it would control the AGN activity.

Key words: galaxies: active — galaxies: nuclei — galaxies: Seyfert — galaxies: starburst — infrared: galaxies

1. Introduction

A galaxy that exhibits bright emission in the nuclear region is termed an Active Galactic Nucleus (AGN). The origin of the radiative energy is a putative release of gravitational energy through accretion of the interstellar medium from the host galaxy onto a central super-massive black hole (SMBH) with an inflated turbulent torus around the central SMBH. However, with limited spatial resolution, it is difficult to detect the emission from the nuclear starbursts, since they are diluted by strong AGN emission. Here, we discern these emissions and estimate the magnitudes of starburst activities using infrared K-band (1.9–2.5 μm) and L-band (2.8–4.2 μm) spectra.

Polycyclic Aromatic Hydrocarbon (PAH) emission at around 3.3 μm in the L-band is a powerful tool for distinguishing starburst emission from AGN emission. PAH molecules are widely distributed throughout interstellar space (Tanaka et al. 1996). The PAH molecules are not destroyed and are excited by non-ionizing UV photons from stars, and then emit the line at 3.3 μm in the Photo-Dissociation Region (PDR) for a starburst (Sellgren 1981), whereas the PAH molecules are destroyed by X-rays (Voit 1992) from AGN. Observationally, a normal starburst galaxy, which consists of HII regions, PDRs, and molecular gas (e.g., M 82 and NGC 253), shows 3.3 μm PAH emission (Tokunaga et al. 1991; Imanishi & Dudley 2000), whereas a pure AGN shows only PAH-free continuum emission from larger-sized AGN-heated hot dust grains (Moorwood 1986; Imanishi & Dudley 2000) because an AGN emits strong X-rays in addition to UV. Additionally, because the 3.3 μm PAH emission feature is very strong, it is for star formation because it can be suppressed in the inner portion by tidal forces from the SMBH. In fact, it was argued that such starburst activity could occur in the dusty torus in the nuclear region (<100 pc) of a Seyfert galaxy (Wada & Norman 2002; Imanishi 2003). We call such starbursts in Seyfert nuclei "nuclear starbursts". Wada and Norman (2002) showed that nuclear starbursts in the dusty torus can produce an inflated turbulent torus around the central SMBH. However, if the nuclear region has a concentration of star formation and it would control the AGN activity.

1 It assumes that LINERs are powered by AGN (Ho et al. 1997).
detectable even if the starbursts are weak.

Nuclear starbursts in Seyfert galaxies can also be investigated through infrared K-band spectra. The CO (Δν = 2–0) absorption feature at λ_{rest} = 2.3–2.4 μm is caused by the CO molecule in the photosphere of a cool stellar population (i.e., red giants and supergiants) (Frogel et al. 1978; Doyon et al. 1994). Empirically, starburst galaxies exhibit a substantially deeper CO (Δν = 2–0) feature than do quiescent spirals (Frogel et al. 1978; Ridgway et al. 1994), and AGNs do not exhibit this absorption feature.

Furthermore dust extinction is much higher in the K- and L-bands than at shorter wavelengths, A_K ~ 0.062 A_V and A_L ~ 0.031 A_V, respectively (Nishiya et al. 2008, 2009), so that the quantitative uncertainty of the dust extinction correction is significantly reduced compared with shorter wavelengths (e.g., UV, optical). Thus, K- and L-band spectra enable us to estimate the relative contributions of AGN and starbursts to emission in an observed spectrum in a quantitatively reliable manner (Olive et al. 1999; Ivanov et al. 2000; Rodríguez-Ardila & Viegas 2003; Imanishi 2003; Imanishi & Alonso-Herrero 2004; Imanishi & Wada 2004; Davies et al. 2007).

The above authors studied mainly nearby Seyfert galaxies with high infrared luminosities (L_{IR} \gtrsim 10^{44} \text{erg s}^{-1}), and found a correlation between the AGN activity and the nuclear starburst activity (Imanishi 2003; Imanishi & Alonso-Herrero 2004; Imanishi & Wada 2004). However, it is unclear whether the correlation holds over a wide range of AGN luminosity. Haas et al. (2005) argued that the height of the torus is smaller in lower luminosity Seyfert galaxies compared with higher luminosity Seyfert galaxies, suggesting that nuclear starbursts are weaker in low-luminosity AGNs. In contrast, Ballantyne (2008) predicted that parsec-scale starbursts would be associated with lower luminosity AGNs. Kawakatu and Wada (2008) predicted that the ratio of the scatter in the AGN to starburst luminosity would increase in low-luminosity AGNs.

To resolve this issue, it is necessary to study Seyfert galaxies over a wide AGN luminosity range. Thus, we performed K- and L-band spectroscopy on a large sample of Seyfert galaxies with luminosity ranging from low to high. Throughout this paper, H_0 = 75 \text{km s}^{-1} \text{Mpc}^{-1}, Ω_M = 0.3, Ω_Λ = 0.7 are adopted.

2. Target Selection

Imanishi (2003), Imanishi and Alonso-Herrero (2004), and Imanishi and Wada (2004) studied Seyfert galaxies taken from CfA (Huchra & Burg 1992) and 12 μm (Rush et al. 1993) samples. The CfA and 12 μm samples were selected through the optical spectroscopy of large numbers of galaxies limited to the optical and IRAS 12 μm fluxes, respectively. The CfA sample is usually regarded as a complete sample of optically selected Seyfert galaxies. However, Ho and Ulvestad (2001) argued that the CfA sample is likely to be complete only for relatively bright objects.

