Nuclear 11.3 µm PAH emission in local active galactic nuclei

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ABSTRACT
We present Gran Telescopio CANARIAS CanariCam 8.7 µm imaging and 7.5 – 13 µm spectroscopy of six local systems known to host an active galactic nucleus (AGN) and have nuclear star formation. Our main goal is to investigate whether the molecules responsible for the 11.3 µm polycyclic aromatic hydrocarbon (PAH) feature are destroyed in the close vicinity of an AGN. We detect 11.3 µm PAH feature emission in the nuclear regions of the galaxies as well as extended PAH emission over a few hundred parsecs. The equivalent width (EW) of the feature shows a minimum at the nucleus but increases with increasing radial distances, reaching typical star-forming values a few hundred parsecs away from the nucleus. The reduced nuclear EW are interpreted as due to increased dilution from the AGN continuum rather than destruction of the PAH molecules. We conclude that at least those molecules responsible for the 11.3 µm PAH feature survive in the nuclear environments as close as 10 pc from the AGN and for Seyfert-like AGN luminosities. We propose that material in the dusty tori, nuclear gas disks, and/or host galaxies of AGN is likely to provide the column densities necessary to protect the PAH molecules from the AGN radiation field.

Key words: galaxies: individual: Mrk 1066, Mrk 1073, NGC 2273, Arp 299, NGC 6240, IRAS 17208–0014 – galaxies: Seyfert – infrared: galaxies – galaxies: active

1 INTRODUCTION
The fueling of active galactic nuclei (AGN) requires that material be driven inwards from the interstellar medium of the host galaxy to physical scales of less than 1 pc (see the review by Alexander & Hickox 2012, and references therein). Therefore, nuclear (< 100 pc regions) star formation appears to be an inevitable consequence of this process. In-
deed, numerical simulations predict that in AGN star formation in the nuclear region should be tightly correlated with the black hole accretion rate (e.g. Kawakatu & Wada 2008; Hopkins & Quataert 2014). Moreover, nuclear star formation via stellar feedback (stellar winds and supernovae) might help sustain the vertical thickness of the optically and geometrically thick dusty torus of the AGN unified model (see e.g. Wada & Norman 2002; Vollmer et al. 2008).

There is plenty of observational evidence for the presence of nuclear star formation in AGN (Davies et al. 2007; Esquej et al. 2014) and especially in Seyfert 2s (Cid Fernandes et al. 2001; González Delgado et al. 2001). However, in the local universe it is not clear whether there is increased star formation activity in the hosts and nuclear regions of type 2 AGN (e.g. Maiolino et al. 1995; Hicks et al. 2009) or not (Clavel et al. 2000; Peeters et al. 2004), and whether the nuclear/circumnuclear star formation level is a function of the activity class (e.g. radio galaxy, quasar, infrared (IR) selected quasars, see Shi et al. 2007) and/or the AGN luminosity (Diamond-Stanic & Rieke 2012; Esquej et al. 2014). Furthermore, observational and theoretical arguments suggest the existence of dynamical delays between the on-set of the nuclear star formation and the fuelling of the AGN (Davies et al. 2007; Wild et al. 2010; Hopkins 2012), perhaps indicating that these two processes might not be coeval.

Classical indicators of the presence of on-going or recent star formation (e.g. UV emission, Hα, Paα, [NeⅡ]12.8 μm, modelling of stellar populations) are difficult to use in the nuclear regions of AGN, as they can be easily contaminated by bright AGN emission. If we assume that polycyclic aromatic hydrocarbon (PAH) features are excited by star formation activity in AGN, they can be used as indicators of the star formation rate of galaxies based on their good correlation with the IR luminosity (Brandl et al. 2006; Smith et al. 2007). However, Peeters et al. (2004) noted that PAH emission might be better suited to trace B stars rather than O stars implying that PAH emission probes star formation over time scales of a few tens of millions of years rather than instantaneous star formation. PAH molecules are also predicted to be excited by AGN heating at distances of approximately 100 pc from the AGN in the case of optically thin radiation (Siebenmorgen et al. 2004). However, for optically thick radiation the PAH features from star formation heating are much stronger than those due to AGN heating (see Siebenmorgen et al. 2004 for more details).

Emission from PAH features is observed in the nuclear/circumnuclear regions of AGN (Roche et al. 1990; Clavel et al. 2000; Laurent et al. 2000; Siebenmorgen et al. 2004; Deo et al. 2004; Wu et al. 2009; Sales et al. 2010; Tommasin et al. 2010; Diamond-Stanic & Rieke 2010; González-Martín et al. 2013; Esquej et al. 2014). However, in general the PAH emission in AGN appears to have a lower contrast compared to the continuum emission than in starburst galaxies. It has been argued theoretically (Voit 1992; Siebenmorgen et al. 2004) and observationally (Aiken & Roche 1985; Wu et al. 2009; Sales et al. 2010) that this might be due to destruction of the PAH molecules in the close vicinity of the harsh radiation field of AGN. However, Diamond-Stanic & Rieke (2010) showed that in local Seyferts it is only the 6.2, 7.7, and 8.6 μm PAH features that are suppressed on kpc scales with respect to the 11.3 μm PAH feature (see also Smith et al. 2007).

Recently, Esquej et al. (2014) found no evidence of destruction of the 11.3 μm PAH carriers in the nuclear regions (typically the central 60 pc) of a sample of 29 local Seyferts as a function of the AGN luminosity. These authors argued that it is likely that the PAH molecules are protected from the AGN radiation field by material in the dusty torus (see also Voit 1992; Miles et al. 1994). Sales et al. (2013) came to a similar conclusion for the low luminosity AGN in NGC 1808. Ruschel-Dutra et al. (2014), on the other hand, interpreted the non-detection of the nuclear 11.3 μm PAH feature in two Seyfert nuclei as due to destruction of the PAH molecules by the AGN radiation field.

The main goal of this work is to explore the behaviour of the 11.3 μm PAH feature and in particular whether the molecules responsible for this feature are destroyed in the close vicinity of an AGN. To this end, we have obtained mid-infrared (mid-IR) imaging and spectroscopy using CanariCam (Telesco et al. 2003) on the 10.4 m Gran Telescopio CANARIAS (GTC) of a sample of local AGN with nuclear star formation. The paper is organised as follows. Section 2...
Table 2. Log of the GTC/CanariCam imaging observations.

| Galaxy   | Date       | $t_{\text{on}}$ (s) | Standard | IQ (arcsec) |
|----------|------------|----------------------|----------|-------------|
| Mrk 1066 | 2013.08.27 | 417                  | HD18449  | 0.24        |
| Mrk 1073 | 2013.08.27 | 626                  | HD19476  | 0.26        |
| NGC 2273 | 2013.09.24 | 626                  | HD42633  | 0.26        |
| NGC 6240 | 2013.08.27 | 626                  | HD151217 | 0.38        |
| IRAS 17208−0014 | 2013.06.07 | 1043                | HD157999 | 0.26        |

summarizes the AGN and star formation properties of the galaxies. Section 3 presents the GTC/CanariCam observations and data reduction as well as mid-IR spectroscopy obtained with the IR spectrograph (IRS, Houck et al. 2004) on board the Spitzer Space Telescope and Section 4 the analysis of the data. Section 5 describes the results on the extended continuum and 11.3 µm PAH feature. In Section 6 we discuss the EW of the 11.3 µm feature, the nuclear spectra of Seyfert galaxies, and PAH survival in the close vicinity of AGN. Finally, we give our conclusions in Section 7. Throughout this work we have assumed $H_0 = 73 \text{ km s}^{-1} \text{Mpc}^{-1}$, $\Omega_\Lambda = 0.73$, and $\Omega_M = 0.27$.

2 THE SAMPLE

We are conducting a mid-IR imaging and spectroscopic survey of approximately 100 local active galaxies using GTC/CanariCam. The sample includes luminosity AGN (PG quasars), Seyfert galaxies, radio galaxies, and low luminosity AGN. Some of these are hosted by luminous and ultraluminous IR galaxies (LIRGs and ULIRGs) with IR luminosities of $L_{\text{IR}} = 10^{11} - 10^{12} L_\odot$ and $L_{\text{IR}} > 10^{12} L_\odot$, respectively. The sample covers almost six orders of magnitude in AGN luminosity. The GTC/CanariCam observations include imaging at 8.7 µm and 7.5 – 13 µm spectroscopy as well as polarimetry for selected objects.

Among the galaxies in our sample already observed with CanariCam (see Section 3.1), we selected for this work six systems for which there is evidence in the literature of AGN activity as well as nuclear and circumnuclear star formation. Additionally, we chose galaxies showing extended 11.3 µm PAH emission in the CanariCam spectra so we could investigate the effects of the AGN on the behaviour of the feature in the vicinity of the active nucleus. We list the main properties of the six systems chosen for this work in Table II. We use, when possible, the intrinsic hard X-ray 2 – 10 keV luminosity as a proxy for the AGN luminosity. In what follows we summarize evidence of nuclear and circumnuclear on-going or recent star formation and the AGN properties for each of them. For Arp 299 (IC 694 + NGC 3690) we refer the reader to Alonso-Herrero et al. (2013, and references therein).

