VLT diffraction-limited imaging at 11 and 18 μm of the nearest active galactic nuclei

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ABSTRACT
Mid-infrared (mid-IR) imaging at resolutions of 300 mas of the central kpc region of 13 nearby, well-known active galaxies is presented. The bulk of the mid-IR emission is concentrated on an unresolved central source within a size of less than 5–130 pc, depending on the object distance. Further resolved emission is detected in 70 per cent of the sample in the form of circumnuclear star-forming rings or diffuse nuclear extended emission. In the three cases with circumnuclear star formation, the stellar contribution is at least as important as that of the active galactic nuclei (AGN). In those with extended nuclear emission – a third of the sample – this emission represents a few per cent of the total measured; however, this contribution may be underestimated because of the chopped nature of these observations. This extended emission is generally collimated in a preferential direction often coinciding with that of the extended ionized gas or the jet. In M87 and Cen A, where the emission extends along their respective jets, the emission is presumably synchrotron. In Circinus, NGC 1386 and NGC 3783, it can be reconciled with thermal emission from dust heated at about 100 K by the active nucleus.

In all cases, the nuclear fluxes measured at 11.8 and 18.7 μm represent a minor contribution of the flux levels measured by large aperture Infrared Astronomical Satellite (IRAS) data at the nearest energy bands of 12 and 25 μm. This contribution ranges from 30 per cent to less than 10 per cent. In only three cases do the AGN fluxes agree with IRAS to within a factor of 2. In the AGN with strong circumnuclear star formation, this component can well account for most of the IRAS flux measured in these objects. But in all other cases, either a low surface brightness component extending over galactic scales or strong extra-nuclear IR sources – e.g. H II regions in spiral arms – have to be the main source of the IRAS emission. In either case, the contribution of these components dwarfs that of the AGN at mid-IR wavelengths.

Key words: galaxies: active – galaxies: nuclei – galaxies: Seyfert – infrared: galaxies.

1 INTRODUCTION
With the advent of interferometry and adaptive optics techniques in the infrared (IR) in large ground-based telescopes, the central regions of active galactic nuclei (AGN) are being studied in ever-increasing detail. The best details have so far been seen on the brightest and nearest AGN observed with the Very Large Telescope (VLT). Here is a list. The nucleus of NGC 1068 is resolved into a parsec-scale disc in near-IR (Weigelt et al. 2004) and mid-IR (Jaffe et al. 2004) interferometry observations. That of Circinus is also resolved into a parsec-scale disc-like structure perpendicular to the ionization cone in adaptive optics images in the near-IR (Prieto et al. 2004), the results being further confirmed by interferometry in the mid-IR (Tristram et al. 2007). In both cases, the resolved nuclear structure fits within the characteristics of a parsec-scale torus. The nucleus of Cen A, however, is so far unresolved down to scales of less than a parsec in adaptive optics images in the near-IR (Häring-Neumayer et al. 2006) and interferometry in the mid-IR (Meisenheimer et al. 2007). Other bright AGN observed with adaptive optics in the near-IR show an unresolved nucleus, so far, down to scales of tens of parsecs (Prieto et al. 2007), and from
those that could be targeted with interferometry in the mid-IR, the available data indicate a resolved nuclear structure, ~2 pc in size, and NGC 4151, and possible resolved emission in NGC 1365, NGC 3783 and NGC 7469 (Tristram et al. 2009). The torus structure may be larger than a few parsecs at mid-IR wavelengths, where dust heated by the AGN to blackbody-equivalent temperatures of 100–300 K may exist at larger radii. One of the problems is that this outermost region may be fully resolved with interferometry and thus will escape detection.

This work presents diffraction-limited VLT observations at 11.8 and 18.7 μm of a sample of the nearest and brightest AGN accessible from Paranal Observatory. The resolutions achieved are a factor of 10 lower than those provided by VLT-MID-infrared Interferometric Instrument (MIDI) interferometry, but are more sensitive to possible extended structures around the nucleus (e.g. Perlman et al. 2001; Siebenmorgen et al. 2008); at the very least, they allow for setting an upper limit to the outer radius of the torus. At the higher resolution achieved in these observations [full width at half-maximum (FWHM) = 0.3 arcsec], this upper-limit radius in the sample galaxies is 35 pc on average (ranging from 5 to 130 pc).

This paper is part of a major project focusing on the study of the central few parsecs of the nearest AGN at optical, IR and radio wavelengths, using the highest spatial resolution data available today. The sample galaxies have been extensively studied across all ranges of the electromagnetic spectrum. For all these objects VLT subarcsec resolution observations, by means of adaptive optics in the 1–5 μm range (Prieto et al. 2009), and at 11.9 and 18.7 μm (this work), were collected. These data are complemented with Hubble Space Telescope (HST) optical information available for all sources, and Very Large Array (VLA) and/or Australia Telescope Compact Array (ATCA) data at subarcsec resolution (Orienti & Prieto 2009). At the distance of the sample galaxies, the spatial scales at which the nuclear regions are studied range from a few pc in the optical, near-IR and radio to several tens of parsecs in the mid-IR. A comprehensive study of the spectral energy distribution (SED) of these AGN using all the available high spatial resolution data is presented in Prieto et al. (2009).

Throughout this paper, \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \) is used.

### 2 Observations and Data Reduction

The basic properties of the AGN sample are shown in Table 1. The galaxies were observed with the 256 × 256 pixel VLT Imager and Spectrometer for mid-Infrared (VISIR; Lagage et al. 2004) with the pixel scale of 0.075 arcsec pixel\(^{-1}\). The filters were selected to be free from polycyclic aromatic hydrocarbon (PAH) features: a filter centred at 11.88 μm and with a half-bandwidth of 0.37 μm and a second one centred at 18.72 μm and half-bandwidth of 0.88 μm were used. In most cases the nodding direction was taken perpendicular to the chopping direction, keeping the four resulting beams inside the VISIR field of view (FOV), which effectively limits the total FOV to \( \sim 9 \times 9 \text{ arcsec}^2 \). Identical distances, typically 8 or 10 arcsec, were used for nodding and chopping. A few galaxies, which were known a priori to harbour extended emission – star-forming clusters or rings – were observed in a parallel nodding mode, providing an FOV of 19.2 × 19.2 arcsec\(^2\). Each science observation was immediately followed by a standard star, which was used for both photometric calibration and point spread function (PSF) control. The accuracy of the absolute flux calibration is limited by the uncertainties in the flux calibration of the mid-IR standard stars and is estimated to be \( \sim 10 \) per cent. Errors given in the later sections and tables are statistical.

Data reduction was done with the European Southern Observatory (ESO) pipeline, which was further modified by us to remove the striping pattern of the detector and to improve the centring of the chopped frames. Using a service mode for the observations guaranteed both reaching the diffraction limit and acceptable levels for striping. As the intensity of striping depends roughly on the brightness of the sky and its variability, observations with strong striping were rejected by the telescope staff and repeated at a later time. Low-level striping was easy to remove by fitting and subtracting a low-order polynomial along image rows with suitable pixel rejection criteria to guarantee that the observed galaxy or star is not included in the fit.