Therefore, we added objects from the Palomar sample (Ho et al. 1995) to this paper. Seyfert galaxies in the Palomar sample were selected through the optical spectroscopy of nearby, bright (B_T ≤ 12.5 mag), northern (declination > 0°) galaxies covering a wider AGN luminosity range. Our aim is to confirm the relationship between AGN and nuclear starburst activity over a wide AGN luminosity range, while paying particular attention to low-luminosity AGN. To be easily observable from Mauna Kea, Hawaii (our observing site; latitude ~ 20°), the declinations of Seyfert galaxies were limited to be greater than −30°. Owing to the telescope limit on the IRTF 3.0-m telescope used in this study, a restriction on a declination of less than 68° was also applied. In total, 13 objects in the Palomar sample (table 1) were observed. We also added some additional re-observed Seyfert galaxies to our targets. These galaxies are those studied by Imanishi (2003), Imanishi and Alonso-Herrero (2004), and Imanishi and Wada (2004), in which PAH emission was barely discernible, but with less than 3σ, as reported in these papers (NGC 262, NGC 513, Mrk 993, MCG −3−58−7, F 03450+0055, NGC 931, and NGC 5548). Moreover, we also included 0152+06 in the CfA sample and MCG −2−8−39 in the 12 μm sample in our targets. Both of them meet the declination criteria of these papers, but were not observed in previous papers. To summarize, 13 objects from the Palomar sample, seven re-observed objects discussed in previous papers, and two new objects from CfA and 12 μm samples are included in this paper.

Six of the 22 targets are Seyfert 1 galaxies, and the remaining 16 targets are Seyfert 2 galaxies. Infrared (8–1000 μm) luminosity of our targets is log L_{IR} = 42.5–44.8 erg s^{-1} for the Palomar sample and log L_{IR} = 43.6–44.8 erg s^{-1} for the CfA and 12 μm samples (see a footnote of table 1 for the definition of L_{IR}). Detailed information on the targets is summarized in table 1. We define type 1–1.5 and type 1.8–2 Seyfert galaxies as Seyfert 1 and Seyfert 2 galaxies, respectively. Mrk 993 was classified as a Seyfert 2 galaxy in the CfA sample, but later reclassified as a Seyfert 1.5 galaxy (Osterbrock & Martel 1993). We adopted the latter classification and thus classified it as a Seyfert 1 galaxy, although it was regarded as being a Seyfert 2 galaxy by Imanishi and Alonso-Herrero (2004).

3. Observations and Data Analysis

Table 2 summarizes our observation log. All targets were observed with SpeX (Rayner et al. 2003) attached to the IRTF 3.0-m telescope on Mauna Kea, Hawaii. SpeX has a 1.9–4.2 μm cross-dispersed spectropolar mode (LXD1.9 mode), enabling us to observe K- and L-band spectra simultaneously. Because the seeing in K measured with the SpeX guiding/imaging mode was about 0''4–0''8 (FWHM) throughout the observations (except on 2009 March 26 and 27), we consistently used a 0''8-wide slit. On 2009 March 26 and 27, the seeing was over 1''0 at K, so we used a 1''6-wide slit during those observations. A standard telescope nodding technique (ABBA pattern) with a throw of 7''5 was employed along the slit to subtract background emission. The physical scale probed by our slit spectroscopy was 24–500 pc, while taking into account the redshift, z = 0.002–0.032, and the slit width. We observed A-K, F-K, and G-type main-sequence stars (table 2) as standard stars. These were used to correct for transmission through the Earth’s atmosphere. We observed the standard stars at airmasses similar to the targets (<0.1 difference), before and after the observation of each target to better correct for possible time variations in the Earth atmosphere.
The spectra were reduced using standard IRAF tasks. Frames taken with an A (B) beam were subtracted from frames taken with a B (A) beam, and then median images were taken with a B (A) beam, and then median images were replaced by cosmic rays were replaced by interpolated values from the surrounding pixels. The spectra were reduced using standard IRAF tasks.

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2 IRAF is distributed by the US National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.

| Object | z   | $D_L$ | Class | $f_{12}$ | $f_{25}$ | $f_{60}$ | $f_{100}$ | $f_{10.8}$ | log $L_{1IR}$ |
|--------|-----|-------|-------|---------|---------|---------|-----------|------------|--------------|
| NGC 676 | 0.0050 | 20.2 | Sy2   | 0.04    | 0.06    | 0.27    | 0.80      | ...        | 42.3         |
| NGC 1167 | 0.0165 | 66.8 | Sy2   | <0.03   | <0.04   | 0.12    | 1.05      | ...        | 43.3         |
| NGC 1275 | 0.0176 | 71.2 | Sy1   | 0.93    | 3.02    | 7.09    | 7.60      | ...        | 44.8         |
| NGC 1358 | 0.0134 | 54.3 | Sy2   | <0.08   | <0.12   | 0.38    | 0.93      | ...        | 43.4         |
| NGC 3982 | 0.0035 | 14.2 | Sy2   | 0.47    | 0.97    | 7.18    | 16.20     | <0.11      | 43.3         |
| NGC 4258 | 0.0015 | 6.2  | Sy2   | 2.25    | 2.81    | 2.81    | 78.40     | ...        | 43.0         |
| NGC 4579 | 0.0050 | 20.3 | Sy2   | 1.12    | 0.78    | 5.93    | 21.40     | 0.08 (0.06) | 43.7         |
| NGC 5194 | 0.0020 | 8.0  | Sy2   | 7.21    | 9.56    | 97.40   | 211.00    | <0.07      | 43.9         |
| NGC 5273 | 0.0036 | 14.4 | Sy2   | 0.12    | 0.29    | 0.90    | 1.560     | ...        | 42.5         |
| NGC 6764 | 0.0080 | 32.4 | Sy2   | 0.54    | 1.33    | 6.62    | 12.40     | ...        | 44.0         |
| NGC 6951 | 0.0048 | 19.1 | Sy2   | 1.34    | 2.16    | 16.20   | 41.80     | ...        | 44.0         |
| NGC 7479 | 0.0079 | 32.0 | Sy2   | 1.37    | 3.86    | 14.90   | 26.70     | ...        | 44.4         |
| NGC 7743 | 0.0057 | 22.9 | Sy2   | 0.10    | 0.18    | 0.92    | 3.40      | ...        | 43.0         |