Mrk 1066 (UGC 2456) — This nearly LIRG ($L_{\text{IR}} \sim 8 \times 10^{10} L_\odot$) is optically classified as a Seyfert 2 galaxy with star formation activity in the nuclear region on scales of $\sim 1.5$ arcsec = 340 pc (González Delgado et al. 2001; Cid Fernandes et al. 2001; Ramos Almeida et al. 2009; Riffel et al. 2010). In particular, Riffel et al. (2010) used near-IR integral field unit (IFU) observations to reveal the presence of two star forming knots at projected distances of 0.5 arcsec southeast and 1 arcsec northwest from the...
nucleus, respectively. However, at radial distances from the AGN of less than approximately 0.5 arcsec the near-IR line ratios are dominated by AGN processes. This galaxy also shows a nuclear molecular gas disk detected in the 2.12 µm H$_2$ emission line. This gas disk is believed to provide the material to feed the AGN (Riffel & Storchi-Bergmann 2011). Mrk 1066 hosts a nearly Compton-thick Seyfert 2 nucleus (X-ray column density of $N_H = 9 \times 10^{23}$ cm$^{-2}$, Guainazzi et al. 2003) with a large observed equivalent width (EW) of the Fe Kα line at 6.4 keV. Marinucci et al. (2012) estimated an absorption corrected intrinsic 2–10 keV luminosity of $7.8 \times 10^{42}$ erg s$^{-1}$.

Mrk 1073 (UGC 2608) — This LIRG is located in the Perseus cluster and it is optically classified as a Seyfert 2, although it shows a broad component detected in the near-IR Paβ line (Veilleux et al. 1997). Mrk 1073 was also included in a radio selected sample of starburst galaxies (Smith et al. 1996). Using optical spectroscopy (González Delgado et al. 2001) and Cid Fernandes et al. (2001) demonstrated that this galaxy experienced starburst activity in the central $\sim 1.5$ arcsec = 660 pc. Mrk 1073 is a Compton-thick ($N_H > 1.6 \times 10^{24}$ cm$^{-2}$, Guainazzi et al. 2003) Seyfert 2 with a large observed EW of the Fe Kα line. We followed Marinucci et al. (2012) to correct the observed 2–10 keV luminosity (see Table 1) and estimated an intrinsic 2–10 keV luminosity of $\sim 1 \times 10^{43}$ erg s$^{-1}$.

NGC 2273 — This Seyfert 2 galaxy hosts a circumnuclear ring of star formation clearly detected in Hα+[NII] line emission with an approximate diameter of $\sim 4$ arcsec (i.e. 500 pc), while the nuclear optical line ratios are more compatible with AGN emission (Perruit et al. 2000). From optical Gemini/GMOS IFU spectroscopy, there is also evidence of the presence of a nuclear ring of star formation about 2 – 3 arcsec in diameter, based on the presence of a nuclear velocity dispersion drop (Barbosa et al. 2006). This galaxy shows nuclear dense gas emission but based on the derived Toomre parameter, Sani et al. (2012) concluded that star formation is unlikely to be taking place in the nuclear region. Using Suzaku observations, Awaki et al. (2009) confirmed the Compton-thick nature of this Seyfert galaxy and derived an absorption corrected 2 – 10 keV luminosity of $1.9 \times 10^{42}$ erg s$^{-1}$ for a 3 arcsec (for our assumed distance).

NGC 6240. — This interacting nearly ULIRG hosts two X-ray identified AGN at a projected separation of approximately 1.5 arcsec = 715 pc (Komossa et al. 2003). From a detailed modelling of the adaptive optics (AO) near-IR VLT/SINFONI IFU observations, Engel et al. (2010) concluded that there is recent merger-induced star formation activity in both nuclei. However, the young starbursts do not dominate the near-IR luminosity of the system. Using Keck mid-IR spectroscopy Egami et al. (2006) showed that the 11.3 µm PAH emission in the nuclear regions is extended over $\sim 3$ arcsec = 1.4 kpc. The Chandra X-ray observations of the nuclei revealed the presence of Fe Kα lines with high EW indicating the Compton-thick nature of the nuclei. The observed 0.1 – 10 keV luminosities of the southern and northern nuclei, are approximately $10^{43}$ erg s$^{-1}$ and $3 \times 10^{41}$ erg s$^{-1}$ (Komossa et al. 2003). The absorption corrected 2–10 keV X-ray luminosities are therefore expected to be a few times $10^{43}$ erg s$^{-1}$. By modelling the IR emission of the southern nucleus using clumpy torus models, Meri et al. (2014) estimated that the AGNs contribute to 30 – 50% of the total luminosity of the system.

IRAS 17208–0014 — This is a late-stage merger ULIRG with a single nucleus. Arribas & Colina (2003) compared optical IFU observations with Hubble Space Telescope (HST) near-IR data and concluded that the optical peak does not coincide with the true near-IR nucleus. They also reclassified the nuclear activity to LINER. There is evidence of nuclear ($\sim 250$ pc) and extended star formation from Keck mid-IR imaging (Soifer et al. 2000). Piqueras-López et al. (2012) obtained VLT/SINFONI near-IR IFU observations of IRAS 17208–0014 and found extended Paα emission over 4 arcsec = 3.2 kpc with an off-nuclear region with a large EW of Paα and located approximately 1 kpc to the southwest. The hard X-ray emission of this galaxy is explained by the presence of a Compton-thick AGN with an intrinsic 2–10 keV luminosity of $9 \times 10^{42}$ erg s$^{-1}$ (González-Martín et al. 2001).

Summarizing, the six systems selected for this work, even those optically classified as LINER (see Table 1), show AGN luminosities that are typical of the Seyfert galaxies in our CanariCam sample. In terms of their IR luminosities, all except NGC 2273, are nearly LIRGs, LIRGs or ULIRGs. This is well understood because we chose them to have strong nuclear and circumnuclear star formation activity as most (U)LIRGs, and in this sense they may not be representative of the entire AGN sample. We will present a full study of the nuclear star formation activity in our sample of AGN using the 11.3 µm PAH feature once the CanariCam observations are finalised.

Table 3. Log of the GTC/CanariCam spectroscopic observations.

| Galaxy     | Date     | $t_{\text{on}}$ (s) | PA (°) | Standard PA | IQ (arcsec) |
|------------|----------|---------------------|--------|-------------|-------------|
| Mrk 1066   | 2013.08.31 | 1061                | 315    | HD18449     | 0.28        |
| Mrk 1073   | 2013.09.10 | 1238                | 75     | HD14146     | 0.34        |
| NGC 2273   | 2013.09.23 | 884                 | 290    | HD14263     | 0.26        |
|            | 2013.09.22 | 354                 | 290    | HD14263     | 0.32        |
| NGC 6240   | 2013.09.15 | 1238                | 16     | HD157999    | 0.40        |
| IRAS 17208–0014 | 2013.09.09 | 1238                | 90     | HD157999    | 0.30        |
Figure 2. Mrk 1073. Symbols as in Fig. 1. The top panel is the GTC/CanariCam 8.7 µm image smoothed with a Gaussian function with σ = 0.6 pixels. The contours are in a linear scale with the lowest contour corresponding to the local background value plus 2 standard deviations measured in the image before rotating and smoothing the images. The middle panel is the partially reduced GTC/CanariCam 2D spectrum. On the y-axis positive offsets indicate northeast and negative offsets southwest. The bottom panel compares the 1D GTC/CanariCam spectra (smoothed as in Fig. 1 bottom panel) and the Spitzer/IRS spectrum. The GTC/CanariCam 0.52 arcsec × 2 arcsec spectrum of Mrk 1073 was scaled down by a factor of 1.8 to match the IRS one.

Figure 3. NGC 2273. Symbols as in Fig. 1. The top panel is the GTC/CanariCam 8.7 µm image smoothed with a Gaussian function with σ = 0.7 pixels. The contours are in a linear scale with the lowest contour corresponding to the local background value plus 1 standard deviations measured in the image before rotating and smoothing the images. The middle panel is the partially reduced GTC/CanariCam 2D spectrum. On the y-axis positive offsets indicate northwest and negative offsets southeast. The bottom panel compares the 1D GTC/CanariCam spectra (smoothed as in Fig. 1 bottom panel) and the Spitzer/IRS spectrum.

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Figure 4. NGC 6240. Symbols as in Fig. 1. The top panel is the GTC/CanariCam 8.7 μm image smoothed with a Gaussian function with \( \sigma = 0.7 \) pixels. The contours are in a linear scale with the lowest contour corresponding to the local background value plus 1.5 standard deviations measured in the image before rotating and smoothing the images. The crosses indicate the positions of the radio sources (Beswick et al. 2001) after we made the radio southern source coincident with the bright mid-IR southern nucleus. The middle panel is the partially reduced GTC/CanariCam 2D spectrum. On the y-axis positive offsets indicate northeast and negative offsets southwest. The northern nucleus is located at approximately +1.5 arcsec from the southern nucleus. Bottom panel are the 1D GTC/CanariCam spectra (smoothed as in Fig. 1) through extraction apertures centered on the southern and northern nuclei compared to the Spitzer/IRS SL spectrum, which encompasses both nuclei.

