The success of extragalactic infrared interferometry: from what we have learned to what to expect

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ABSTRACT

Infrared interferometry has lead to a breakthrough in the investigation of Active Galactic Nuclei (AGN) by allowing to resolve structures on sizes of less than a few parsecs in nearby galaxies. Measurements in the near-infrared probe the innermost, hottest dust surrounding the central engine and the interferometrically determined sizes roughly follow those inferred from reverberation measurements. Interferometry in the mid-infrared has revealed parsec-sized, warm dust distributions with a clear two component structure: a disk-like component and polar emission – challenging the long-standing picture of the "dusty torus". New beam combiners are starting to resolve the kinematic structure of the broad line region and are expected to provide true images of the dust emission. Nevertheless, most AGN will remain only marginally resolved by current arrays and next generation facilities, such as the Planet Formation Imager (PFI), will be required to fully resolve out larger samples of AGN.

Keywords: Infrared Interferometry, galaxies: nuclei, galaxies: Seyfert, galaxies: active

1. INTRODUCTION

In astronomy, long baseline infrared interferometry is used to study compact thermal emission as well as compact line emission (e.g. using the Brγ line at $2.166\mu m$). For the coherent combination of light from astronomical objects, sufficiently high signal to noise ratios are required in order to detect the fringes and measure their contrast. This is because the fringes are constantly shifting in phase and group delay, due to the turbulence in Earth's atmosphere. As a consequence, when integrating longer than the coherence time[1] the fringes get smeared out and become undetectable. In practice, this means only sufficiently bright astronomical sources can be observed, e.g. K $\lesssim$ 11mag ($\gtrsim$ 30mJy) and N $\lesssim$ 6mag ($\gtrsim$ 100mJy) for current technology. At the same time the sources have to have sizes $<$ 100mas for interferometry to be a reasonable alternative to direct imaging using space telescopes or large telescopes on the ground with adaptive optics.

To this date, for extragalactic sources only Active Galactic Nuclei (AGN) fulfil these requirements, although only by a small margin. Except for a couple of sources, AGN are faint for infrared interferometers and a combination of good atmospheric conditions, a good AO correction and optimised instrument performance are required to be able to record scientifically useful fringes. In this paper the success of extragalactic infrared interferometry will be described. The paper is divided as follows: Sec. 2 gives an introduction into AGN; in Sec. 3, measurements leading to size estimates are discussed; Sec. 4 focuses on the results obtained from continuum studies going beyond size estimates; Sec. 5 focuses on a few detailed studies of individual sources; Sec. 6 presents prospects to use emission line studies; Sec. 7 reviews results using AGN variability as well as using interferometry to obtain distances; and finally Sec. 8 concludes with an outlook of what can be expected in the future for the field.

In total, AGN studies with 4 beam combining instruments at 2 different facilities, the Keck Interferometer and the Very Large Telescope Interferometer (VLTI) have been published, leading to 29 publications as of June 2018 (see table 1), with many more using the measurements or their results for further investigations or modelling. In these publications, successful measurements of 15 sources in the near-infrared and of 25 sources in the mid-infrared are presented.

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Table 1. List of all long baseline infrared interferometry publications of extragalactic sources as of June 2018, inlcuding the objects studied, the interferometer used to obtain the data as well as the wavelength band used.

First Author	Date	Objects	Interferometer	Band
Swain[2] et al.	2003-10	NGC4151	Keck	K band
Wittkowski[3] et al.	2004-04	NGC1068	VINCI	K band
Jaffe[4] et al.	2004-05	NGC1068	MIDI	N band
Poncelet[5] et al.	2006-05	NGC1068	MIDI	N band
Meisenheimer[6] et al.	2007-08	Centaurus A	MIDI	N band
Tristram[7] et al.	2007-11	Circinus galaxy	MIDI	N band
Beckert[8] et al.	2008-08	NGC3783	MIDI	N band
Kishimoto[9] et al.	2009-01	NGC1068, Mrk1239, NGC3783, NGC4151	Keck & MIDI	K & N band
Raban[10] et al.	2009-04	NGC1068	MIDI	N band
Tristram[11] et al.	2009-07	8 targets ("Snapshot Survey")	MIDI	N band
Burtscher[12] et al.	2009-11	NGC4151	MIDI	N band
Kishimoto[13] et al.	2009-12	4 type 1 targets	Keck	K band
Pott[14] et al.	2010-06	NGC4151	Keck	K band
Burtscher[15] et al.	2010-10	Centaurus A	MIDI	N band
Kishimoto[16] et al.	2011-03	8 type 1 targets	Keck	K band
Tristram & Schartmann[17]	2011-07	10 targets ("Snapshot Survey")	MIDI	N band
Kishimoto[18] et al.	2011-12	6 type 1 targets	MIDI	N band
Weigelt[19] et al.	2012-05	NGC3783	AMBER	K band
Petrov[20] et al.	2012-07	3C273	AMBER	K band
Hönig[21] et al.	2012-08	NGC424	MIDI	N band
Hönig[22] et al.	2013-07	NGC3783	MIDI	N band
Burtscher[23] et al.	2013-10	23 targets ("AGN Large Programme")	MIDI	N band
Kishimoto[24] et al.	2013-10	NGC4151 & 5 further type 1 targets	Keck	K band
Tristram[25] et al.	2014-03	Circinus galaxy	MIDI	N band
López-Gonzaga[26] et al.	2014-05	NGC1068	MIDI	N band
López-Gonzaga[27] et al.	2016-06	23 targets ("AGN Large Programme")	MIDI	N band
GRAVITY Collaboration[28]	2017-06	PDS456	GRAVITY	K band
Fernández-Ontiveros[29] et al.	2018-03	IC3639	MIDI	N band
Leftley[30] et al.	2018-06	ESO323-G77	MIDI	N band