(1): Object name. †, ‡, § are reference; † Palomar sample (Ho & Ulvestad 2001), ‡ CfA (Huchra & Burg 1992), § 12 μm (Rush et al. 1993).

(2): Redshift. (3): Luminosity distance in Mpc. (4): AGN class. (5)–(8): Fluxes at 12, 25, 60, and 100 μm in Jy, respectively from IRAS faint source catalog. (9): Ground-based 10.8 μm photometric data, observed with the Palomar 5-m telescope using a 1.75 aperture (Gorjian et al. 2004).

* NGC 4579 was observed also by Horst et al. (2009) using VLT/VISIR with a 1.7 arcsecond aperture. (10): Decimal logarithm of infrared (8–1000 μm) luminosity in erg s⁻¹ calculated with $L_{1IR} = 2.17 \times 10^{39} \times D_L^2 (\text{Mpc})^2 \times (13.48 \times f_{12} + 5.16 \times f_{25} + 2.58 \times f_{60} + f_{100})$ erg s⁻¹ (Sanders & Mirabel 1996).

4. Results

4.1. L-Band Spectrum

Figure 1 shows flux-calibrated 3.0–3.6 μm slit spectra in the L-band. Although the full L-band (2.8–4.2 μm) wavelength range is covered by SpeX, both ends of the L-band are noisy because of poor transmission through the Earth’s atmosphere ($\lambda < 3.0 \mu m$) and high background emission from the Earth’s atmosphere ($\lambda > 3.6 \mu m$). We removed those data points for the discussions in this paper because they were not...
necessary for our scientific aims. In these plots, some objects show a clear excess at $3.29\mu m \times (1+z)$, whose wavelength corresponds to the redshifted $3.3\mu m$ PAH emission feature. We regard the features as being detected when at least two consecutive data points at around $3.29\mu m$ are higher than 1.5-times the scatter of the continuum level. Using this criterion, objects with detectable PAH emission are marked with “$3.3\mu m$ PAH”, and PAH non-detected objects are marked with “$3.3\mu m$ PAH(?)” in the figure. We fitted the emission line to a Gaussian function by setting the normalization, full width at half maximum (FWHM), and central wavelength of the emission as free parameters, and then estimated the flux ($I_{3.3\mu m}$), luminosity ($L_{3.3\mu m}$), and rest-frame equivalent width ($EW_{3.3\mu m}$) of the $3.3\mu m$ PAH emission. For objects with no clear PAH emission features, we estimated the upper limits by fitting the emission line with a Gaussian function, whose height, central wavelength, and FWHM were fixed as $3\sigma$, where $\sigma$ was the dispersion of its continuum emission, $3.29 \times (1+z)\mu m$ and $0.02 \times (1+z)\mu m$ (Tokunaga et al. 1991), respectively. The strengths of the $3.3\mu m$ PAH emission features are summarized in Table 3 (in p1517).

The $3.3\mu m$ PAH emission feature was detected in $\sim 23\%$ (5/22) of the observed Seyfert galaxies (NGC 6764, 5194, 5273, F 03450+0055, and MCG $3\mu m$), whose wavelength is as high as those of starburst galaxies ($\sim 100\mu m$: Imanishi & Dudley 2000). Although four objects (NGC 5194, NGC 5273, F 03450+0055, and MCG $3\mu m$) show detectable $3.3\mu m$ PAH emission, the $EW_{3.3\mu m}$ values are significantly smaller than $\sim 100\mu m$. The other 17 objects do not display detectable PAH features.

### 4.2. K-Band Spectrum

Flux-calibrated 2.0–2.5$\mu m$ slit spectra in the $K$-band are shown in figure 2 (in p1518). Most of the spectra show a flux depression at $\lambda_{\text{obs}} > 2.3\mu m$ in the observed frame, which is attributed to the CO ($\Delta v = 2\rightarrow 0$) molecular absorption feature. The strength of the CO absorption feature was quantified by a spectroscopic $CO_{\text{spec}}$ index defined by Doyon et al. (1994) as follows:

$$CO_{\text{spec}} \equiv -2.5 \log_{10}(R_{2.3\mu m}).$$

where $(R_{2.3\mu m})$ is an average of the actual signal at $\lambda_{\text{rest}} = 2.31$–2.40$\mu m$ divided by a power-law continuum ($F_{\lambda} = \alpha \times \lambda^{\beta}$) extrapolated from shorter wavelengths. Since some strong emission features appear at around 2$\mu m$ in $K$-band, such as
Infrared 3.0–3.6 μm slit spectra (L-band) of 22 Seyfert nuclei. The abscissa and ordinate are the observed wavelength in μm and $F_\lambda$ in $10^{-15}$ W m$^{-2}$ μm$^{-1}$, respectively. The length of the bar at the upper right of each figure indicates the 1σ error for the continuum. The phrase “3.3 μm PAH” [“3.3 μm PAH(?).”] indicates the detectable (undetectable) 3.3 μm PAH emission. The best-fit Gaussian profile is shown for objects with detected 3.3 μm PAH emission. For our 3.3 μm PAH detection criteria, please refer to subsection 4.1 in the text.