The data reduction procedure consists of simply shifting and stacking chopped/nodded frames. To provide the most accurate combination of frames for bright sources, the shortest individual

### Table 1

The AGN sample observed with VISIR. The distance, \( D \), was derived from the velocity \( v_{\text{H} \beta} \) provided in NASA/IPAC Extragalactic Database (NED), except for NGC 1386, NGC 5128 and Circinus, which are from Madore et al. (1999), Ferrarese et al. (2007) and Freeman et al. (1977), respectively. Galaxy morphology and classification are from NED. The 12 and 25 μm IRAS fluxes are from Mosher et al. (1990). The last two columns give total on-source integration time.

| Galaxy          | \( z \)  | \( D \) (Mpc) | Scale (arcsec) | Host type | AGN 12 μm (Jy) | AGN 25 μm (Jy) | \( t_{11.8} \) (s) | \( t_{18.7} \) (s) | Observing date |
|-----------------|--------|--------------|---------------|-----------|----------------|----------------|-----------------|----------------|----------------|
| NGC 1097        | 0.004 240 | 15.1         | 73            | SBb       | Sy1            | 1.985          | 5.509           | 660            | 1000           | 2006-09-04     | 2006-09-05     |
| NGC 1386        | 0.002 895 | 18.6         | 90            | SB0       | Sy1            | 0.493          | 1.433           | 600            | 1000           | 2006-08-17     | 2006-08-16     |
| NGC 1566        | 0.005 017 | 20.5         | 99            | SABbc     | Sy1            | 0.831          | 1.219           | 600            | 1120           | 2006-09-05     | 2006-09-05     |
| ESO 434-G040    | 0.008 486 | 39.2         | 190           | SA0       | Sy2            | 0.600          | 1.020           | 600            | 1800           | 2005-12-18     | 2006-04-28     |
| Mrk 1239        | 0.019 927 | 86.6         | 420           | E-S0      | Sy1.5          | 0.65           | 1.141           | 600            | 1000           | 2006-04-28     | 2006-05-16     |
| NGC 3783        | 0.001 703 | 44.3         | 215           | SBa       | Sy1            | 0.840          | 2.492           | 600            | 600            | 2006-04-29     | 2006-03-13     |
| M87             | 0.004 360 | 22.4         | 109           | E0–1 pec  | Sy1.9          | 0.386          | 0.497           | 800            | –              | 2006-04-09     | 2005-05-17     |
| Sombrero        | 0.003 416 | 18.7         | 91            | SaA       | Sy1.9          | 0.386          | 0.497           | 800            | –              | 2006-03-13     | 2006-03-13     |
| NGC 5128        | 0.001 825 | 3.4          | 17            | S0 pec    | Sy2            | 13.26          | 17.26           | 300            | 750            | 2006-03-15     | 2006-03-22     |
| NGC 5506        | 0.006 181 | 29.0         | 141           | Sa pec    | Sy1.9          | 1.282          | 3.638           | 600            | 1000           | 2006-06-06     | 2006-06-06     |
| Circinus        | 0.001 448 | 4.2          | 20            | SaB       | Sy2            | 18.8           | 68.44           | 500            | 1000           | 2006-06-05     | 2006-03-27     |
| NGC 7469        | 0.016 317 | 61.9         | 300           | SABA      | Sy1.2          | 1.348          | 5.789           | 600            | 1020           | 2006-07-14     | 2006-08-06     |
| NGC 7582        | 0.005 254 | 18.3         | 89            | SBab      | Sy2            | 1.620          | 6.436           | 750            | 1000           | 2006-08-06     | 2006-06-16     |
exposures at each chopping position – typically an integration time of a few seconds – were combined by using centroiding on the source itself (marked with a * in Table 2). For fainter sources, centroiding was done on the combined nodding/chopping exposure – typically representing around 1 min of integration time (marked with a ** in Table 2). A few sources are too faint at 11.8 μm for any centroiding, and we were forced to rely on telescope guiding for combining each beam. This is typically also the case at 18.7 μm. The same combination scheme was always used for both the galaxy and its associated PSF standard. Finally, the four beams were combined.

The accuracy of the absolute flux calibration is limited by the uncertainties in the flux calibration of the mid-IR standard stars and is estimated to be 5–10 per cent. Flux errors given in the tables are statistical. When available, we compared our VISIR photometry with equivalent measurements reported in the literature. The agreement is in general good within the errors, but some discrepancies exist. The result of this comparison is discussed on a case basis at each object section.

### 3 Analysis

#### 3.1 Quality of the PSF

The FWHM resolution achieved in the standard star images is typically 0.31–0.35 arcsec at 11.8 μm and 0.49–0.53 arcsec at 18.7 μm (Table 2). The observations of the PSF stars often show an elongation, predominantly along the nodding direction. The reason for the elongation is unclear: Tokovinin, Sarazin & Smette (2007) suggest that it may be related to the tilt anisoplanatism between the guide star and the object. The direction of elongation does not depend on the rotation angle of the instrument and is therefore not caused by the support structure of the secondary mirror. Table 2 gives the residual ellipticity of the images ε = 0.10–0.24 at 11.8 μm (e = 0.15 on average) and slightly lower e = 0.03–0.15 (e = 0.10 on average) at 18.7 μm.

In order to investigate this intrinsic, variable elongation and its effect on the analysis of the science data further, an average of all standard star observations was taken and subtracted this from the individual standard star observation. A typical residual was a pair of central symmetric lobes with varying position angles (PA; Fig. 1). The same residual is often present when comparing the galaxy observation with its associated PSF star (e.g. Fig. 8) and is therefore taken to be an artefact in the present analysis.

The FWHM of the PSF stars is rather stable and similar to that measured at the nucleus of the galaxies. The standard deviation of the FWHM measurements in the PSF star frames is σ = 0.014 arcsec at 11.8 μm and σ = 0.013 arcsec at 18.7 μm. In two cases the nucleus FWHM is significantly higher than that of the corresponding PSF star, both in the 18.7 μm images: NGC 7582, where the extended emission from the star-forming ring affects the measurement of the core width, and NGC 1386, which presents the strongest extended nuclear emission in the sample.

#### 3.2 Extended emission

In all cases, the most conspicuous source at these wavelengths is the nucleus. The detection of low surface brightness emission around the nucleus is limited by the chopping technique used in ground mid-IR observations. Nevertheless, in some cases extended nuclear emission and circumnuclear star-forming regions are strong enough to be detected. To search for extended emission, both PSF subtraction and radial profile analysis were used. In the first case, the PSF star was subtracted from its associated-in-time galaxy observation after normalizing it to the galaxy peak at the nucleus. The residual map thus has zero flux at the very centre, and possible differences in the shapes of the PSF star and galaxy are then visible as negative or positive fluxes. In some cases, these residuals take the form of two symmetric central blobs and should be ignored (see Section 3.1). In addition, radial profiles were extracted by azimuthally averaging the emission about the nucleus. This analysis is more sensitive to the presence of extended emission due to the accumulated higher signal-to-noise ratio (S/N) and is also less affected by PSF variations. Therefore, radial profiles are used as primary indicators for the presence of extended emission.