Figure 5. IRAS 17208–0014. Symbols as in Fig. 1. The top panel is the GTC/CanariCam 8.7 μm image smoothed with a Gaussian function with \( \sigma = 0.6 \) pixels. The contours are in a linear scale with the lowest contour corresponding to the local background value plus two standard deviations measured in the image before rotating and smoothing the images. The middle panel is the partially reduced GTC/CanariCam 2D spectrum. On the y-axis positive offsets indicate east and negative offsets west. The bottom panel compares the 1D GTC/CanariCam spectra (smoothed as in Fig. 1) bottom panel) and the Spitzer/IRS spectrum.
3 OBSERVATIONS AND DATA REDUCTION

3.1 GTC/CanariCam observations

The new CanariCam observations in this work were taken as part of an ESO/GTC large programme (182.B-2005), which totals 180 hours of observing time. At the time of writing approximately 75% of the observations have already been taken. We have an additional \(\sim\) 100 hours for this project through the CanariCam guaranteed time programme.

We obtained imaging observations of the galaxies using the Si-2 filter \((\lambda_c = 8.7 \mu m\) and width \(\Delta \lambda_{cut} = 1.1 \mu m\) at 50% cut-on/off). The observations were taken in queue mode under photometric conditions using the standard mid-IR chop-nod technique. The chop and nod throws were 15 arcsec, whereas the chop and nod angles were chosen for each target to avoid extended galaxy emission in the sky image. We also observed standard stars immediately before or after the galaxy observations to perform the photometric calibration, measure the image quality (IQ) of the observations, and perform the point spread function (PSF) subtraction.

The plate scale of the CanariCam 320 × 240 Si:As detector is 0.0798 arcsec/pixel, which provides a field of view in imaging mode of \(\sim 26\) arcsec × 19 arcsec. We measured the IQ of the data by fitting the observations of the standard stars with a Gaussian function and obtained values of 0.2 – 0.4 arcsec (full width half maximum, FWHM). In Table 2 we summarize details of the imaging observations, including the date of the observations, the on-source integration time \(t_{on}\), the standard star used, and the IQ of the observations.

We also obtained long-slit spectroscopy of the nuclear regions of the galaxies using the low spectral resolution 10 \(\mu m\) grating, which covers the \(N\)-band \(\sim 7.5 – 13 \mu m\) with a nominal spectral resolution of \(R = \lambda / \Delta \lambda \sim 175\). We used a 0.52 arcsec wide slit for all the galaxies with the position angles (PA) of the slits, measured from the north to the east, listed in Table 3. The observing sequence was first to take an acquisition image of the galaxy with the Si-2 filter, then place the slit, and finally integrate for the on-source times given in Table 3. The chop-nod parameters were as for the imaging observations. We also observed standard stars using the same observing sequence to provide the photometric calibration, the telluric correction, and the slit loss correction. We also used the acquisition images of the standard stars to obtain the IQ of the observations (see Table 3).

We reduced the data using the CanariCam pipeline REDCAN, which is thoroughly described by González-Martín et al. (2013). Briefly, the reduction process of the imaging data includes sky subtraction, stacking of the individual images, and rejection of bad images. The flux calibration of the galaxy images is done using the observations of the standard stars. We show the fully reduced GTC/CanariCam 8.7 \(\mu m\) images of the galaxies of our sample in the top panels of Figs 1 through 6.

For the spectroscopy the first three steps of the data reduction are the same as for the imaging. Additionally REDCAN performs the two-dimensional (2D) wavelength calibration of the galaxy and standard star spectra using sky lines. Finally, the trace determination is done using the standard star data. Figs 1 through 6 (middle panels) show 2D spectral images after the wavelength calibration but before correction for atmospheric transmission. From these figures we can clearly observe nuclear and extended emission of the 11.3 \(\mu m\) PAH feature in all five galaxies. The last steps of the spectroscopic data reduction are the spectral extraction either as point sources or extended sources (see Section 3.2), and finally, the correction for slit losses in the case of point source extractions.

3.2 Spitzer/IRS spectroscopy

All the galaxies in our sample were observed with Spitzer/IRS using the short-low (SL) spectral resolution \((R \sim 60 – 120)\) module covering the spectral range \(\sim 5 – 15 \mu m\). Table 2 summarizes information about the observations. All the observations were taken in staring mode, except for those of Arp 299 which were taken using the IRS spectral mapping mode capability. Alonso-Herrero et al. (2009) and Alonso-Herrero et al. (2013) provide all the details on the data reduction and extraction of the nuclear spectra of Arp 299 as a point sources, respectively. For the rest of the galaxies observed in staring mode, we downloaded the fully-calibrated spectra from the Cornell Atlas of Spitzer/IRS Sources (CASSIS v4: Lebouteiller et al. 2011). CASSIS provides spectra with optimal extraction regions to ensure the best signal-to-noise (S/N) ratio. For the galaxies in this work the optimal CASSIS extraction was equivalent to a point source extraction. The SL slit width of these observations is 3.7 arcsec.

4 ANALYSIS

4.1 Imaging: source size and aperture photometry

We measured the size of the nuclear regions before rotating and smoothing the GTC/CanariCam images using a Gaussian function. The measured sizes (FWHM) of the mid-IR emission in arcseconds and pc for the nuclear regions of the galaxies are listed in Table 4. The nuclear sizes \((0.3 – 0.4\) arcsec) at 8.7 \(\mu m\) of Mrk 1066, Mrk 1073, NGC 2273, and NGC 6240S are consistent with the presence of an unresolved source, although there is also extended emission. The nuclear region of IRAS 17208--0014 and NGC 6240N appear clearly resolved at 8.7 \(\mu m\) in good agreement with previous observations for instance at near-IR wavelengths (see e.g., Piqueras-López et al. 2012; Engel et al. 2014, respectively).

We performed aperture photometry on the images using IRAF routines. The nuclear 8.7 \(\mu m\) flux densities (without the correction for point source emission) measured through different apertures are given in Table 5. We also list in this table the uncertainties due to the background subtraction, which increase with the size of the aperture used. Additionally the typical errors of the photometric calibration in the \(N\)-band window are estimated to be approximately 10 – 15%.

For those galaxies with nuclear FWHMs similar to those of their corresponding standard stars we also estimated the unresolved nuclear fluxes. To do so, we used

1 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.
the fluxes measured through the smallest aperture and estimated the aperture correction for the total flux using the standard star observations. We note that the unresolved nuclear fluxes estimated using this method (see Table 5) are likely to be slightly overestimated as there is always a small fraction of resolved emission from the galaxy even in the smallest aperture. This is the case for Mrk 1066, where Ramos Almeida et al. (2014) estimated an unresolved nuclear flux by PSF scaling of 63 ± 9 mJy.

### 4.2 Extracting spectra

For all the galaxies except NGC 6240N and IRAS 17208–0014, which appear resolved in the GTC/CanariCam images at 8.7 μm (see previous section and Table 5), we extracted the nuclear spectra as point sources. In this case redcan uses an extraction aperture that increases with wavelength to take care of the decreasing angular resolution. It also performs a correction to account for slit losses. We checked the flux calibration of the nuclear spectra against the photometry done on the GTC/CanariCam images after applying a correction for point source emission. We found a good agreement between them to within 15 – 20%. We also extracted spectra for all the galaxies as extended sources using an aperture of 0.52 arcsec × 2 arcsec. For NGC 6240N and IRAS 17208–0014 we extracted the nuclear spectra as extended sources with a 0.52 arcsec × 1 arcsec extraction aperture.

In Figs 1 through 5 (bottom panels) we compare the GTC/CanariCam flux-calibrated nuclear and 0.52 arcsec × 2 arcsec spectra with the CASSIS Spitzer/IRS SL spectra. The SL IRS spectra have an approximate angular resolution of ~4 arcsec.

The 2D GTC/CanariCam spectra of Mrk 1066, Mrk 1073, and NGC 6240 show high S/N extended 11.3 μm PAH emission and continuum emission (see Figs 1, 2, and 4, respectively). Therefore, for these galaxies we investigate the spatial variations of the EW and flux of the 11.3 μm PAH feature and local continuum in Section 5. To do so, we used redcan to extract from the wavelength calibrated 2D images the nuclear spectra as well as spectra at different radial distances along the slit out to 1.5 – 2 arcsec on both sides of the nuclei by binning together four pixels (0.32 arcsec) in the spatial direction and assuming an extended source extraction.

### 4.3 Measuring the 11.3 μm PAH feature

For each of the extracted GTC/CanariCam and Spitzer/IRS spectra we measured the flux and EW of the 11.3 μm PAH feature following the method described by Hernán-Caballero & Hatziminaoglou (2011) and implemented for ground-based spectroscopy by Esquej et al. (2014). We fitted a local continuum at 11.25 μm by interpolating between two narrow bands (10.75 – 11.0 μm and 11.65 – 11.9 μm) on both sides of the feature. To measure the flux of the PAH feature we integrated the spectrum in the range λ_{rest} = 11.05 – 11.55 μm (see Hernán-Caballero & Hatziminaoglou 2011, for full details).