H$_2$ 1–0 S(1) ($\lambda_{\text{rest}} = 2.122$ μm), Brγ ($\lambda_{\text{rest}} = 2.166$ μm), and H$_2$ 1–0 S(0) ($\lambda_{\text{rest}} = 2.223$ μm), we used data points at $\lambda_{\text{rest}} = 2.1–2.29$ μm to fit the continuum level after excluding these emission lines. The continuum level is shown as a solid line in figure 2. The $CO_{\text{spec}}$ of all our targets are given in table 3. The $CO_{\text{spec}}$ values of cool stars are typically 0.2–0.3 (Doyon et al. 1994). For objects with a clear CO absorption feature ($CO_{\text{spec}} > 0.02$), “CO absorption” signature is written in figure 2. About 77% (17/22) of observed Seyfert galaxies show clear CO absorption features. Figure 3 (in p1521) is a histogram of the $CO_{\text{spec}}$ of Luminous Infrared Galaxies (LIRGs: their luminosities are generally explained by starbursts) measured by Ridgway et al. (1994). It suggests that their typical value is also ~0.2–0.3. If the properties of nuclear starbursts in Seyfert galaxies are similar to those of starbursts in LIRGs, the $CO_{\text{spec}}$ of the starbursts in Seyfert galaxies is also expected to be 0.2–0.3. However, the observed $CO_{\text{spec}}$ is smaller than the typical value for a LIRG, because featureless AGN emission is superposed in the K-band spectrum.

5. Discussion

5.1. K–L Color

Because we took K- and L-band spectra simultaneously, the possible slit loss caused by IRTF/Spex tracking error is similar, and the sky conditions are the same for the...
The derived $K - L$ colors are very reliable. The emission from normal stars ($>2000\,K$) in the $L$-band is much weaker than that in the $K$-band, whereas hot ($\sim 1000\,K$) dust heated by an AGN emits strongly in both the $K$- and $L$-bands. Thus, the $K - L$ colors become smaller (bluer) with increasing relative contribution from stellar emission to the total emission of the nuclear region. Indeed, intrinsic $K - L$ colors of Seyfert 1 galaxies are typically $1 - 2\,\text{mag}$ (Alonso-Herrero et al. 2003), and those of normal spiral galaxies are $K - L < 0.4$ (Willner et al. 1984). Therefore, the color enables us to distinguish starburst-important Seyfert galaxies from AGN-dominant ones. The nuclear $K - L$ colors derived from our slit spectra are summarized in column (6) of table 3.

For the combined sample used in this paper, taken from Imanishi (2003), Imanishi and Alonso-Herrero (2004), and Imanishi and Wada (2004), we compared the $K - L$ colors of Seyfert 1 and 2 galaxies (figure 4). Most of the Seyfert 1 galaxies are distributed in the $K - L = 1 - 2\,\text{mag}$ range, whereas the colors of almost half of Seyfert 2 galaxies are bluer than the Seyfert 1 galaxies ($K - L < 1\,\text{mag}$). This shows that stellar contamination is relatively larger in Seyfert 2s than Seyfert 1s in the observed total emission. Two possibilities could explain the result. First, AGN emission is strongly affected by the extinction of a dusty torus compared with nuclear starburst emission. In the AGN unified model, because the AGN emission comes from the central region, the emission from a Seyfert 2 galaxy passes through the dusty torus, and is more strongly absorbed by it than those from a Seyfert 1 galaxy. Thus, the observed AGN emission of Seyfert 2 galaxies is significantly weaker. Second, the starburst activity in Seyfert 2 galaxies is more extensive than in Seyfert 1 galaxies, leading to a larger contribution from stellar emission.
would be relatively weak compared to Seyfert 1 galaxies. However, if the nuclear starbursts are occurring in the outer region of the dusty torus, then the absorption effect would not be much different between these types of Seyfert galaxies. In this case, the starburst contribution to the total emission would be relatively significant in Seyfert 2s when compared with Seyfert 1s, and then the $K - L$ colors of Seyfert 2s would be bluer than those of Seyfert 1s. Another possible explanation is starbursts in the central region in Seyfert 2 galaxies could be more active than those in Seyfert 1 galaxies. If strong nuclear starbursts inflate the dusty torus more thickly than weaker starbursts, then a Seyfert galaxy with active starbursts is much more likely to be observed as type 2, and its color would be bluer than one with weak starbursts. However, as we discuss in sub-subsection 5.2.1, we find no clear difference between Seyfert 1 and 2 galaxies in the quantitatively measured 3.3 µm PAH luminosity. It is thus unlikely that the difference in the $K - L$ colors between Seyfert 1s and 2s is caused by the intrinsic difference of starburst activities in them. Therefore, we suggest that the bluer $K - L$ colors of Seyfert 2s than Seyfert 1s are due to obscuration of AGN emission and to relative contamination of the stellar emission in Seyfert 2 galaxies. Kotilainen et al. (1992) and Alonso-Herrero et al. (1996) deconvolved the surface brightness profile of Seyfert 1s and 2s within 3′ aperture into the combination of a nuclear source (non-stellar component), a bulge component and a disk component, and suggested that the stellar contamination to the total emission is larger in Seyfert 2s than in Seyfert 1s.