#### 3.3 Nuclear photometry

Nuclear point-like fluxes were derived from both the radial profile analysis and direct aperture photometry (Table 3). In cases where the emission is clearly extended, a nuclear point-like flux (Table 3)

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**Table 2.** FWHM, ellipticity ε and PA for the standard star observations and galaxies. The measurements marked with * and ** are produced by using centroiding for exposure with an integration time of a few seconds (*) or around 1 min (**); see Section 2 for details.

| Object    | HD       | 11.8 μm PSF star observations | 18.7 μm PSF star observations | Galaxy observations |
|-----------|----------|-------------------------------|-------------------------------|---------------------|
|           |          | FWHM (arcsec) | ε (°) | PA (°) | FWHM (arcsec) | ε (°) | PA (°) | FWHM (arcsec) | ε (°) | PA (°) |
| NGC 1097  | 16815    | 0.35            | 0.10  | 86     | 0.50        | 0.15  | 82    | 0.37        | 0.13  | 3      | 0.54   | –     | –     |
| NGC 1386  | 26967    | 0.33*           | 0.21  | 80     | 0.53        | 0.08  | 70    | 0.36*       | 0.27  | 1      | 0.58   | 0.28  | –     |
| NGC 1566  | 26966    | 0.34            | 0.19  | 79     | 0.49        | 0.03  | 6     | 0.32        | 0.38  | –5     | 0.50   | 0.56  | 16    |
| ESO 434-G040 | 75691   | 0.31*           | 0.11  | 87     | 0.48        | 0.10  | 79    | 0.31*       | 0.10  | –3     | 0.50   | 0.28  | –63   |
| M87       | 108985   | 0.31            | 0.10  | 81     | –           | –     | –     | 0.35        | 0.55  | –9     | –     | –     | –     |
| NGC 5128  | 119193   | 0.31*           | 0.11  | 71     | 0.51**      | 0.45  | 82    | 0.31*       | 0.05  | –76    | 0.52** | 0.11  | 47    |
| NGC 5506  | 124294   | 0.32*           | 0.24  | 78     | 0.49**      | 0.15  | 83    | 0.33*       | 0.26  | 86     | 0.52** | 0.22  | 89    |
| Circinus  | 128068   | 0.35*           | 0.14  | 67     | 0.50**      | 0.08  | 78    | 0.36*       | 0.11  | –44    | 0.51** | 0.17  | –77   |
| NGC 7469  | 5112     | 0.32*           | 0.17  | 86     | 0.49        | 0.14  | 80    | 0.33*       | 0.51  | –74    | 0.51   | 0.10  | 33    |
| NGC 7582  | 2261     | 0.33            | 0.11  | 83     | 0.49        | 0.12  | 87    | 0.33        | 0.06  | –45    | 0.70   | 0.27  | –11   |

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Table 3. Photometry.

| Object       | Total flux in (radius r) | Nucleus size | Unresolved source | Circumnuclear  | Extended emission |
|--------------|--------------------------|--------------|-------------------|---------------|-----------------|
|              | 11.8 μm (mJy) | 18.7 μm (mJy) | 11.8 μm (mJy) | 11.8 μm (mJy) | 11.8 μm (mJy) | 11.8 μm (mJy) |
| NGC 1097     | 25 ± 2(0.75) | 41 ± 4(0.75) | 27             | 26            | 49              | >500          |
| NGC 1386     | 353 ± 4(1.13) | 757 ± 6(1.13) | 32             | 195          | 330             | 170          |
| NGC 1566     | 59 ± 3(0.75) | 114 ± 4(0.75) | 31             | 63            | 128             |
| ESO 434-G040 | 573 ± 6(1.50) | 1540 ± 7(1.13) | 60             | 590          | 1450            |
| Mrk 1239     | 570 ± 4(1.13) | 890 ± 10(1.13) | 134           | 590          | 930             |
| NGC 3783     | 555 ± 4(1.13) | 1470 ± 10(1.13) | 69             | 520          | 1400            | 90           |
| MS7          | 16 ± 0.8(0.75) | 18 ± 0.75     | 35             | 17            | 1.6             |
| Sombredo     | <7          | -             | -              | -             | -               |
| NGC 5128     | 1150 ± 5(1.13) | 2900 ± 30(1.5) | 5              | 1150         | 2300            | 30          |
| NGC 5506     | 958 ± 5(1.5) | 1990 ± 20(1.5) | 47             | 900          | 1400            | 65          |
| Circinus     | 11400(2.63) | 24700(2.63) | 7              | 9300         | 17600           | 2100         |
| NGC 7469     | 917 ± 8(2.25) | 2470 ± 20(2.25) | 99             | 530          | 1270            | 390          |
| NGC 7582     | 943 ± 7(2.63) | 1880 ± 20(2.63) | 29             | 405          | 550             | 540          |

Note. Columns 2 and 3 are integrated fluxes in a radius r, in brackets; errors refer to background noise; Column 4 is an upper limit to the nuclear size; Columns 5 and 6 are nuclear point-like source fluxes; values marked with a † are inferred from the fitting analysis; all others are from aperture photometry (see Section 3.3); Columns 7 and 8 are fluxes from the extended component, whose size and orientation are given in Column 9.

is derived from a fit to the radial profile. The fit has two components: a disc profile \( f = I_0 \exp^{-r/a} \) convolved with the associated PSF star representing the extended component and the profile of the PSF star representing the unresolved nucleus. For some galaxies, the associated PSF star was too faint at the wing levels. In that case, a combined PSF profile was created by replacing the region beyond ∼1 arcsec with the profile of the brightest PSF star in the sample, HD 2261 (35 Jy at 11.8 μm and 15 Jy at 18.7 μm).

In galaxies with weak extended emission, nuclear aperture photometry was used instead. The optimal aperture radius was determined by comparing the galaxy radial profile with that of the PSF star. The radius at which the galaxy radial profile began to diverge from that of the PSF was selected and a core flux derived. The point-like flux in Table 3 is the core value multiplied by a correction factor – to account for the additional unresolved nuclear flux contained in the PSF wings.

Finally, in pure unresolved nuclear sources, fluxes are directly those measured in an aperture containing all the observed emission. We note, however, that in these cases emission from the nuclear PSF wings is weak or undetected. Following the same procedure as before, a correction factor – derived from the PSF star radial profile – to account for the additional flux in the nuclear PSF wings was applied to the total observed emission and this is given in the point-like flux column in Table 3. It can be seen from the comparison between the observed flux and the point-like flux that this correction factor is small, between <5 and 10 per cent on average.

4 DESCRIPOTION OF GALAXIES

Figs 2, 5–8 and 10 present VLT-VISIR 11.8 and 18.7 μm images for the sample galaxies. For each image, there is a residual map after a PSF star subtraction and a radial profile analysis. Only the central 5 × 5 arcsec² region is shown, as no emission is detected further out except in the case of NGC 1097 (Fig. 3). In all cases, the lowest contour level displayed is 3σ.