We estimated the uncertainties in the measurements by performing Monte Carlo simulations using the calculated dispersion around the measured fluxes and EWs in a hundred simulations of the original spectrum with random noise distributed as the rms for the GTC/CanariCam data and error of the spectra for the Spitzer/IRS data. PAH fluxes obtained with a local continuum are lower than those using a continuum fitted over a large spectral range (e.g. measurements done with pahfit, see Smith et al. 2007). We therefore corrected the measured fluxes of the 11.3 μm PAH

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**Table 4. Spitzer/IRS spectroscopy.**

| Galaxy   | Program ID | PI         | Cycle | Mode     |
|----------|------------|------------|-------|----------|
| Mrk 1066 | 30572      | V. Gorjian | 6     | Staring  |
| Mrk 1073 | 30323      | L. Armus   | 6     | Staring  |
| NGC 2273 | 86         | M. Werner  | 1     | Staring  |
| Arp 299  | 21         | J. R. Houck| 1     | Spectral Mapping |
| NGC 6240 | 105        | J. R. Houck| 1     | Staring  |
| IRAS 17208–0014 | 105 | J. R. Houck | 1 | Staring |

**Table 5. GTC/CanariCam aperture photometry and unresolved nuclear fluxes at 8.7 μm.**

| Galaxy   | FWHM Nucleus | 0.48 arcsec | 0.96 arcsec | Fluxes 1.92 arcsec | 4 arcsec | Unresolved |
|----------|--------------|-------------|-------------|--------------------|---------|------------|
| Mrk 1066 | 0.30         | 67          | 41 ± 1      | 79 ± 3             | 135 ± 10| 193 ± 30   |
| Mrk 1073 | 0.33         | 146         | 30 ± 1      | 60 ± 1             | 109 ± 5 | 160 ± 20   |
| NGC 2273 | 0.30         | 37          | 53 ± 1      | 94 ± 2             | 132 ± 8 | 189 ± 30   |
| NGC 6240N| 0.45         | 214         | 8 ± 1       | 20 ± 4             | —       | —          |
| NGC 6240S| 0.38         | 181         | 45 ± 1      | 98 ± 4             | —       | 231 ± 19*  |
| IRAS 17208–0014 | 0.52 | 421         | 23 ± 1      | 55 ± 1             | 105 ± 3 | 151 ± 8   |

Notes.— The listed apertures are diameters. The quoted errors in the photometry are only due to uncertainties in the background estimate. *The 4 arcsec-diameter photometry for NGC 6240 is for an aperture centered between the two nuclei.
Nuclear 11.3 µm PAH emission in local AGN

5 EXTENDED NUCLEAR MID-IR EMISSION

In this section we present the results on the extended nuclear mid-IR emission as derived from the GTC/CanariCam imaging and spectroscopy and compare them with Spitzer/IRS SL spectroscopy, which probes larger physical scales.

5.1 Mrk 1066

The GTC/CanariCam 8.7 µm image of Mrk 1066 (Fig. 1) shows a bright unresolved nuclear source (FWHM ≤ 67 pc, see Table 5) as well as disk-like extended emission detected out to radial distances of approximately 1.5 arcsec. The extended component has a morphology similar to that observed in the near-IR continuum (Quillen et al. 1999) and Paβ and Brγ hydrogen recombination lines (see Figure 4 of Riffel et al. 2010). The region with extended emission contains the narrow line region (NLR) detected in the optical [OIII]λ5007 emission line and also regions with active star formation (see Riffel et al. 2010 and references therein). The similarity between the extended 8.7 µm emission and hydrogen recombination lines is common in other IR bright galaxies and star forming galaxies (Helen et al. 2004; Alonso-Herrero et al. 2006; Díaz-Santos et al. 2008). This in principle suggests that the mid-IR extended emission at 8 µm traces sites of on-going or recent star formation activity but there can be some contribution from dust in the NLR in AGN (see e.g. Radomski et al. 2002; Packham et al. 2002).

For the GTC/CanariCam spectroscopy, we oriented the slit along the major axis of the extended mid-IR emission at a PA= 315°. In Fig. 4 we compare the nuclear and 0.52 arcsec × 2 arcsec GTC/CanariCam spectra with the Spitzer/IRS spectrum. The nuclear spectrum probes approximately a region of 116 pc in size and shows bright 11.3 µm PAH emission (also from the 8.6 µm PAH feature). This is indicative of the presence of nuclear star formation activity. There is also evidence of the silicate feature in absorption. The nuclear contribution to the ~4 arcsec (~0.9 kpc) 11.3 µm PAH feature measured in the Spitzer/IRS spectrum is 35% (see Table 6). Based on the EW of the 11.3 µm PAH feature in the Spitzer/IRS spectrum (Hernán-Caballero & Hatziminaoglou 2011) classified this galaxy as starburst, while the nuclear value of the EW is lower, as expected, due to the higher contribution from the AGN continuum (see discussion in Section 6.1 and also Ramos Almeida et al. 2014).

We can make use of the spatial information afforded by the GTC/CanariCam spectroscopy to produce spatial profiles of the mid-IR emission (Section 4.2). Fig. 6 shows the spatial profiles of the EW of the 11.3 µm PAH feature (star symbols) and its normalized flux (circles) together with the normalized local continuum (squares) as a function of the projected distance from the AGN, δAGN. The 11.3 µm PAH emission is detected out to projected radial distances of ~300 pc on both sides of the nucleus. The intensity of the PAH feature peaks at the nucleus. From the modelling of the optical spectrum (González Delgado et al. 2001) showed that the nuclear emission of Mrk 1066 is dominated by the emission of young and intermediate age stellar populations. Since we detected nuclear 11.3 µm PAH emission in the central ~100 pc and PAH molecules are excited by the UV emission from O stars and B stars (Peeters et al. 2004), we conclude that the 11.3 µm PAH emission can be used to reveal the presence of on-going/recent nuclear star formation in the nuclear regions of AGN.

Table 6. Measurements of the 11.3 µm PAH feature.

| Galaxy      | GTC/CanariCam Nuclear | Spitzer/IRS Circum nuclear | L_{11.3 μm} PAH Nuc/Circum |
|-------------|------------------------|---------------------------|----------------------------|
|             | Region (pc) | EW (µm) | Lum (erg s⁻¹) | Region (kpc) | EW (µm) | Lum (erg s⁻¹) | |
| Mrk 1066    | ≤ 116       | 0.35 ± 0.02 | 5.6 × 10¹¹ | 0.8          | 0.53 ± 0.01 | 1.6 × 10¹² | 0.35 |
| Mrk 1073    | ≤ 230       | 0.08 ± 0.03 | 3.2 × 10¹¹ | 1.6         | 0.43 ± 0.01 | 2.8 × 10¹² | 0.11 |
| NGC 2273    | ≤ 64        | 0.03 ± 0.01 | 2.8 × 10¹⁰ | 0.5          | 0.33 ± 0.01 | 3.1 × 10¹¹ | 0.09 |
| NGC 3690    | ≤ 111       | ≤ 0.01     | ≤ 9.3 × 10¹⁰ | 0.8          | 0.13 ± 0.01 | 1.6 × 10¹² | ≤ 0.06 |
| IC 694      | ≤ 111       | 0.14 ± 0.01 | 2.9 × 10¹¹ | 0.8          | 0.51 ± 0.01 | 2.5 × 10²² | 0.12 |
| NGC 6240N   | 247 × 475   | 0.86 ± 0.11 | 1.4 × 10¹² | 1.8          | 0.62 ± 0.01* | 7.1 × 10²²* | 0.20 |
| NGC 6240S   | ≤ 247       | 0.27 ± 0.01 | 2.0 × 10¹² | 3.0          | 0.90 ± 0.01 | 7.8 × 10²² | 0.31 |
| IRAS 17208−0014 | 421 × 809 | 0.56 ± 0.08 | 2.4 × 10¹² | 3.0          | 0.90 ± 0.01 | 7.8 × 10²² | 0.31 |

Note.— For the nuclei not resolved by CanariCam the quoted size (diameter) of the region is less or equal to the slit width. For the Spitzer/IRS SL data the size of the region is the slit width. We applied a multiplicative factor of 2 to the measured 11.3 µm PAH luminosities to be able to compare with results obtained with pahfit. See Section 4.3 for details. *The Spitzer/IRS SL spectroscopy of NGC 6240 includes the two nuclei of the system (Armus et al. 2006).
The spatial profile of the local interpolated continuum at 11.25 μm measured from the GTC/CanariCam spectrum has its maximum also at the nucleus, but it is narrower than that of the PAH feature. This indicates that in the nuclear region the continuum at this wavelength has a strong component presumably arising from the unresolved AGN emission. Additionally, the PAH spatial profile shows a secondary peak at a radial distance of ∼ 150 pc to the northwest that is approximately coincident with one of the starburst sites detected in the near-IR (see Riffel et al. 2010). Also, on both sides of the nucleus the PAH flux profile extends out to the radial distances of ∼ 300 pc.

The spatial profile of the EW of the 11.3 μm PAH feature at 11.25 μm shows a minimum (EW= 0.35 ± 0.02 μm) at the nuclear position, which is typical of Seyfert galaxies with nuclear/circumnuclear star formation (Sales et al. 2014; Tommasin et al. 2014; Hernán-Caballero & Hatziminaoglou 2011; Esquej et al. 2014). At larger radial distances from the nucleus, the EW of the feature increases reaching values typical of star forming galaxies (EW≈ 0.5 – 1 μm). This behaviour is well understood in terms of the increased continuum from the AGN towards the nuclear regions rather than a fall-off of the PAH emission because the 11.3 μm PAH feature peaks at the nucleus (see a detailed discussion in Section 6.1). Even at the location of the two starburst sites, the observed EW of the feature still has a relatively low value due to contamination from continuum produced by AGN heated dust. Indeed, when the extracted spectra are corrected for this AGN contamination, the measured EW are consistent with pure star formation. We refer the reader to Ramos Almeida et al. (2014) for a detailed study of the star formation and torus properties of this galaxy.