Figures 5a and 5b (in p1522) show the $K - NUL_L$ color versus the $EW_{3\mu m PAH}$ and $CO_{spec}$ of the sample. These figures show that both $EW_{3\mu m PAH}$ and $CO_{spec}$ increase with reddening $K - L$ color. Thus, they are useful tracers for estimating the

![Fig. 1. (Continued)](https://academic.oup.com/pasj/article-abstract/62/6/1509/1503683/29 July 2018)
starburst contribution to the nuclear spectra inside our slit. The trends of Seyfert 2 galaxies in figure 5 are similar to those for Seyfert 1 galaxies. In figure 5b, however, some fraction of Seyfert 2 galaxies in our sample reach to $C_{\text{spec}} = 0.2$–0.3, which is closer to those of LIRGs, compared to Seyfert 1 galaxies. This is in good agreement with the suggestion above. In other words, the $C_{\text{spec}}$ values of some fraction of Seyfert 2 galaxies are not strongly diluted by AGN emission.

5.2. Comparison of Nuclear Starbursts with AGN Power

5.2.1. IRAS 12 and 25 $\mu$m luminosity

We compare the nuclear starburst activity with the AGN activity over a wide AGN luminosity range. The nuclear starburst activity is reasonably quantifiable from the observed 3.3 $\mu$m PAH emission luminosity inside our slit spectrum. Meanwhile, Alonso-Herrero et al. (2003) showed that the obscuring effects of the AGN emission for Seyfert galaxies became insignificant at longer than 10 $\mu$m. IRAS 60 and 100 $\mu$m luminosities contain more contamination of emission from star formation in the host galaxy than do IRAS 12 and 25 $\mu$m luminosities (Spinoglio & Malkan 1989; Rodriguez Espinosa & Perez Garcia 1997; Alonso-Herrero et al. 2002), so we use IRAS 12 and 25 $\mu$m luminosities as good tracers of the AGN power in Seyfert galaxies. A comparison between the IRAS 12 and 25 $\mu$m luminosities and the observed nuclear 3.3 $\mu$m PAH emission luminosity is shown in figures 6a and 6b (in p1522), respectively. In these figures, we combined our data with the data of four sources observed by Rodriguez-Ardila and Viegas (2003) using the 0.8 slit width of IRTF/SpEx.

We see no clear difference in $L_{3.3\text{PAH}}$ between the two types of Seyfert galaxies when normalized to the AGN power. This means that we see no evidence of the possibility that Seyfert 2 galaxies tend to show intrinsically stronger starburst activities than do Seyfert 1 galaxies, a possibility discussed in section 6. In figure 6, the nuclear 3.3 $\mu$m PAH luminosities for our objects combined with previous data are $L_{3.3\text{PAH}} \sim 10^{38}$–$10^{39}$ erg s$^{-1}$. In starburst-dominated galaxies, the 3.3 $\mu$m PAH-to-far-infrared (40–500 $\mu$m) luminosity ratios ($L_{3.3\text{PAH}}/L_{\text{FIR}}$) are $\sim 1 \times 10^{-3}$ (Mouri et al. 1990). The nuclear star-formation rates (SFR) were calculated by SFR $M_\odot$ yr$^{-1} = (L_{\text{FIR}}/2.2 \times 10^{43}$ erg s$^{-1}$) (Kennicutt 1998). Thus, the SFR of our sample could be up to 4.5–450 $M_\odot$ yr$^{-1}$. Wada et al. (2009) showed that a supernova rate (SNR) of 5.4 to 540/yr, corresponding to 7.7–770 $M_\odot$ yr$^{-1}$ (SNR $\approx 0.007$ SFR), can produce torus heights as large as 10 pc at the outer side, $\approx 5$ pc. Hence, the star-formation rate of almost our entire sample could be high enough to create a geometrically thick dusty torus. We should note, however, that we have only upper limits on the nuclear 3.3 $\mu$m PAH luminosities for many objects in our sample, so it is likely that the sample contains Seyfert galaxies that do not have a thick dusty torus.

The figures show that the nuclear starburst luminosity decreases with decreasing AGN power, and that the trend does not change over a wide AGN luminosity range. The ratios of starburst activity to AGN activities for both Seyfert 1 and 2 galaxies show the same levels of scatter, and we find no obvious difference between them. We applied the generalized Kendall rank correlation statistics provided in the Astronomy
Survival Analysis package (ASURV: Isobe et al. 1986) (which handles data with upper limits) to figures 6a and 6b. The probabilities that a correlation is not present for the figures were both found to be ~0.005%. The results show that there is a tight correlation between the 3.3 μm PAH luminosity in the central region and the IRAS 12 and 25 μm luminosities.