A brief description of the results for each galaxy is provided in the following sections. The VISIR nuclear fluxes are compared with the large-aperture satellite measurements generally used at these mid-IR wavelengths. IRAS 12 and 25 μm are taken as a reference. The IRAS 12 μm bandpass is 8.5–15 μm and the IRAS 25 μm bandpass is
Seyfert galaxies at 11 and 18 μm

Figure 2. The 11.8 and 18.7 μm images for NGC 1097 and NGC 1386. North is up and east is to the left. Left: observed emission, the circle on the left corner represents the PSF FWHM and the size of the cross at the nucleus indicates the size of the first diffraction ring (1.22λD−1). The location of the ionization cone in NGC 1386 is indicated by an arrow. The 11.8 μm map of NGC 1097 suffers from poor sky subtraction. Middle: residual after PSF subtraction. Upper right: radial profiles in logarithmic flux units normalized at r = 0 for the galaxy plotted with error bars, the PSF standard (red line), fitted disc component (blue line) and the combined model (black line). Lower right: the residual observed — model in per cent is shown. Contours are at 3σ, 5, 7, 11 and 19 levels; 1σ in NGC 1097 is 29 mJy arcsec−2 at 11.8 μm and 16 mJy arcsec−2 at 18.7 μm; in NGC 1386, it is 19 mJy arcsec−2 at 11.8 μm and 33 mJy arcsec−2 at 18.7 μm.
NGC 1097 has a low-ionization nuclear emission-line region (LINER)/Seyfert 1 nucleus surrounded by a star-forming ring of radius \( r \approx 8 \) arcsec or \( \sim 600 \) pc. In the 2–4.5 \( \mu m \) range, the nuclear region is unresolved down to scales of FWHM < 10 pc from adaptive optics VLT/NaCo images (Prieto, Maciejewski & Reunanen 2005a).

Fig. 2 shows the central \( 5 \times 5 \) arcsec\(^2 \) region in the 11.8 and 18.7 \( \mu m \) VISIR images. The most prominent feature is the nucleus, unresolved at the achieved spatial resolution: FWHM < 30 pc. The residual images after the subtraction of the associated PSF star do not reveal any extended nuclear emission and the radial profiles show that both the nucleus and the PSF star profiles agree to within the errors. The complete VISIR FOV at 18.7 \( \mu m \) (Fig. 3) is one of the deepest images of the star-forming ring and nucleus of this galaxy at this wavelength, presenting more than 12 star-forming knots in the ring. The VISIR 11.8 \( \mu m \) image is worse in quality, due to a high background residual, and only three regions of the ring are detected. More star-forming regions at this wavelength are detected by Mason et al. (2007) using Gemini/Thermal-Region Camera Spectrograph (T-ReCS).

The nuclear fluxes reported by Mason et al. (2007) in a 1.5 arcsec aperture radius are larger by a factor of \( 2 \) at 11 \( \mu m \) and a factor of 1.5 at 18 \( \mu m \) than those found by us, either after integrating in an aperture containing all the observed emission or from the radial profile analysis (Table 3). The reason for this difference is not clear. Mason et al.’s filters are much broader than the ones used by us (their filters are 18.3 \( \mu m \) filter with half-bandwidth = 1.51 \( \mu m \) and 11.7 \( \mu m \) filter with 1.13 \( \mu m \) half-bandwidth). Accordingly, their 11.7 \( \mu m \) may include the contribution of the usually strong 11.2 \( \mu m \) PAH feature. However, the results from IR nuclear spectroscopy carried by the same authors indicate the absence of other PAH features in the nucleus of NGC 1097. Thus, the plausible explanation for the difference is genuine nuclear variability, by a factor of 2 or so in a time-scale of 1 yr, the spanning time between both observation sets.

Comparing with large-aperture IRAS (Table 1) or Spitzer (6.6 Jy at 24 \( \mu m \); Dale et al. 2005) fluxes, they are two orders of magnitudes larger than the nuclear fluxes reported here. In this case, the IR satellite fluxes are dominated by the prominent star-forming ring of NGC 1097. The observed 18.7 \( \mu m \) flux in the ring is \( \gtrsim 500 \) mJy (no reliable estimate is possible at 11.8 \( \mu m \).) This is a lower limit due to the observational limitation of chopping; also the full extension of the ring is not included within the VISIR FOV. Still this lower limit is already an order of magnitude higher than that of the AGN, indicating that at mid-IR wavelengths star formation and not the AGN is the dominant contributor. This is full in line with the result derived from the analysis of the SED of this nucleus based on very high resolution data, from UV to optical to IR. This study shows that the genuine AGN luminosity in NGC 1097 is indeed a tiny fraction, less than 1 per cent, of the total IR luminosity integrated over the galaxy (Prieto et al. 2009).

### 4.2 NGC 1386

NGC 1386 is an inclined, barred lenticular galaxy with a Seyfert 2 nucleus. The nuclear region is crossed by dust lanes, which are preferentially distributed along the galaxy major axis at PA \( \sim 20^\circ \). The [O\textsc{iii}] 5007 Å emission is highly collimated and extends along the same direction, north-to-south, up to \( \sim 3 \) arcsec radius from the centre (Schmitt et al. 2003; Fig. 2).

Both 11.8 and 18.7 \( \mu m \) VISIR images also show elongation along the north–south direction but up to \( \sim 1 \) arcsec from the centre (Fig. 2). Although the elongation is in the direction of telescope chopping and could be caused by this, we tend to believe that it is real as it is present at both wavelengths, covering a similar size. None of the PSF star observations in either band shows similar structure (see Table 2). Also, the symmetric double-lobe residual seen after subtracting the PSF (Fig. 2) remains the same even if the PSF is rotated by 90°. As north–south is a preferential emission direction in this galaxy, we consider the extension to be genuine. The radial profiles at both wavelengths (Fig. 2) are similar, presenting excess emission up to even larger distances of 1.5–2.0 arcsec. Fig. 4 shows a residual image at 11.8 \( \mu m \) after scaling the PSF star to 75 per cent of the galaxy peak. The scalefactor is chosen to minimize negative fluxes seen when scaling to 100 per cent of the peak (Fig. 2). The resulting morphology is now smoother and continuous, in line with that seen in the [O\textsc{iii}] line emission.

The total integrated flux at 11.8 \( \mu m \) is a 15 per cent difference from that reported by Siebenmorgen, Krügel & Spoon (2004) using ESO 3.6-m/Thermal Infrared Multimode Instrument (TIMMI2) with a much broader filter centred at 11.9 \( \mu m \) (FWHM = 2.26 \( \mu m \)). Since this filter includes the strong PAH feature at 11.2 \( \mu m \), the flux difference can partially be attributed to this contribution and the photometry errors.

The results from the profile fitting analysis further indicate that the contribution of the unresolved source (the AGN) is \( \sim 50 \) per cent of the total measured at each of the wavelengths, with the other half being associated with the north–south extended emission. Comparing with the large-aperture IRAS data, the inferred AGN contribution is again much less, \( \sim 40 \) per cent of the IRAS 12 \( \mu m \).
and \(\sim\) 20 per cent of the IRAS 25 \(\mu\)m flux levels. It can be readily seen that the difference with the IRAS 12 \(\mu\)m flux is the contribution of the extended nuclear emission seen by VISIR. This is not the case at 25 \(\mu\)m, and thus most of the emission at this wavelength must come, plausibly, from a more diffuse extended emission over the galaxy.

4.3 NGC 1566

NGC 1566 is a face-on spiral galaxy with a Seyfert 1 nucleus. The nucleus is known to be variable from X-rays to IR (Baribaud et al. 1992; Glass 2004). At near-IR wavelengths, 1–4 \(\mu\)m adaptive optics images, the nucleus is unresolved down to scales of FWHM \(<11\) pc at 2 \(\mu\)m (Prieto et al. 2007, 2009). The HST [O iii] images show a one-sided ionization cone towards the south-west direction (Schmitt & Kinney 1996).