5.2 Mrk 1073

The GTC/CanariCam nuclear spectrum of Mrk 1073 shows the silicate feature in moderate absorption with weak 8.6 μm and 11.3 μm PAH emission (Fig. 2, bottom panel). The PAH features become more apparent on the ∼ 1.6 kpc scale probed by the Spitzer/IRS spectrum with an EW of the 11.3 μm PAH feature being consistent with a composite AGN/starburst nature (Sales et al. 2014; Tommasin et al. 2014; Hernán-Caballero & Hatziminaoglou 2011; Esquej et al. 2014). The nuclear contribution to the observed 11.3 μm PAH feature luminosity in the central 1.6 kpc of Mrk 1073 is only 11%, but consistent with findings for other Seyfert galaxies (see Esquej et al. 2014). The low value of the nuclear EW of the 11.3 μm PAH feature (EW=0.08 ± 0.03 μm, see Table 5) clearly indicates that on nuclear scales the mid-IR emission of Mrk 1073 is dominated by emission from the AGN, unless the PAHs get destroyed by the AGN (but see Section 6.3).

Fig. 7 shows the spatial profiles of the flux and EW of the 11.3 μm PAH feature emission and the flux of the local continuum at 11.25 μm. The PAH feature is detected out to projected distances from the AGN of < 146 pc (see Table 5). There is also extended emission in the disk of the galaxy with an approximate diameter of 2.6 arcsec ≈ 1.1 kpc. For the spectroscopy we placed the GTC/CanariCam slit along the major axis of this emission (PA= 75°).
uniform along the spatial direction at PA = 75°. This is in good agreement with the relatively constant contribution of the young stellar populations (≤ 100 Myr) in the central few kpc of this galaxy (Raimann et al. 2003). We note that the spatial profiles plot the observed (not corrected for extinction) flux of the 11.3 µm PAH feature. The slight decrease of the flux of the PAH feature at the location of the nucleus might be due a higher extinction there as indicated by the moderate depth of the silicate feature. The EW of the 11.3 µm on the other hand, has its minimum value in the nuclear region, consistent with the presence of a strong AGN produced continuum there. At projected distances ∼ 300 pc and further away from the nucleus the measured values of the EW are consistent with that observed in regions of pure star formation activity.

5.3 NGC 2273

The GTC/CanariCam 8.7 µm image of NGC 2273 (see Fig. 3) shows a bright nucleus point source with an unresolved size of ≤ 37 pc (FWHM). There is also diffuse emission out to a radial distance of approximately 1.5 arcsec = 190 pc, which appears to be more prominent to the north of the nucleus.

Ferruit et al. (2000) detected a ring of star formation using HST narrow-band Hα+[NII] imaging. To compare the extended mid-IR and optical emission, we first subtracted the bright nuclear unresolved component in the GTC/CanariCam images. We used the standard star observation taken for the photometric calibration as a representation of the PSF and followed the method for PSF subtraction explained by Ramos Almeida et al. (2009). We note that we did the PSF subtraction before rotating and smoothing the NGC 2273 image. We used the bright nuclear emission to align the optical and mid-IR images.

Fig. 8 shows the PSF-subtracted 8.7 µm image compared with the Hα+[NII] image. The diffuse emission detected at 8.7 µm to the north of the nucleus at ∼ 1.5 arcsec has a reasonable resemblance with the optical line emission. Some of the differences might be due to the fact that we did not subtract the continuum from the optical line image. Therefore, there is an additional component due to stellar emission. To the south of the nucleus the emission from the ring appears less prominent. In the central 2 arcsec = 250 pc, the PSF-subtracted 8.7 µm image reveals the presence of extended nuclear emission with a similar orientation as the Hα+[NII] nuclear emission. Since there is also diffuse extended 11.3 µm PAH emission in the nuclear region, as can be seen from the 2D GTC/CanariCam spectrum (Fig. 3), the extended emission in the Si-2 filter has likely a contribution from the 8.6 µm PAH feature. This extended nuclear emission might be related to dense molecular gas emission detected in the nuclear region (central ∼ 2 arcsec) of this galaxy (see Sani et al. 2012) and the nuclear ring identified by Barbosa et al. (2006) by the presence of a velocity dispersion (σ) drop. The nuclear HST optical line ratios appear to have some contribution from the NLR emission (Ferruit et al. 2000).

The GTC/CanariCam nuclear spectrum of NGC 2273 (see Fig. 3) is dominated by the bright AGN continuum with weak, but detectable, 11.3 µm PAH emission with EW = 0.03 ± 0.01 µm. The modest angular resolution and high sensitivity of the Spitzer/IRS SL spectrum, on the other hand capture the diffuse emission within the central 4 arcsec ∼ 500 pc as bright 8.6 µm and 11.3 µm PAH emission. The measured EW of the 11.3 µm PAH feature within the IRS aperture reflects the starburst/AGN composite nature of the emission (see Sales et al. 2010, Tommasin et al. 2010, Hernan-Caballero & Hatziminaoglou 2011, Esquej et al. 2014).

The nuclear contribution to the observed 11.3 µm PAH emission within this region is 9%, thus indicating that most of the star formation in the central 500 pc of this galaxy arises from the circumnuclear ring (that is, outside the inner region). We note that some of the structure seen there, especially the two knots at PA of about 50°, might be due to imperfect PSF subtraction.

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**Figure 8.** NGC 2273. Left panel. GTC/CanariCam PSF-subtracted 8.7 µm in a square-root colour scale. The hatched circle is the FWHM of the PSF. Right panel. HST/PC Hα+[NII]+continuum image with the 8.7 µm contours superimposed. The lowest 8.7 µm contour is as in Fig. 3 (top panel).
ner ~ 60 pc). Still, the detection of the 11.3 µm PAH feature in the nuclear region (inner ≤ 64 pc) implies a star formation rate of 0.08 M⊙ yr⁻¹ (0.21 M⊙ yr⁻¹ for the ~ 60 pc × 250 pc aperture), using the calibration of Diamond-Stanic & Rieke (2012). This appears in contradiction with the Toomre parameter calculated by Sani et al. (2012) that seems to indicate that the central ~ 100 pc of this galaxy should be stable against star formation.

5.4 Arp 299

The GTC/CanariCam observations and modeling of the AGN properties of this interacting system were presented in Alonso-Herrero et al. (2013a). Here we only discuss briefly the 11.3 µm PAH feature. In the nuclear region of the eastern component of Arp 299, IC 694, the nuclear 11.3 µm PAH feature is detected with EW = 0.14 ± 0.01 µm, which is indicative of a composite starburst/AGN nature. Alonso-Herrero et al. (2000) concluded that the IR emission of this component is dominated by star formation activity. However, there is also evidence of the presence of AGN activity, based on the reduced EW when compared to that measured on kpc scales with Spitzer/IRS and the modelling of the nuclear spectrum (Alonso-Herrero et al. 2013a).

In the case of NGC 3690, the nucleus of the western component of Arp 299, the nuclear (distance from the AGN dAGN ≤ 50 pc) 11.3 µm PAH feature is not detected. The 2σ upper limit is EW ≤ 0.01 µm, whereas in the IRS spectrum we measured EW = 0.13 ± 0.01 µm. Alonso-Herrero et al. (2000) showed that the star formation rate in the nucleus of NGC 3690 is about five time less than in IC 694. The upper limit (at the 2σ level) to the 11.3 µm PAH luminosity in the nucleus of NGC 3690 compared with that of IC 694 (see Table 6) is compatible with this. We cannot therefore reach a firm conclusion as to whether PAHs are destroyed near the nucleus of NGC 3690 or the low EW is due to dilution by the luminous AGN continuum (Section 6.1). We also note that the HST/NICMOS Paα image shows that there is extended emission approximately 1.1 arcsec southwest from the nucleus of NGC 3690 (i.e. sources B16 and B1, respectively, see figures 2b and 7b in Alonso-Herrero et al. 2000), which is likely to be associated with the star formation detected in the Spitzer/IRS spectrum. These regions of star formation, however, did not fall in the GTC/CanariCam slit.

![Figure 9. NGC 6240. Left panel. GTC/CanariCam PSF-subtracted 8.7 µm (only unresolved emission from the southern nucleus was subtracted) in a square-root colour scale. The hatched circle is the FWHM of the PSF. The contours are the 8.7 µm emission with the lowest value as in Fig. 4 (top panel). Right panel. VLT/SINFONI continuum-subtracted Brγ image in a square-root colour scale from Engel et al. (2010). We repixelated and smoothed the SINFONI image to match the pixel size and angular resolution of the CanariCam image. The contours are the Brγ emission with the lowest value set at the background level plus 8 standard deviations (before smoothing the image).](image)

![Figure 10. As Fig. 9 but for NGC 6240. The 0 position on the x-axis marks the location of the southern nucleus. The secondary peak in the local continuum at 11.25 µm at a projected distance of 760 pc to the northeast marks the approximate location of the northern nucleus of NGC 6240. The large star symbol is the measurement of the EW in the northern nucleus from the 0.52 arcsec × 1 arcsec spectrum (see also Table 6), shown as the horizontal error bar.](image)
NGC 6240 was previously imaged in the mid-IR using MIRLIN on the Keck II telescope (Esquej et al. 2008) and VISIR on the VLT telescope (Asmus et al. 2014). The GTC/CanariCam 8.7 μm image of NGC 6240 (Fig. 4) shows mid-IR emission arising from both nuclei, with the southern nucleus being approximately five times brighter than the northern one (Table 5). The CanariCam image shows also diffuse emission around and in between the nuclei. We detected extended emission in the central 4 arcsec ~ 1.9 kpc of the system. The core of the southern nucleus appears unresolved at the resolution of the CanariCam images (≤ 181 pc, FWHM), while the northern nucleus is resolved (see also Asmus et al. 2014) with a FWHM = 214 pc.