### 5.2.2. Ground-based N-band luminosity

Although the contamination from star formation activity in IRAS 12 and 25 μm is less than in the IRAS 60 and 100 μm, it could be that the IRAS 12 and 25 μm data still contain a significant amount of emission from star-forming activity of the host galaxies in our low luminosity AGN sample, given the large aperture of IRAS 12 μm (0.75 × 4.5) and 25 μm (0.75 × 4.6). Ramos Almeida et al. (2009) compared small aperture unresolved nuclear 10 μm emission (0.5′-0.5′/5) and 20 μm emission (0.5′-0.5′/5) with the IRAS 12 μm and 25 μm emission, respectively, and found that the large-aperture data are highly contaminated by starlight. It is thus likely that the IRAS 12 μm and 25 μm emission is significantly contaminated by star formation in the host galaxies. To reduce any possible ambiguity, we should compare the 3.3 μm PAH emission with an AGN indicator measured with a smaller aperture. The N-band (λ0 = 10.78 μm, Δλ = 5.7 μm) is observable from the ground, and its luminosity is also thought to be a good tracer of AGN power (Alonso-Herrero et al. 2002; Ramos Almeida et al. 2009; Levenson et al. 2009). Gorjian et al. (2004) presented N-band photometric data for the central regions of Seyfert galaxies. They used the Palomar 5-m telescope with a 1.5′ aperture. Only 41% (9/22) of our objects were measured by Gorjian et al. (2004). We combine these data with data from Imanishi and Wada (2004), which is shown in figure 7 (in p1523). Although the number of low-luminosity AGNs is small and their 3.3 μm PAH emission luminosities are only upper limits, the three low luminosity Seyfert galaxies are distributed around a line extrapolated from the stronger AGN activity region. We also applied the generalized Kendall rank correlation statistics to figure 7. The uncorrelated probability is ~0.03% for the figure. These results mean that the correlation between the luminosities of the nuclear starbursts detected inside the slit spectra and the central AGNs is statistically confirmed in Seyfert galaxies for all observed quantities. We found the relation between the luminosities of 3.3 μm

| Object  | f_{3.3PAH} \times 10^{4} \text{erg s}^{-1}\text{cm}^{-2} | \log(L_{3.3PAH}) \text{ (erg s}^{-1}) | EW_{3.3PAH} \text{ (nm)} | CO_{spec} | K − L \text{ (mag)} | SFR \text{ (M}_{\odot}\text{yr}^{-1}) |
|---------|-----------------------------------------------|------------------|-----------------|-----------------|--------------------|-----------------|
| NGC 676 | < 11.58                                       | < 39.73           | < 10.79          | 0.20            | --0.08             | < 0.24           |
| NGC 1167| < 7.85                                        | < 40.60           | < 18.02          | 0.23            | 0.14               | < 1.80           |
| NGC 1275| < 31.58                                       | < 41.26           | < 4.26           | 0               | 1.79               | < 8.22           |
| NGC 1358| < 9.21                                        | < 40.49           | < 21.53          | 0.18            | --0.04             | < 1.39           |
| NGC 3982| < 6.17                                        | < 39.15           | < 28.42          | 0.16            | 0.27               | < 0.06           |
| NGC 4258| < 13.57                                       | < 38.77           | < 4.17           | 0.16            | 0.95               | < 0.03           |
| NGC 4579| < 3.22                                        | < 39.17           | < 1.37           | 0.18            | 0.61               | < 0.07           |
| NGC 5194| 6.99                                          | 38.71             | 12.08            | 0.20            | 0.14               | 0.02             |
| NGC 5273| 8.55                                          | 39.30             | 9.57             | 0.11            | 0.72               | 0.09             |
| NGC 6764| 40.50                                         | 40.68             | 91.72            | 0.22            | 0.54               | 2.18             |
| NGC 6951| < 6.05                                        | < 39.40           | < 19.64          | 0.24            | 0.15               | < 0.11           |
| NGC 7479| < 16.53                                       | < 40.28           | < 10.77          | 0.10            | 1.59               | < 0.87           |
| NGC 7743| < 4.39                                        | < 39.42           | < 4.76           | 0.25            | 0.28               | < 0.12           |
| NGC 262 | < 13.01                                       | < 40.74           | < 1.94           | 0.02            | 1.98               | < 2.51           |
| NGC 513 | < 4.35                                        | < 40.49           | < 5.92           | 0.11            | 1.11               | < 1.41           |
| NGC 931 | < 11.15                                       | < 40.76           | < 1.34           | 0               | 1.74               | < 2.61           |
| NGC 5548| < 14.63                                       | < 40.88           | < 5.09           | 0.01            | 1.54               | < 3.43           |
| Mrk 993 | < 4.72                                        | < 40.32           | < 10.98          | 0.16            | 0.57               | < 0.96           |
| MCG −2−8−39 | < 6.24                                   | < 41.02           | < 21.46          | 0.16            | 1.20               | < 4.80           |
| MCG −3−38−7 | < 10.64                                | 41.32             | 1.96             | 0.02            | 1.84               | 9.40             |
| F 03450+0055 | < 3.36                               | 40.79             | 0.56             | 0.01            | 1.65               | 2.78             |
| 0152+06 | < 2.35                                        | < 40.12           | < 6.70           | 0               | 1.02               | < 0.60           |

(1): Object name. (2): 3.3 μm PAH emission flux in 10^{-14} erg s^{-1} cm^{-2}. (3): Decimal logarithm of nuclear 3.3 μm PAH emission luminosity in erg s^{-1}. (4): Rest-frame equivalent width of 3.3 μm PAH emission line in nm. (5): Spectroscopic CO_{spec} index at λ_{rest} = 2.3–2.4 μm in the rest frame. The definition appears in the text subsection 4.2. (6): K − L color (mag) measured in this work. (7): Nuclear star-formation rate in M_\odot yr^{-1} inside our slit sizes.
Fig. 2. Infrared 2.0–2.5 μm slit spectra (K-band) of 22 Seyfert nuclei. The abscissa and ordinate are the same as in figure 1. The phrases “S(1)”, “Brγ”, and “S(0)” show the excess emission lines of H2 1–0 S(1) (λrest = 2.122 μm), Brγ (λrest = 2.166 μm), and H2 1–0 S(0) (λrest = 2.223 μm), respectively. Indistinct lines are marked as “S(1)(?)”, “Brγ(? )”, and “S(0)(?)”. The symbol “CO absorption” indicates a clear absorption feature at λrest = 2.3–2.4 μm.