The VISIR images (Fig. 5) at both wavelengths just reveal a dominant central unresolved source with size FWHM \(<31\) pc at 11.8 \(\mu\)m. The large-aperture IRAS 12 \(\mu\)m and ISOCAM 8.5–10.7 \(\mu\)m fluxes (Ramos Almeida et al. 2007) are larger, by factors of 13 and 4, respectively, than the 11.8 \(\mu\)m nuclear flux reported here. The IRAS 25 \(\mu\)m flux is a factor of 10 higher than the 18.7 \(\mu\)m flux. The poor Infrared Space Observatory (ISO) spatial resolution can be improved by deconvolution to the ISOCAM radial light profile. The deconvolved ISOCAM flux reported by Ramos Almeida et al. is even smaller than at 11.8 \(\mu\)m, possibly due to the strength of the silicate absorption band. Thus, most of the emission measured in this object in IR large-aperture data is dominated by other sources in the galaxy, and the AGN contribution to the total is minor. The analysis of the SED of this nucleus based on very high resolution observations.

4.4 ESO 434-G040

ESO 434-G040 (MCG-05-23-016) is an SA galaxy with a Seyfert 2 nucleus but with broad Paschen and Brackett series H\(\alpha\) lines (Veilleux, Goodrich & Hill 1997). A dust lane crosses the nuclear region on its south-eastern side, at a distance of less than 1 arcsec from the centre. The [O iv] gas emission extends in the north-east-south-west direction by 1 arcsec (Ferruit, Wilson & Mulchaey 2000), as shown in Fig. 5.

The VISIR images are dominated by a bright point-like source (Fig. 5). The structure seen in the residual image at 11.8 \(\mu\)m is an artefact (Section 3.1); the nature of the residuals at the 18.7 \(\mu\)m image is uncertain. However, there is marginal excess emission in the 18.7 \(\mu\)m radial profile \((\sim190\) mJy; see Table 3). No reported IRAS measurements were found.

4.5 Mrk 1239

Mrk 1239 is an elliptical/S0-class galaxy with a Seyfert 1.5 nucleus. It is the most distant object in the sample, 20 times the distance to Circinus (Table 1).

VLT/MIDI interferometric observations in the 8–12 \(\mu\)m range are consistent with an unresolved nucleus (Tristram et al. 2009). VLT/NACO adaptive optics images in the 1–4 \(\mu\)m range set an upper limit for the unresolved nucleus down to scales of FWHM \(<38\) pc at 2 \(\mu\)m (Prieto et al. 2009). VISIR 11.8 and 18.7 \(\mu\)m images are also dominated by an unresolved central source with no extended emission detected in either the residuals or the radial profile analysis (Fig. 6). The extended optical ionized gas in this galaxy has a halo-like morphology and extends around the nucleus up to about 8 arcsec radius (Mulchaey, Wilson & Tsvetanov 1996).

Our photometry at 11.8 \(\mu\)m is in excellent agreement, 5 per cent difference, with that reported by Maiolino et al. (1995), who observed with a 5.3 arcsec-aperture bolometer at the Multiple Mirror Telescope (MMT) using an N-band filter centred at 10.6 \(\mu\)m. The agreement indicates that this nucleus is not variable on time-scales of at least 11 yr, and that no active star formation is occurring in the nucleus, as otherwise emission from PAH features should have made a difference at the N-band filter observations.

Mrk 1239 is one of the three galaxies in the sample – the other cases are NGC 5506 and NGC 3783 – where the AGN accounts for almost all of the IR emission measured in the entire galaxy: the VISIR fluxes are 80–90 per cent of the IRAS fluxes at 12 and 25 \(\mu\)m, respectively (Tables 1 and 3).

4.6 NGC 3783

NGC 3783 is a nearly face-on spiral galaxy with a Seyfert 1 nucleus. The [O iv] emission extends over a surrounding halo up to 200 pc from the centre (Schmitt et al. 2003); higher ionization coronal gas ([Fe x]), [Fe x]) extends further up to 400 pc from the nucleus in the north–south direction (Rodríguez-Ardila et al. 2006).

From VLT/NACO adaptive optics images in the 1–4 \(\mu\)m range, the nucleus is unresolved down to scales of FWHM \(<22\) pc at 2 \(\mu\)m (Prieto et al. 2007, 2009). New VLT/MIDI interferometry results in the 8–12 \(\mu\)m range point to a resolved nuclear structure with a size of \(<3.5\) pc (Kishimoto et al. 2009).

VISIR 11.8 and 18.7 \(\mu\)m images are dominated by a central bright source (Fig. 6). The central two-blob structure in the 11.8 \(\mu\)m residual image is due to PSF mismatch (see Section 3.1). The radial profile at both wavelengths shows some marginal excess emission but that may still be introduced by slight variations in the PSF star profile. We consider the VISIR emission unresolved at the S/N limit.
Figure 5. As in Fig. 2 but for NGC 1566 and ESO 434-G40. The location of the respective ionized-gas cones is outlined in the figures. $1\sigma$ level is 22 mJy arcsec$^{-2}$ at 11.8 $\mu$m and 42 mJy arcsec$^{-2}$ at 18.7 $\mu$m for NGC 1566, and 32 mJy arcsec$^{-2}$ at 11.8 $\mu$m and 55 mJy arcsec$^{-2}$ at 18.7 $\mu$m for ESO 434-G040.
Figure 6. As in Fig. 2 but for Mrk 1239 and NGC 3783. The 1σ level is 23 mJy arcsec$^{-2}$ at 11.8 μm and 55 mJy arcsec$^{-2}$ at 18.7 μm for Mrk 1239, and 23 mJy arcsec$^{-2}$ at 11.8 μm and 70 mJy arcsec$^{-2}$ at 18.7 μm for NGC 3783.
of these observations, setting an upper limit for the nucleus size of FWHM < 68 pc at 11.2 μm (Table 2).

Our photometry at 11.8 μm differs by 20 per cent with respect to the value reported by Haas et al. (2007), using also VISIR but a narrow-band filter just centred on the PAH feature at 11.2 μm (FWHM = 0.6 μm). Thus, the higher flux measured by Haas et al. may be due to PAH contribution – the photometric errors in both observations are about 10 per cent. If this is the case, some level of star formation may be present at the nuclear region at scales of less than 70 pc – the resolution of these observations. Alternatively, the difference may be due to variability at a very low level: these observations and that of Haas et al. are separated by 1 yr.

Comparing with the IRAS flux levels at 12 and 25 μm, the VISIR nuclear fluxes are ~60 per cent lower in either band. This is a small difference as compared with most of the objects in this sample, emphasizing the dominance of this AGN over the host galaxy light. The analysis of the SED of this nucleus on the basis of high spatial resolution data indeed shows that this AGN behaves like a quasar dominating the integrated light at any aperture size in the 1–100 μm range (Prieto et al. 2009).

4.7 M87

M87 is a giant elliptical galaxy with a LINER-type nucleus. It has a one-sided jet at PA = −66° extending up to 2 kpc from the nucleus. The radio, optical and X-ray jet has several knots of which the innermost one – HST-1 at 0.85 arcsec from the nucleus – has brightened 50-fold in the X-rays in the period 2000–2005 (Harris et al. 2006). A sudden increase in the brightness from HST-1 has also been seen in the IR in our VLT/NACO K-band images during the same period, reaching flux levels comparable to that of the nucleus.