In order to study the extended mid-IR 8.7 μm emission in more detail we subtracted the unresolved emission (PSF subtraction) from the southern nucleus of NGC 6240. We show the result in Fig. 9 compared with the VLT/SINFONI continuum-subtracted Brγ image from Engel et al. (2010). The latter emission in NGC 6240 is mostly believed to be tracing the starburst activity in this galaxy. We re pixeled and smoothed the SINFONI image to match the pixel size and angular resolution of the CanariCam image.

As can be seen from this figure, there is a fairly good correspondence between both emissions, especially around the northern nucleus where the AGN contribution in the mid-IR is low (see below). There is also extended 8.7 μm emission to the south of the southern nucleus, which has also been detected in the near-IR continuum, Brγ, and other mid-IR wavelengths (Asmus et al. 2014). This again indicates that the extended 8.7 μm emission probes recent star formation activity. Some of the differences in morphologies might be attributed to the high extinction affecting the K-band emission in and around the nuclei (see Figure 9 in Engel et al. 2009). It is also interesting to note that the peaks of the Brγ line emission and the 8.7 μm emission around the northern nuclei are nearly coincident with the northern radio source (Beswick et al. 2001) to within one CanariCam pixel (~ 0.08 arcsec), while that is not the case for the peak of the 2 μm continuum (see Max et al. 2007; Engel et al. 2010).

The radio source is believed to mark the position of the accreting black hole in the northern nucleus. At λ > 2 μm the peaks coincide with the radio ones (Mori et al. 2014).

Fig. 4 (bottom panel) compares the CanariCam nuclear spectra with that observed through the Spitzer/IRS SL ~ 4 arcsec aperture, which contains the two nuclei (Armus et al. 2006). Both nuclear spectra show relatively bright emission from the 8.6 and 11.3 μm PAH features. The IRS spectrum and that of the southern nucleus also show bright molecular hydrogen lines H2 at 8.025, 9.665, and 12.279 μm. The spatial profiles of Fig. 10 show that there is 11.3 μm PAH emission extending 3 arcsec ~ 1.4 kpc along the slit. Both the local continuum at 11.255 μm and the 11.3 μm PAH feature peak at the southern nucleus, although the PAH emission appears to be slightly more extended. There is also extended PAH emission to the southwest of this nucleus where there is also detected extended emission in the 8.7 μm and Brγ images. Around the northern nucleus the PAH emission is fainter than in the southern nucleus but it appears rather constant extending approximately 1.5 arcsec (~ 700 pc) including the region between the two nuclei.

The spatial profile of the EW of the PAH feature shows a minimum (EW=0.28 ± 0.02 μm) at the southern nucleus and a secondary minimum at the location of the northern nucleus (EW=0.50 ± 0.11 μm). This clearly indicates the presence of a continuum, most likely associated with dust heated by the AGN in both nuclei, which is more dominant in the southern nucleus (see Mori et al. 2014, for a detailed analysis of the AGN IR emission of the southern nucleus). To the southwest of the southern nucleus and in the regions around the northern nucleus the EW of the feature is similar to that measured in starburst galaxies, as is also the case for the Spitzer/IRS spectrum.

5.6 IRAS 17208–0014

The GTC/CanariCam 8.7 μm image of IRAS 17208–0014 (Fig. 5) shows emission extending over approximately 2 arcsec = 1.6 kpc. The morphology is similar to the Keck mid-IR 7 and 12 μm images (see Soifer et al. 2000) and the VLT/SINFONI PaO emission (Piqueras-Lopez et al. 2012). The measured size of the nuclear region at 8.7 μm, which appears resolved in the CanariCam image, is 0.52 arcsec = 421 pc (FWHM), and therefore there is no clear evidence of the putative nuclear unresolved emission expected to be associated with the AGN.

The 2D GTC/CanariCam spectrum (see Fig. 5b) shows extended PAH emission. The measured nuclear EW of the 11.3 μm feature (EW=0.56±0.08 μm) shows that on scales of a few hundred pc the mid-IR emission of this galaxy is dominated by star formation. However, the lower nuclear value of the EW of the 11.3 μm PAH feature compared to the value measured in the IRS spectrum (EW=0.90±0.01 μm) indicates a higher continuum contribution there, which might be due to the AGN-produced mid-IR continuum. This is similar to findings for the nuclei of Arp 299 (see Table 5). Alternatively, the decreased nuclear EW in this galaxy could be due to an increased starburst continuum, as found in some purely star-forming nuclei (Tacconi-Garman et al. 2008; Diaz-Santos et al. 2010). Finally, the nuclear contribution to the Spitzer/IRS 11.3 μm PAH feature emission in IRAS 17208–0014 is 31%, indicating that the emission of this feature is extended over at least a few kpc.

6 DISCUSSION

For this work we selected six systems (8 galaxies) known to harbour an AGN and have intense star formation activity on nuclear and circumnuclear regions. We detected 11.3 μm PAH feature emission in all the galaxy nuclei (inner regions between 64 and 420 pc), except NGC 3690. Moreover, because some of them are LIRGs or ULIRGs they tend to show more highly concentrated 11.3 μm PAH emission (i.e. star formation rate) than typical Seyferts (Esquej et al. 2014). This would be in line with the interpretation that local LIRGs may represent an IR-bright star-forming phase taking place prior to most of the AGN phase (Alonso-Herrero et al. 2013b). The galaxies in this work also have relatively high X-ray column densities, which may also be related to the
resent the range of expected ratios for the case of uniform PA H kpc scales with Spitzer emission taking into account the difference between ground-based symbols) from 8-10 m-class telescopes vs. that on circumnuclear slits (0 arcsec). The line represents the typical 0.2 ratio between the nuclear and burst contribution circumnuclear PAH emission in RSA Seyferts (see Esquej et al. for more detail the nuclear regions of AGN (Section 6.3). In what follows, we discuss in

Figure 11. EW of the 11.3 µm PAH feature measured on nuclear scales (this work red symbols and Esquej et al. 2014 blue symbols) from 8-10 m-class telescopes vs. that on circumnuclear kpc scales with Spitzer/IRS SL spectra. The two solid lines represent the range of expected ratios for the case of uniform PAH emission taking into account the difference between ground-based slits (0.35 – 0.75 arcsec) and the IRS slit width. The dotted line represents the typical 0.2 ratio between the nuclear and circumnuclear PAH emission in RSA Seyferts (see Esquej et al. 2014). The shaded region shows the predicted EW for a starburst contribution ≥ 50% to the observed mid-IR emission (see Hernán-Caballero & Hatziimanolou 2013).

material protecting the PAH molecules in the nuclear regions of AGN (Section 6.3). In what follows, we discuss in more detail the nuclear 11.3 µm PAH emission in local AGN.

6.1 Understanding the EW of the nuclear 11.3 µm PAH feature of Seyfert galaxies

The EW of the PAH features is routinely used to obtain a general classification of the dominant source of activity in galaxies (AGN vs. star formation) in the near and mid-IR (see examples using the 3.3, 6.2, 7.7, and 11.3 µm PAH features in Imanishi & Dudley 2006; Spoon et al. 2007; Genzel et al. 1998; Hernán-Caballero & Hatziimanolou 2011, respectively). It is also used to detect AGN not previously identified in the optical in LIRGs and ULIRGs (see e.g. Nardini et al. 2008; Alonso-Herrero et al. 2012). This is because generally high metallicity star-forming galaxies show remarkably similar mid-IR spectra (Brandl et al. 2006), while the nuclear spectra of AGN are dominated by a strong continuum due to dust heated by the AGN. This results in AGN-dominated sources having much lower EWs of the PAHs than starburst galaxies. There is also both observational and theoretical evidence that PAH emission can be diminished/suppressed near (scales of a few pc) the ionizing sources in sites of intense star formation (e.g. Siebenmorgen et al. 2004; Tacconi-Garan et al. 2005; Tielens 2013).

A number of works using mid-IR spectra of AGN noted a tendency of decreasing EWs of PAHs with increasing hard-ness of the AGN radiation field and interpreted it as evidence of PAH destruction in the nuclear regions of AGN (see e.g. Wu et al. 2009; Sales et al. 2010). However, other interpretations for the decreased EW of PAH features in AGN include dilution from the intense mid-IR continuum produced by the AGN (see e.g. Lutz et al. 1995; Clavel et al. 2000) and reduction of the star formation activity from kpc scales to the nuclear regions of AGN (Hönig et al. 2010).