PAH emission within our slit width and of the N-band. However it is of concern that the L3.3PAH is affected by the physical aperture size probed by the slits. This means that we are concerned about the possibility that the L3.3PAH of the most luminous object is due to the largest area that we observed. If the star formation traced by L3.3PAH is spatially extending in a wide area of the host galaxy, then L3.3PAH becomes higher with a larger physical scale. To explore this, we compared the L3.3PAH with the physical area of each source (figure 8). The figure clearly shows that not all high L3.3PAH objects have a wide physical area coverage. That is to say, star formation would be occurring in the central region inside the slits and not spatially extend.

5.3. Trigger of Accretion onto SMBH

We find no evidence that the ratio of starbursts to the AGN luminosity deviates upward in low-luminosity AGNs, as predicted by Kawakatu and Wada (2008), or that nuclear starburst activities increase with decreasing AGN activities, as predicted by Ballantyne (2008). Furthermore, we find no clear change in the correlations over a wide AGN luminosity range. This is explained if the main mechanism that connects the AGN and nuclear starbursts is the same at each luminosity range. A model shown in Wada and Norman (2002; see also Wada et al. 2009), which predicts the enhancement of the mass-accretion rate onto a central SMBH owing to increased
turbulence of molecular gas in the torus caused by nuclear starbursts, is one possible scenario that could account for the luminosity correlation.

5.4. The Origin of the CO\text{spec} Index

We calculated the stellar luminosity ($L_{\text{Kstellar}}$) from CO\text{spec}. If nuclear starbursts with properties similar to star-formation-dominated LIRGs appear inside our slit and the entire K-band emission comes from stars, then the detected CO\text{spec} must be 0.2–0.3. We assumed that the original CO\text{spec} of the cool star was 0.25. When the contributions of stellar emission to the total emission are 100%, the average signal at $\lambda_{\text{rest}} = 2.31–2.4\mu m$ is reduced by about 20.5% compared with the extrapolation from a shorter wavelength. When the contribution of AGN emission to the total emission is 100%, the absorption feature does not appear. When the contributions of both stellar and AGN emission are equal, the average signal at $\lambda_{\text{rest}} = 2.31–2.4\mu m$ should be 10.25%, reduced from the shorter wavelength, and the CO\text{spec} should be 0.117.

In the case that the CO\text{spec} is 0.1 or 0.15, the contributions of the stellar emission to the total emission should be 43% or 63%, respectively. We can thus estimate $L_{\text{Kstellar}}$.

Figure 9 compares $L_{\text{Kstellar}}$ and the 3.3 $\mu m$ PAH emission luminosity in the nuclear region detected inside our slit spectra combined with figure 5 of Imanishi and Alonso-Herrero (2004). Although they plotted these results for Seyfert 2 galaxies only, we include in figure 9 Seyfert 1 galaxies whose CO\text{spec} were derived in Imanishi and Wada (2004).
The $K$-band to infrared luminosity ratios of starburst-dominated LIRGs were estimated to be $L_K/L_{\text{IR}(8-1000\mu m)} \sim 10^{-1.6 \pm 0.2}$ (Goldader et al. 1997). If the nuclear starbursts in Seyfert galaxies have properties similar to the starburst-dominated LIRGs, then the same relation should hold. The 3.3 $\mu$m PAH to the infrared luminosity ratios in starbursts were found to be $L_{3.3\text{PAH}}/L_{\text{FIR}(40-900\mu m)} \sim 10^{-3}$ (Mouri et al. 1990). Assuming $L_{\text{IR}} \sim L_{\text{FIR}}$ for starbursts, the luminosity of the 3.3 $\mu$m PAH emission to the $K$-band stellar luminosity ratios are expected to be $L_{3.3\text{PAH}}/L_{\text{stellar}} \sim 10^{-1.4}$, if both luminosities trace the same starbursts. The value is shown as a solid line in figure 9. Most of our Seyfert 1 galaxies and about half of the Seyfert 2 galaxies plotted in the figure are distributed around the line. However, the remaining half of the Seyfert 2 galaxies are distributed under the line. Given that in figure 6, the $L_{3.3\text{PAH}}$ distribution of both Seyfert 1 and 2 galaxies is similar within their dispersions, and no obvious difference is seen between them, the discrepancy must be caused by $L_{\text{Kstellar}}$. As discussed above, $L_{\text{Kstellar}}$ is estimated from the $CO_{\text{spec}}$ value, which is related to the fraction of stellar to AGN emission. Nuclear starbursts are expected to occur at the outer part of the dusty torus and the AGN radiation of a type-2 Seyfert galaxy is significantly attenuated by the dusty torus. Therefore, $CO_{\text{spec}}$ is likely to increase, and thus increase $L_{\text{Kstellar}}$ in Seyfert 2 galaxies. In contrast, because $L_{3.3\text{PAH}}$ is estimated from the flux of 3.3 $\mu$m PAH emission, the PAH-estimated starburst luminosity is not affected by the absorption of AGN emission. In summary, we suggest that because $L_{\text{Kstellar}}$ represents a relative value of stellar-to-AGN emission, and $L_{3.3\text{PAH}}$ represents an absolute value of the stellar emission, it is possible that $L_{\text{Kstellar}}$ is overluminous and that the ratio of $L_{3.3\text{PAH}}/L_{\text{Kstellar}}$ decreases in Seyfert 2 galaxies.
Another possibility is that the signatures of stellar emission detected in the $K$-band spectra are significantly contaminated by old bulge stars in the nuclear part of the host galaxy, whereas the 3.3 $\mu$m PAH emission originates in spatially unresolved (smaller than subarcsecond) nuclear starbursts in the dusty torus because old stars do not have enough PAH-exciting UV photons. Ivanov et al. (2000) and Imanishi and Alonso-Herrero (2004) suggested that the emission of old stars in the host galaxy mainly produces the $K$-band spectra. However, most of the Seyfert 1 and some fraction of the Seyfert 2 galaxies have $L_{3.3\text{PAH}}/L_{\text{stellar}}$ ratios similar to the value expected when the origin of both luminosities is the same. Therefore, although the old stars in the host galaxy may contribute to the observed $K$-band spectra of some fraction of Seyfert galaxies, it is not likely that old stars dominate the $K$-band spectra in all objects.
6. Conclusion