M87 was observed in 2006 with VISIR. At that time, only the nucleus was bright at 11.8 μm (Fig. 7) but barely detected at 18.7 μm. At 11.8 μm, a faint source (1.6 ± 0.3 mJy; 5σ) just coinciding with the position of HST-1 is seen at both the original and the residual images. A deeper Gemini image by Perlman et al. (2001), using a broad-band filter centred at 10.8 μm (FWHM = 5.3 μm), shows additional jet components at larger distances. They report on marginal nuclear excess emission up to R > 0.6 arcsec from the centre. The VISIR image has slightly better spatial resolution than that by Gemini (0.32 versus 0.46 arcsec), and so far our results on the residual image and radial profile analysis are consistent with the nucleus of M87 being point-like.

The nuclear photometry was done in an aperture radius r < 0.75 arcsec (Table 3) which avoids the HST-1 region. The resulting flux at 11.8 μm is virtually the same as that reported by Perlman et al. (2001). Considering the width of the filter used by Perlman et al., the agreement emphasizes the dominance of the continuum light over any line feature, in particular PAHs, in the spectrum of M87; also the nucleus was in the same steady state in 2001 (Gemini) as in 2006 (VISIR), precisely when HST-1 was active.

M87 nucleus is detected at 18.7 μm with VISIR but the signal is very low; the integrated flux in an aperture including all the detected emission represents 3σ (Table 3).

M87 was not detected in the IRAS 25 μm band. At 11.8 μm, the nuclear flux accounts for less than 7 per cent of the flux measured in the IRAS 12 μm band. Thus, most of the extra emission seen by IRAS has to come from low surface brightness light from the galaxy itself with a minor contribution from the jet (~20 mJy is the sum of the jet knots contribution detected in Perlman et al.).

4.8 The Sombrero Galaxy

The Sombrero Galaxy (NGC 4594) is a spiral with a Seyfert 1.9/LINER nucleus. The galaxy is almost edge-on and is crossed mid-plane by a distinctive dust lane.

It was undetected at 11.8 μm and thus no observations at 18.7 μm were attempted. A formal 6σ upper limit for an unresolved source is 7 mJy. Bendo et al. (2006) report an 8 μm flux of 34.4 mJy based on Spitzer imaging; however, such a flux level would have clearly been detected by VISIR. Thus, the mid-IR emission probed by Spitzer or IRAS has to be largely diffuse, escaping detection in ground-based observations because of the chopping technique. The AGN contribution, if any, is tiny at these wavelengths.

4.9 NGC 5128

NGC 5128 is the closest object in this sample. Its jet, at PA = 55°, is visible from the radio to the X-ray. Adaptive optics images in the 1–5 μm range and interferometric spectra in the 8–12 μm range are both compatible with an unresolved nucleus down to scales of less than 1 pc (Haring-Neumayer et al. 2006; Meisenheimer et al. 2007).

The VISIR images are dominated by a bright central source (Fig. 7). At 11.8 μm the source is rather symmetric, but the radial profile reveals some marginal excess beyond ~1 arcsec. At 18.7 μm, the nuclear emission appears elongated in the direction of the jet. In this case, a fit to the radial profiles was attempted and the results are shown in Fig. 7. At 11.8 μm, the fit is compatible with a single point source: the resulting point-like flux and the total integrated one are the same; at 18.7 μm, the difference is ~20 per cent. This excess represents ~600 mJy and presumably is from the jet. Our photometry at 11.8 and 18.7 μm differ, respectively, by 50 and 20 per cent with respect to the 11.7 and 17.75 μm nuclear fluxes reported by Whysong & Antonucci (2004). These observations were done with the Keck telescope in 2002 using filters centred at the respective wavelengths above indicated, both having an FWHM = 1 μm. These authors get similar spatial resolutions as the ones obtained with VISIR, and in both cases the quoted flux is integrated over the total observed emission. The difference in photometry is thus significant, in particular considering that no PAH features are seen in the nuclear spectrum (Siebenmorgen et al. 2004). Cen A nucleus is the only source in Prieto et al.’s study (2009) whose high spatial resolution SED from radio to millimetre to IR can be fitted by a single synchrotron model (Prieto et al. 2007). Thus, we believe that the difference in the fluxes is genuine and linked to the AGN variability.

Comparing with the large-aperture IRAS 12 and 25 μm fluxes, the VISIR fluxes are a factor of 13 and 8 smaller, respectively. The analysis of the high spatial resolution SED shows that the AGN indeed represents a few per cent of the total galaxy emission in the IR. Thus, most of the IRAS emission has to come from a source other than the AGN, presumably from a low surface brightness component.

4.10 NGC 5506

NGC 5506 is an Sa galaxy with a Seyfert type 1.9 nucleus. It is orientated edge-on and crossed by dust lanes along its mid-plane, in the east–west direction. Analysis of the HST/ WFCPC2-F660W image shows that the Hα+[N II] gas extends from the centre towards the north following a cone-like morphology (Fig. 8).

The nucleus, fully obscured at optical wavelengths, reveals in full realm in VLT/NACO adaptive optics images in the 1–5 μm
Seyfert galaxies at 11 and 18 \( \mu m \)

Figure 7. As in Fig. 2 but for M87 and NGC 5128 (Cen A). M87 is barely detected at 18.7 \( \mu m \), and it is not shown. The diagonal stripes in the 11.8 \( \mu m \) image of NGC 5128 are due to sky residuals. The jet directions in M87 and NGC 5128 are indicated by an arrow in each figure. The 1\( \sigma \) level is 8 mJy arcsec\(^{-2}\) at 11.8 \( \mu m \) and 57 mJy arcsec\(^{-2}\) at 18.7 \( \mu m \) (not shown) for M87, and 32 mJy arcsec\(^{-2}\) at 11.8 \( \mu m \) and 123 mJy arcsec\(^{-2}\) at 18.7 \( \mu m \) for NGC 5128.

The VISIR 11.8 and 18.7 \( \mu m \) images are both dominated by the nuclear source (Fig. 8). Still, there is clear extended emission, more evident at 11.8 \( \mu m \), along the east–west direction. The residual images are dominated by the symmetric two-blob structure caused by the PSF mismatch (Section 3.1), but some weak emission at radii larger than 1 arcsec is still apparent. The radial profiles reveal a net excess emission at both wavelengths.

A fit to the radial profiles using a composite model, a PSF star profile and a disc (Section 3.2) yields a dominant contribution for the point-like source at 11.8 \( \mu m \), but at 18.7 \( \mu m \) the contribution of the extended emission becomes more relevant, \( \sim 30 \) per cent of the total flux (Table 3). Our photometry at 11.8 \( \mu m \) agrees very well – \( \sim 5 \) per cent difference – with that of Siebenmorgen et al. (2004), the latter obtained in 2002 with the ESO-3.6 m/TIMMI2 camera. The total integrated fluxes measured in both cases are compared.