Owing to the high angular resolution of the CanariCam data we showed in Section 5 that the nuclear EW of the 11.3 µm PAH feature varies with the distance from the AGN, always increasing at larger radial distances from the nucleus. This is similar to findings for Circinus and NGC 1808 using ground-based spatially-resolved mid-IR spectroscopy (see Roche et al. 2006; Sales et al. 2013, respectively). We also demonstrated that since the 11.3 µm PAH flux peaks in the nuclear region, the minimum value of its EW in the nuclei of these AGN is due to an increased contribution from the AGN produced continuum and not to PAH destruction (see also Tacconi-Garan & Sturm 2013 for the 3.3 µm PAH feature emission in the nuclear region of Centaurus A). Finally, in galaxies with a higher nuclear concentration of the star formation activity (Mrk 1066, NGC 6240, and IRAS 17208–0014, see last column in Table 5), the observed nuclear EW of the PAH feature is larger than those with smaller nuclear fractions of the PAH emission (NGC 2273, Mrk 1073, and NGC 3690). This simply reflects a higher contribution of the star formation activity with respect to the AGN emission.

In Fig. 11 we compare the EWs of the 11.3 µm PAH feature measured typically on hundreds of pc scales with Spitzer/IRS and nuclear scales with GTC/CanariCam. We also plotted in this figure data from Esquej et al. 2014 for Seyferts in the revised Shapley-Ames (RSA) galaxy catalog (Maiolino & Rieke 1995) where the nuclear ground-based spectroscopy comes from 8-10 m telescopes and probes typically nuclear regions of 60 pc in size. The solid lines are the predictions for the nuclear EW in the presence of an AGN assuming that the PAH emission is distributed uniformly taking into account the range of slit sizes of the nuclear spectra and that of the Spitzer/IRS spectra. The dotted line represents the average value between nuclear and circumnuclear 11.3 µm PAH luminosities of 0.2 found for RSA Seyferts. Measurements above this line indicate galaxies with strong nuclear star formation, as also expected from values of the EW if star formation contributes more than 50% of the observed mid-IR emission. Since we selected the galaxies observed with CanariCam as having intense nuclear star formation, it is not surprising to see that the nuclear mid-IR emission in many of them is dominated by star formation when using the EW of the feature. It is also clear from this figure, that unless there is a strong nuclear starburst, we should expect that the nuclear values of the EW are smaller than those measured on circumnuclear scales from Spitzer/IRS (Siebenmorgen & Krogius 2007).

6.2 Mid-IR spectra of Seyfert nuclei

In this section we investigate further the detection of the 11.3 µm PAH feature in the close vicinity of AGN by constructing mean mid-IR spectra of Seyfert nuclei. We used the nuclear (typically the central 65 pc) mid-IR ground-
The 11.3 μm PAH feature is detected in the average nuclear spectrum of the three types. Table 7 lists the mean and standard deviation of the EW of the 11.3 μm feature in emission of the three types. The three types clearly show different mid-IR properties.

Table 7. EW of the 11.3 μm PAH feature in the spectra of Seyfert nuclei.

| Class          | No. | Nuclear Region (pc) | EW (μm)       | Spitzer/IRS Region (pc) | EW (μm)       |
|----------------|-----|---------------------|---------------|-------------------------|---------------|
| Seyfert 1      | 8   | 104                 | 0.015 ± 0.007 | 650                     | 0.192 ± 0.056 |
| Seyfert 2      | 9   | 104                 | 0.028 ± 0.016 | 720                     | 0.228 ± 0.075 |
| Moderate absorption | 9 | 67                 | 0.047 ± 0.038 | 625                     | 0.233 ± 0.071 |

Notes.— No. indicates the number of spectra combined and region the median value of the projected slit widths (in pc) of the nuclear and Spitzer/IRS spectra.

We divided the nuclear spectra in three categories, namely, Seyfert 1, Seyfert 2, and Seyfert nuclei with silicate features in moderate absorption. We chose this last category because in these Seyfert 2 nuclei the silicate feature is likely to have a contribution from extended dust absorbing components in the host galaxy in addition to that due to the dusty torus (Deo et al. 2009; Alonso-Herrero et al. 2011; Goulding et al. 2012; González-Martín et al. 2013). These nuclei are generally in merger galaxies, galaxies with nuclear dust lanes, and/or highly inclined systems (see also Hönig et al. 2014). We combined the nuclear mid-IR spectra after normalising them at 12 μm.

Fig. 12 shows the resulting mean mid-IR spectra of RSA Seyfert 1 and Seyfert 2 nuclei, and Seyfert nuclei with silicate features in moderate absorption compared to their corresponding circumnuclear Spitzer/IRS SL spectra. The nuclear spectra of Seyfert 1s and Seyfert 2s show similar mid-IR spectral indices (that is, ratio between 8 and 12 μm), consistent with the results of Hönig et al. (2010) comparing individual galaxies. However, the nuclear Seyfert 1 spectrum shows a flat or slightly in emission silicate feature whereas the Seyfert 2 shows the 10 μm feature slightly in absorption (see also Hönig et al. 2014).

The 11.3 μm PAH feature is detected in the average nuclear spectrum of the three types. Table 7 lists the mean and standard deviation of the EW of the 11.3 μm PAH feature for the average nuclear and IRS spectra for each type. We estimated the uncertainties of the EW in the combined spectra using bootstrap resampling. To do so, first we selected at random, and with replacement, a subset of the individual spectra used to build the composite. The size of the resample was equal to the size of the original set of spectra. We then obtained a composite spectrum for this subset and measured the EW of the feature. We repeated this routine 100 times to get the bootstrap distribution of the EW.

As expected, the nuclear EWs of all three types are smaller than those measured in the circumnuclear regions from the Spitzer/IRS spectra. This is due to the higher contribution of the mid-IR AGN continuum in the nuclear regions. The measured EW of the 11.3 μm PAH feature of Seyfert 1 and Seyfert 2 nuclei are similar, within the uncertainties. The average spectrum of the nuclei with the silicate feature in moderate absorption shows a slightly higher EW with a larger dispersion, but again consistent with those of Seyfert 1 and 2 nuclei. Since most of the nuclei with relatively deep silicate features are in highly inclined systems there might be some contamination from star formation in the line of sight of the host galaxy. Additionally, in these systems the silicate feature is likely to absorb the compact warm nuclear emission more than the diffuse PAH emission which arises from a much larger region. This suppresses the 11 μm continuum from the compact nuclear emission more than the 11.3 μm PAH emission and an increased EW is expected in these cases.

From this section and Section 6.1 we conclude that...
luminosity $L_X$, and the total hydrogen column density of the intervening material $N_H(tot)):

$$\tau \sim 700 \, \text{yr} \left( \frac{N_H(tot)}{10^{22} \, \text{cm}^{-2}} \right)^{1.5} \left( \frac{d_{AGN}}{\text{kpc}} \right)^2 \left( \frac{L_X}{10^{44} \, \text{erg} \, \text{s}^{-1}} \right)^{-1}. \quad (1)$$

Fig. 13 summarizes graphically the predictions for PAH survival, assuming a time scale for reaccretion of carbon onto a fractured PAH molecule of 3000 yr (see Voit [1992, Miles et al. 1994]). We show lines of constant total hydrogen column densities as a function of the AGN X-ray luminosity and distance from the AGN. Below these lines, PAH molecules might not survive the AGN radiation field. For a given column density, the more luminous the AGN is, the further away the PAH molecules ought to be in order to survive. Also, at a given AGN luminosity, higher column densities of the intervening material allow for smaller distances to the AGN of the star forming regions where the PAH molecules could survive. We also show in this figure for comparison the predictions from Siebenmorgen et al. [2004] where the only dependence is the distance from the AGN, that is, PAH molecules would be destroyed at distances of less than approximately 10 pc from the AGN but survive at distances of more than 100 pc.

In Fig. 13 we also plotted the RSA Seyferts from Esquej et al. [2014] and the galaxies from this work. For the closest galaxies in [Esquej et al. [2014] sample (Circinus, NGC 4945 and NGC 5128) the distances from the AGN correspond to those probed by the Spitzer/IRS SL slit (see below). As can be seen from this figure, the majority of the galaxies with nuclear 11.3 μm PAH detections cluster around the $N_H(tot) = 10^{23} \, \text{cm}^{-2}$ line and a few just around the $N_H(tot) = 10^{24} \, \text{cm}^{-2}$ line.

The derived total column densities from fitting the nuclear IR emission of Seyfert nuclei with clumpy torus models are in this range (Ramos Almeida et al. 2009, 2011, Lira et al. 2013). Independently, Hicks et al. [2008] derived typical column densities of $N_H \sim 5 \times 10^{23} \, \text{cm}^{-2}$ in the nuclear gas disks (radii of 30 pc) of Seyfert galaxies. Therefore, material in the dusty torus and/or gas disk has in principle sufficient column density to shield the PAH molecules from the AGN radiation field (see also Sales et al. 2013, Esquej et al. 2014). Moreover, Hicks et al. [2008] proposed that the molecular gas is mixed with the stellar population and is likely to be associated with the outer regions of the obscuring material (i.e. the torus). This scenario fits nicely with the physical scales where nuclear 11.3 μm PAH feature emission is detected in this work (inner few tens of pc) and with the relatively compact sizes inferred for the AGN tori (Ramos Almeida et al. 2009a, 2011; Tristram et al. 2003; Alonso-Herrero et al. 2011; Kishimoto et al. 2011; Burtscher et al. 2013).