The results of an infrared $K$- and $L$-band spectroscopic study of 13 Seyfert galaxies from the Palomar sample, and seven Seyfert galaxies with non-detectable 3.3 $\mu$m PAH emission discussed in previous papers and two new Seyfert galaxies from CfA and 12 $\mu$m samples are presented. Our $L$-band spectroscopic method successfully detected the 3.3 $\mu$m PAH emission in $\sim 23\%$ ($= 5/22$) of the observed Seyfert galaxies. Also, our $K$-band spectroscopic method showed that $\sim 77\%$ ($= 17/22$) of Seyfert nuclei in our sample have clear CO absorption feature. We examined the relationship between the AGN activity and the nuclear starburst activity over a wide AGN luminosity range using our spectra together on previously published spectra (Imanishi 2003; Imanishi & Alonso-Herrero 2004; Imanishi & Wada 2004). Our conclusions are summarized as follows:

1. The $K - L$ colors of Seyfert 2 galaxies are widely distributed toward the blue, compared with those of Seyfert 1 galaxies. This implies either that the dusty torus absorbs the AGN emission of Seyfert 2 galaxies from the central region, or that Seyfert 2 galaxies tend to have stronger nuclear starbursts than do Seyfert 1 galaxies. Since the $L_{3.3\text{PAH}}$ of Seyfert 1 and 2 galaxies do not differ significantly, we have interpreted this as being a result of the effect that the AGN emission of Seyfert 2s is absorbed by dust of the torus, and then the stellar emission becomes relatively larger.

2. $L_{3.3\text{PAH}}$ shows the same range in Seyfert 1 and 2 galaxies. The star-formation rates of our sample are up to $4.5 - 450 \times 10^{-3} M_{\odot} \text{yr}^{-1}$, which could be sufficient to swell the dusty torus by a supernova explosion; in short, it is geometrically thick, although many objects we provided are only with upper limits on the 3.3 $\mu$m
Fig. 7. Same as figure 6, but the abscissa is the ground-based $N$-band luminosity measured with a small aperture. Almost all $N$-band data in the abscissa are $10.8\mu m$ luminosity measured with a $1''$ aperture (Gorjian et al. 2004). Galliano et al. (2005) observed $10.4\mu m$ luminosity with $2''$ aperture for NGC 2992 and NGC 7469 using ESO 3.6-m telescope/TIMMI2, and Horst et al. (2009) observed $10.49\mu m$ luminosity with $1''$ aperture for NGC 4579, Mrk 509, and MCG –3–34–64 using VLT/VISIR. We adopted the new values for the five objects. Among the four sources studied by Rodríguez-Ardila and Viegas (2003), only two objects (NGC 3227 and NGC 4051) are plotted because of the availability of measured $10.8\mu m$ luminosity (Gorjian et al. 2004). The abscissa is a good indicator of the AGN power, and the ordinate probes nuclear starburst luminosities.

Fig. 8. Relationship between the physical scale we probed with slits and the $3.3\mu m$ PAH emission luminosity inside the slits (same symbols as in figure 6). Since all physical areas of objects, except 5 objects (Mrk 34, Mrk 78, Mrk 273, Mrk 463, Mrk 477) plotted in the figure are smaller than $2$ square kpc, larger figure focuses on the physical area from $0.001$ to $1.827$ kpc$^2$ to show the distribution. A small figure including these 5 objects is pasted on the lower right of the larger figure.

Fig. 9. Comparison between the $K$-band stellar luminosity (abscissa) and the nuclear $3.3\mu m$ PAH luminosity detected inside our slit spectra (ordinate). Symbols are the same as in figure 5. The length of the bar at the lower right of the figure represents the range in the uncertainty of $L_{\text{Kstellar}}$ due to $CO_{\text{spec}} = 0.2-0.3$. The solid line shows the predicted ratio of $L_{\text{3.3PAH}}/L_{\text{Kstellar}}$ ($\sim 10^{-1.4}$) for starbursts as seen in LIRGs.

PAH luminosities.

3. $L_{\text{3.3PAH}}$ correlates with the mid-infrared ($N$-band) luminosity with a small aperture (= tracing AGN activities), and their luminosity ratio does not vary significantly over a wide AGN luminosity range. Moreover, $L_{\text{3.3PAH}}$ is independent of the physical scale that we probed with slits. Therefore, $L_{\text{3.3PAH}}$ (i.e., star formation) would concentrate on the central region, and the nuclear star formation would induce accretion onto the SMBH and encourage AGN activity. In this work, we found no evidence that nuclear starbursts are stronger in lower-luminosity AGN.

4. We suggest that the $3.3\mu m$ PAH emission luminosity and $K$-band stellar luminosity ($L_{\text{Kstellar}}$) originate in the same phenomenon. However, for some fraction of Seyfert 2 galaxies, $L_{\text{Kstellar}}$ is likely to be overestimated because of flux attenuation of AGN emission caused by a dusty torus and contaminated by old stars in the spheroid of the host galaxy.

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