At both 11.8 and 18.7 \( \mu m \) though, the AGN largely dominates the IR light of the entire galaxy in a similar situation as it happens in the previously described AGN Mrk 1239 and NGC 3783: the unresolved nuclear fluxes represent 70 per cent, at 11.8 \( \mu m \), and 40 per cent at 18.7 \( \mu m \), of the total flux measured by IRAS at 12 and 25 \( \mu m \), respectively. The analysis of the high spatial resolution SED of this nucleus shows that this is indeed another case of a Seyfert nucleus dominating the host galaxy light in a similar way as a quasar (Prieto et al. 2009).
Figure 8. As in Fig. 2 but for NGC 5506 and Circinus. The direction and morphology of the extended ionized gas in Circinus and NGC 5506 are outlined. The 1σ level is 23 mJy arcsec$^{-2}$ at 11.8 μm and 72 mJy arcsec$^{-2}$ at 18.7 μm for NGC 5506, and 25 mJy arcsec$^{-2}$ at 11.8 μm and 110 mJy arcsec$^{-2}$ at 18.7 μm for Circinus.
4.11 Circinus galaxy

The Circinus galaxy and Cen A are the two nearest AGN in this sample. Circinus is also the brightest in the IR, by an order of magnitude. Its optical ionization gas cone (Wilson et al. 2000) is seen in one direction only, north-west from the nucleus (Fig. 8); in the IR however, the high ionization coronal gas – [Si vi] 1.96 μm, [Si vii] 2.48 μm – reveals the counter cone location, at about the same direction as the optical ionization cone, but more collimated (Maiolino et al. 2000; Prieto, Marco & Gallimore 2005b).

The nucleus of Circinus is resolved at 2 μm with adaptive optics observations (Prieto et al. 2004; Mueller Sánchez et al. 2006). It shows a disc-like structure, ~2 pc (~0.1 arcsec) in size, oriented perpendicular to the ionization cone. The analysis of the optical-to-IR SED of this structure is compatible with emission by dust heated at ~300 K by the AGN (Prieto et al. 2004). Further VLTI/MIDI interferometry in the 8–12 μm range confirms this structure (Tristram et al. 2007). All the results together strongly suggest this structure to be the nuclear torus.

The VISIR images are dominated by a bright central source surrounded by a large halo (Fig. 7). A similar morphology is seen in the Gemini/T-ReCS mid-IR images (Packham et al. 2005). Within the halo, a fairly collimated light beam extends across the nucleus in the east–west direction. This is better contrasted in the 11.8 μm residual image. The beam light is co-spatial with the also rather collimated emission defined by the [Si vii] 2.48 μm gas traced with adaptive optics observations by Prieto et al. (2005b), see Fig. 9. As this high ionization gas traces pure AGN photons, the common spatial location is an indication that the mid-IR emission is caused by dust directly heated by the AGN.

The Circinus nucleus is unresolved in the VISIR images. The achieved resolution (Table 2) corresponds to a physical scale of FWHM < 7 pc at 11.8 μm. Thus, any further extended emission from the ~2 pc scale torus seen at 2 μm has to extend less than ~3 pc radius from the centre.

Fig. 9. Comparison between the VLTNaCo [Si vii] 2.48 μm coronal line emission map (Prieto et al. 2005b) and the VISIR residual image at 11.8 μm, the latter with contours. The solid contours are at 2.5, 5, 10, 20 and 40σ levels and dotted contours indicate negative residuals. The central two-blob feature in the residual image is due to PSF mismatch (Section 3.1).

A composite point-like source plus disc model (Section 3.3) was fitted to the 11.8 and 18.7 μm radial profiles (Fig. 7). The unresolved component is the dominant contribution, accounting for ~70–80 per cent of the total VISIR flux at those wavelengths. Deriving the nuclear fluxes by direct photometry in small apertures leads to similar values. The VISIR total flux at 18.7 μm (Table 2) is in very good agreement with the 18.3 μm flux reported by Packham et al. (2005), both measured in a 5 arcsec diameter aperture. The difference is less than 5 per cent. That at 11.8 μm is also in good agreement, 5 per cent difference, with the 12 μm flux measured in the ESO-3.6 m/TIMMI2 spectrum presented in Siebenmorgen et al. (2004). However, Galliano et al. (2005) reports a total flux of about 45 per cent higher with TIMMI2 in the N-broad-band filter which we do not understand considering the fact that these observations are contemporaneous with those of Siebenmorgen et al.

The contribution of the extended emission component in Circinus is not negligible in absolute terms, the corresponding fluxes are at the level of a few janskys at the observed VISIR wavelengths (Table 3). Comparing with IRAS fluxes, the unresolved source at both VISIR wavelengths accounts for 40–20 per cent of the 12 and 25 μm IRAS fluxes, respectively. As in most of the objects in the sample, the IR light of the galaxy dominates over that of the AGN, the relevance of this contribution becoming higher with increasing wavelength as revealed by the SED of this nucleus (Prieto et al. 2009).

4.12 NGC 7469

NGC 7469 is an SABa galaxy with a Seyfert 1 nucleus surrounded by a starburst ring at a radius of ~1 arcsec from the centre (300 pc). The current VISIR images at 11.8 and 18.7 μm show a very bright nucleus and several clumps from the star-forming ring (Fig. 10). The ring is better contrasted in the residual images (the central two-blob features in both residual images are caused by a PSF mismatch, Section 3.1).

Nuclear fluxes were derived from direct aperture photometry on the images following the procedure described in Section 3.3. A composite point-like source plus a disc model (Section 3.3) fit to the radial profiles was found not adequate because of the presence of the star-forming ring. Nevertheless, despite this additional contribution being not accounted for in the fit, the nuclear fluxes derived from the radial profile fit turn to be slightly larger than those from the aperture photometry. The total integrated flux – i.e. including the nucleus and the stellar ring (Table 3) – at 11.88 μm differs by less than 10 per cent from that by Galliano et al. (2005) who uses ESO-3.6 m/TIMMI2 and the broad-band filter centred at 11.9 μm (FWHM = 2.26 μm).

The emission from the star-forming ring was estimated as the difference between the total integrated flux in the image and that of the nucleus. This represents about half of the total integrated emission (Table 3), and some emission from the ring may still be lost due to the limited nod throw of these observations, 8 arcsec. Thus, the star-forming ring is at least as powerful as the AGN. The corresponding AGN contribution to the IRAS flux is relatively small, from 40 per cent at 11.8 μm to 20 per cent at 18.7 μm of the 12 and 25 μm fluxes, respectively. Thus, the remaining IRAS flux at 11.8 μm most plausibly comes in this galaxy from the star-forming ring.

4.13 NGC 7582

NGC 7582 is an SB galaxy with a Seyfert type 2 nucleus with broad recombination lines in the IR (Reunanen, Kotilainen & Prieto...
Figure 10. As in Fig. 2. The green line is the difference between total emission and fitted point-like source. The location of the ionization cone in NGC 7582 is outlined. The $1\sigma$ level is 27 mJy arcsec$^{-2}$ at 11.8 $\mu$m and 65 mJy arcsec$^{-2}$ at 18.7 $\mu$m for NGC 7469, and 17 mJy arcsec$^{-2}$ at 11.8 $\mu$m and 60 mJy arcsec$^{-2}$ at 18.7 $\mu$m, for NGC 7582.
2003). Several star-forming regions within a few arcseconds from the nucleus are seen along the west side of the nucleus (Prieto, Reunanen & Kotilainen 2002). These regions indeed form part of a circumnuclear ring in which more than 20 independent regions have been isolated in VLT/NACO adaptive optics images at 2 μm (Fernandez-Ontiveros et al., in preparation). The [O iii] 5007 Å gas follows a cone-like morphology on the west side of the nucleus (Storchi-Bergmann & Bonatto 1991), outlined in Fig. 10. The VISIR images show a prominent nucleus, several star-forming regions from the ring and diffuse emission, the latter being better contrasted in the residual images. A VISIR image taken with a filter centred on the [Ne ii] 12.81 μm line plus continuum (Wold & Galliano 2006) reveals a similar morphology.