We can also see from Fig. 13 that those nuclei where the 11.3 μm PAH feature is not detected do not lie in a particular region of the diagram. Rather, they are mostly located between the lines of constant $N_H = 10^{23} \, \text{cm}^{-2}$ and $N_H = 10^{24} \, \text{cm}^{-2}$, as those with nuclear detections of the feature. The question for the non-detections is whether they just do not have nuclear star formation or whether the PAH carriers have been destroyed. For Circinus and NGC 5128, which are the nearest galaxies in Esquej et al. [2014], the nuclear PAH emission is not clearly detected at distances of less 10 pc from ground-based spectroscopy.
We also included in our analysis the nuclear mid-IR spectra of the AGN between 30 and 210 pc, depending on the galaxy. Observations allowed us to probe projected distances from the AGN of a few hundred pc the EW of the feature increasing further away from the AGN. At projected distances from the AGN of a few hundred pc the EW of the feature reaches values consistent with those of star-forming galaxies.

(i) We detected nuclear (inner ~ 60 – 420 pc) mid-IR spectrum of AGN-dominated nuclear mid-IR emission (NGC 3690, NGC 2273, and Mrk 1073) to intermediate cases (IC 694) to starburst-dominated nuclear mid-IR emission (both nuclei of NGC 6240, Mrk 1066, and IRAS 17208–0014).

(ii) We measured GTC/CanariCam nuclear EW of the 11.3 µm PAH feature ranging from values indicating AGN-dominated nuclear mid-IR emission (NGC 3690, NGC 2273, and Mrk 1073) to intermediate cases (IC 694) to starburst-dominated nuclear mid-IR emission (both nuclei of NGC 6240, Mrk 1066, and IRAS 17208–0014).

(iii) The GTC/CanariCam spatially-resolved spectroscopy shows that the 11.3 µm PAH feature emission peaks in the galaxy nuclei with the EW of the feature increasing further away from the AGN. At projected distances from the AGN of a few hundred pc the EW of the feature reaches values consistent with those of star-forming galaxies.

Finally, some galaxies with a clear detection of the 11.3 µm PAH feature in the nuclear mid-IR spectrum (e.g. NGC 3783 and NGC 7469, see Honig et al. 2014) do not show it in well-resolved interferometric observations probing much smaller physical scales (see Burtscher et al. 2013, and references therein). The second generation instruments planned for the VLTI will provide more sensitive data and the possibility of image reconstruction. This will be useful to understand the behaviour of the nuclear 11.3 µm PAH feature of AGN on smaller physical scales than those probed by mid-IR spectroscopy on 8-10 m class telescopes.

7 CONCLUSIONS

We presented GTC/CanariCam Si-2 (λc = 8.7 µm) imaging and 7.5 – 13 µm spectroscopy of six local systems (eight galaxies) known to host both an AGN and nuclear (regions of less than 500 pc) star formation activity. The main goal of this work was to explore the behaviour of the 11.3 µm PAH feature in the close vicinity of an AGN. The high angular resolution (0.24 – 0.40 arcsec) of the GTC/CanariCam observations allowed us to probe projected distances from the AGN between 30 and 210 pc, depending on the galaxy. We also included in our analysis the nuclear mid-IR spectra of 29 RSA galaxies presented by Esquej et al. (2014). We summarize our main conclusions as follows.

For Seyfert-like AGN luminosities and distances to the nucleus probed by high angular resolution (0.2 – 0.4 arcsec) mid-IR measurements the implied minimum column densities of the intervening material needed to protect the molecules responsible for the 11.3 µm PAH feature are N_H = 10^{23} cm^{-2} (see also Esquej et al. 2014). Current modelling of the nuclear IR emission of Seyfert galaxies with clumpy torus models indicates that the compact torus is able to provide such column densities, even for most type 1 AGN (Ramos Almeida et al. 2009a, 2011; Alonso-Herrero et al. 2011). Likewise, column densities N_H ~ 5 x 10^{23} cm^{-2} are derived for the nuclear gas disks of nearby AGN (Hicks et al. 2000).

We conclude that the 11.3 µm PAH feature can be used to probe nuclear star formation activity for Seyfert-like AGN luminosities and at least to distances to the AGN of 10 pc, assuming that the AGN contribution to the excitation of the 11.3 µm PAH feature is small or negligible.

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REFERENCES

Aitken D. K., Roche P. F., 1985, MNRAS, 213, 777
Alexander D. M., Hickox R. C., 2012, NewAR, 56, 93
Alonso-Herrero A., et al., 2013a, ApJ, 779, L14
Alonso-Herrero A., et al., 2013b, ApJ, 765, 78
Alonso-Herrero A., Pereira-Santaella M., Rieke G. H., Rigopoulou D., 2012, ApJ, 744, 2
Alonso-Herrero A., et al., 2011, ApJ, 736, 82
Alonso-Herrero A., Rieke G. H., Colina L., et al. 2009, ApJ, 697, 660
Alonso-Herrero A., Colina L., Packham C., Díaz Santos T., Rieke G. H., Rudomski J. T., Telesco C., 2006, ApJ, 625, L83
Alonso-Herrero A., Rieke G. H., Rieke M. J., Scoville N. Z., 2000, ApJ, 532, 845
Armus L., et al., 2006, ApJ, 640, 204
Arribas S., Colina L., 2003, ApJ, 591, 791
Asmus D., Hönig S. F., Gandhi P., Smette A., Duschl W. J., 2014, MNRAS, 439, 1648
Awaki H., Terashima Y., Higaki Y., Fukazawa Y., 2009, PASJ, 61, S317
Barbosa F. K. B., Storchi-Bergmann T., Cid Fernandes R., Winge C., Schmitt H., 2006, MNRAS, 371, 170
Bewick R. J., Pedlar A., Mundell C. G., Gallimore J. F., 2001, MNRAS, 325, 151
Brandl B. R., et al., 2006, ApJ, 653, 1129
Burtscher L., et al., 2013, A&A, 558, A149
Cid Fernandes R., Heckman T., Schmitt H., González Delgado R. M., Storchi-Bergmann T., 2001, ApJ, 558, 81
Clavel J., et al., 2000, A&A, 357, 839
Davies R. I., Müller Sánchez F., Genzel R., et al., 2007, ApJ, 671, 1388
Della Ceca R., et al., 2002, ApJ, 581, L9
Deo R. P., Richards G. T., Crenshaw D. M., Kraemer S. B., 2009, ApJ, 705, 14
Diamond-Stanic A. M., Rieke G. H., 2012, ApJ, 746, 168
Diamond-Stanic A. M., Rieke G. H., 2010, ApJ, 724, 140
Díaz-Santos T., Alonso-Herrero A., Colina L., Packham C., Levenson N. A., Pereira-Santaella M., Roche P. F., Telesco C., 2010, ApJ, 711, 328
Díaz-Santos T., Alonso-Herrero A., Colina L., Packham C., Rudomski J., Telesco C., 2008, ApJ, 684, 241
Egami E., Neugebauer G., Soifer B. T., Matthews K., Becklin E. E., Ressler M. E., 2006, AJ, 131, 1253
Engel H., et al., 2010, A&A, 524, A56
Esquej P., Alonso-Herrero A., González-Martín O., Hönig S., Hernán-Caballero A., et al., 2014, ApJ, 780, 86
Ferruit P., Wilson A. S., Mulchaey J., 2000, ApJS, 128, 139
Genzel R., et al. 1998, ApJ, 498, 579
González Delgado R. M., Heckman T., Leitherer C., 2001, ApJ, 546, 845
González-Martín O., Rodríguez Espinosa J. M., Díaz-Santos T., et al., 2013, A&A, 553, A35
González-Martín O., Masegosa J., Máquez I., Guainazzi M., 2009, ApJ, 704, 1570
Goulding A. D., et al., 2012, ApJ, 755, 5
Guainazzi M., Matt G., Perola G. C., 2005, A&A, 444, 119
Helou G., et al., 2004, ApJS, 154, 253
Hernán-Caballero A., Hatziminaoglou E., 2011, MNRAS, 414, 500
Hicks E. K. S., Davies R. L., Malkan M. A., Genzel R., Tacconi L. J., Müller Sánchez F., Sternberg A., 2009, ApJ, 696, 448
Hönig S., Gandhi P., Asmus D., Mushotzky R. F., Antonucci R., Ueda Y., Ichikawa K., 2014, MNRAS, 438, 647
Hönig S., et al., 2010, A&A, 515, 23
Hopkins P. F., Quataert E., 2010, MNRAS, 407, 1529
Hopkins P. F., 2012, MNRAS, 420, L8
Houck J. R., Roellig T. L., van Cleve J., et al., 2004, ApJS, 154, 18
Imanishi M., Dudley C. C., 2000, ApJ, 545, 701
Kawakatu N., Wada K., 2008, ApJ, 681, 73
Kishimoto M., Hönig S. F., Antonucci R., et al., 2011, A&A, 536, 78
Komossa S., Burwitz V., Hasinger G., et al., 2003, ApJ, 582, L15
Laurent O., et al., 2000, A&A, 359, 887
Lebouteiller V., Barry D. J., Spoon H. W. W., et al., 2011, ApJS, 196, 8
Lira P., Videla L., Wu Y., Alonso-Herrero A., Alexander D., Ward M., 2013, ApJ, 764, 59
Lutz D., Spoon H. W. W., Rigopoulou D., Moorwood A. F. M., Genzel D., 1998, ApJ, 505, L103
Maiolino R., Ruiz M., Rieke G. H., Keller L. D., 1995, ApJ,
Nuclear 11.3 $\mu$m PAH emission in local AGN