As in NGC 7469, the nuclear fluxes are also derived here from direct aperture photometry on the images following the procedure described in Section 3.3. The composite PSF plus a disc model yields a poor fit at radii r ≳ 0.4 arcsec (Fig. 10). We note, however, that the nuclear fluxes derived from a formal fit to the radial profile differ by ~5 per cent at 11.8 μm and ~9 per cent at 18.7 μm, with respect to those derived from the aperture photometry. The emission from the star-forming ring was then estimated as the difference between the total integrated flux in the image and that of the nucleus (Table 3).

As in NGC 7469, the contribution from the star formation ring is as important as that of the AGN. In particular, the emission at 18.7 μm is almost a factor of 3 larger than that of the AGN. As compared with IRAS, the AGN represents ~30 per cent of the 12 μm IRAS flux and <10 per cent of the 25 μm IRAS flux.

5 DISCUSSION AND CONCLUSIONS

The mid-IR observations presented in this work, reaching spatial resolutions down to FWHM ~ 0.3 arcsec, allow us to constrain the AGN emission at mid-IR wavelengths within regions of 35 pc size in diameter on average (range from 5 to 130 pc). Within the central kpc region, most of the emission is concentrated in the nuclear region, and in most cases the bulk of it is linked to an unresolved component. Considering the physical scales sampled in these AGN, the outer radius of the torus at mid-IR wavelengths should on average be less than 18 pc, less than 4 pc in Circinus, this being the only galaxy in the sample with a detected parsec scale disc-like structure at its centre at near- and mid-IR wavelengths. Resolved or extended emission is detected in most of the objects within a few arcsec of the centre. The measured contribution of this extended component is a lower limit as part of the emission, particularly if diffuse, may easily be subtracted out in ground-based chopped observations. Further detection of emission from the galaxy is severely limited by the nod-throw of these observations, typically in the range of 8–10 arcsec.

On the basis of 13 AGN studied, the following results are found.

(i) In three AGN (NGC 7582, NGC 7469 and NGC 1097), strong circumnuclear star-forming regions within a few arcsec from the centre are detected. These are located at radii of ~130 pc in NGC 7582, 600 pc in NGC 1097 and 900 pc in NGC 7469. In all cases, their associated emission is comparable with, or even larger than, that of the AGN, particularly at 18.7 μm.

(ii) In six further AGN, extended emission on scales from 1 to 3 arcsec from the centre is detected. This emission is preferentially distributed along a particular direction, usually coinciding with the ionization cone or the jet direction. In all cases, this contribution represents a few per cent of the AGN flux.

(iii) Only in four AGN, the emission is concentrated into a central unresolved source, and in one galaxy, the Sombrero, no detection is reached.

(iv) In comparing the present photometry with previous works, most centred at ~11 μm and using broad filters that include PAH features, differences of up to 15–20 per cent in some cases which may be attributed to the contribution of PAH features are found; in M87 and NGC 5507 the agreement is within 5 per cent indicating the absence of PAH features in these nuclei and hence of active star formation. Only in NGC 1097 and Cen A, whose nuclear spectrum does not present PAH features, genuine variability by a factor of 2 at 11.8 μm in a time-scale of 1–4 yr, respectively, is indicated.

In the six AGN with extended emission around the centre, it appears to be mostly collimated. In Cen A and M87, it is aligned with the jet (in M87, it coincides with the brightest jet knot, HST-1). In Circinus, NGC 1386 and NGC 3783, the extended emission is co-spatial with the extended ionized gas. Only in NGC 5506, the extended component spreads along the mid-plane of the galaxy, being perpendicular to the optical ionization cone main axis. The mid-IR filters used in this work, narrow and centred on windows where emission lines or PAH features are unimportant, are thus targeted to measure pure continuum emission. Thus, the extended emission in M87 and Cen A is presumably of synchrotron origin; in all other cases, its nature is more ambiguous. Possibilities include free–free emission due to cooling of the ionized gas in the ionization cone (Contini, Viegas & Prieto 2004) or/and emission from dust heated by the AGN. Considering the intrinsic AGN luminosities of these objects, inferred from either high spatial resolution IR SED (Prieto et al. 2007, 2009): ~8 × 10^2 erg s^{-1} in Circinus and ~4 × 10^3 erg s^{-1} in NGC 3783, or X-ray data: ~1.3 × 10^4 erg s^{-1} in NGC 1386 (Levenson et al. 2006), and the distances at which mid-IR emission is detected – in the range from 30 pc in Circinus to 400 pc in NGC 3783 (see Table 3) – the nature of this emission could be reconciled with dust directly heated by the AGN provided its equilibrium temperature is in the 100 K range (Barvainis’ 1987 formalism is assumed).

The contribution of free–free emission in the mid-IR could also be important if strong shocks exciting the gas are occurring (see e.g. fig. 2c of Contini & Viegas-Aldrovandi 1990). Evidence for high gas velocities in the above objects is inferred from the kinematic analysis of their high ionization coronal lines. Specifically, the FWHM of [Fe ii] ~6087 Å is ~400 km s^{-1} in Circinus and ~1400 km s^{-1} in NGC 1386 and NGC 3783 (Rodriguez-Ardila et al. 2006). Moreover, the size of the extended mid-IR emission closely coincides with the observed sizes of the Fe or Si coronal region (Rodriguez-Ardila et al.) and with their spatial location, which indicates that a fraction of the mid-IR emission is due to free–free emission from predominantly shock-heated coronal gas. Estimating this contribution requires detailed modelling and is currently being explored.

Mid- and far-IR emission of galaxies is usually derived from large-aperture data obtained by IR satellites. For galaxies with an AGN, it is widely assumed that most of this emission comes from the nucleus. The flux level of the nuclear point source in the AGN studied in this work proves the assumption to be inadequate in most cases. The estimated 11.8 and 18.7 μm nuclear fluxes are larger, by factors of >3, than the fluxes measured by IRAS at 12 and 25 μm in 70 per cent of the sample, the largest discrepancy being more than an order of magnitude in five galaxies: NGC 1097, NGC 1566, M87, Cen A and NGC 7582 (in the latter case only at 18.7 μm). In the remaining 30 per cent of the sample, the IRAS flux levels are still larger but within a factor of 2.
The ‘extra’ IR excess measured by IRAS has to come from a source other than the AGN, either strong IR sources, presumably located outside the central 20 × 20 arcsec\(^2\) region – common FOV in ground-based mid-IR observations – or from a more extended low surface brightness component across the galaxy. For example, in the three AGN with circumnuclear star-forming regions, the total integrated emission (AGN plus star-forming ring) accounts for the IRAS flux levels within a factor of 2. This is the case of NGC 7582.

For all other cases, either a low surface brightness component across the galaxy. For example, in the three AGN with circumnuclear star-forming regions, the total integrated emission (AGN plus star-forming ring) accounts for the IRAS flux levels within a factor of 2. This is the case of NGC 7582.

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