2. ACTIVE GALACTIC NUCLEI

AGN are the most luminous persistent light sources in the universe, with high energy outputs sustained for millions of years. The large amounts of energy released in the nucleus have a significant influence on the surrounding galaxy and the intergalactic medium, e.g. preventing the gas from cooling and by quenching star formation in the host galaxy. The influence of the AGN on its environment is often referred to as "AGN feedback". AGN are therefore believed to play a fundamental role for galaxy evolution, that is for the build-up of galaxies.[31]

The driving engine responsible for the energy release in an AGN is accretion onto the supermassive black hole at the centre of a galaxy. Indeed, most massive galaxies host a central black hole with a mass between 10^6 and 10^9 $M_\odot$. The result of the accretion process are jets and radiation over the entire electromagnetic spectrum from x-rays to radio wavelengths. The emission has a peak in the infrared, the "IR bump", which is thought to come from dust reprocessing the x-rays and ultra violet light from the central accretion disk and its corona (the "big blue bump"). The main components of and AGN in the standard picture are therefore: (1) a central accretion disk around the supermassive black hole on scales of $\lesssim 0.001$ pc; (2) high velocity, ionised gas emitting broad (up to several thousand m/s) emission lines in the so-called Broad Line Region (BLR) on scales of 0.01 to 0.1 pc; (3) warm dust and molecular gas on scales of a parsec responsible for the infrared emission; (4) more distant, typically outflowing gas in ionisation cones or the so-called Narrow Line Region (NLR) reaching out to kiloparsec scales; as well as (5) relativistic jets of plasma probably launched close to the accretion disk and extending out to tens or hundreds of kiloparsecs.

AGN can be classified in two different types, those showing both broad and narrow emission lines ("type 1" / "Seyfert 1") and those *only* showing narrow emission lines ("type 2" / "Seyfert 2"). The discovery of "hidden" broad emission lines in polarised (that is scattered) light for NGC1068[32] gave birth to the unified scheme of AGN.[33,34] The idea is essentially that there is a type 1 nucleus hidden in each type 2 nucleus: the warm dust and gas have a toroidal distribution, the "dusty and molecular torus", leading to a viewing angle dependent obscuration of the central engine. When seen face-on, our view towards the accretion disk and BLR are unobscured (type 1 case), when seen edge-on the central regions are obscured. We refer to Refs. 35 and 36 for comprehensive recent reviews of AGN unification and obscuration.

The angular sizes of the BLR and the torus are very small and appear unresolved in single dish observations down to 100 mas even for the closest active nuclei.[37] Information about the morphology and kinematics of this material can therefore only be inferred indirectly, e.g. by modelling of the Spectral Energy Distribution (SED) or by analysing the variability of the emitted radiation, especially reverberation mapping of the BLR and the hottest dust. However any interpretations will remain highly ambiguous.

Only with interferometry is it possible to reach the angular scales required to resolve the inner regions of AGN on millarcsecond scales:

1. Using Very Large Baseline Interferometry (VLBI) in the radio to observe water maser disks and outflows.[38]
2. Submm interferometry using ALMA, tracing the morphology and kinematics of the warm molecular material.[39–41]
3. Infrared interferometry probing the dust emission as well as more recently the properties of line emitting gas such as in the BLR.

The main open questions for AGN are related to the physics of the accretion flow on parcsec scales, to the geometry and role of the nuclear obscurer, as well as to the kinematics of the BLR and torus region. It is still unclear what keeps the torus geometrically thick and prevents it from collapsing to a thin disk. Is the material close to Keplerian rotation as suggested by maser disks, is it rather inflowing, or outflowing? Is there any substructure, such as the filaments or small clumps suggested by torus models[42–45]? These questions can be best tackled by actually resolving the respective structures.

3. SIZE ESTIMATES

The simplest quantity to measure using interferometry are sizes – in fact the first interferometric measurement in astronomy was precisely to measure the sizes of stars, as first proposed by Fizeau in 1868 and then carried out by Michelson & Pease in 1921.[46] The same is true for extragalactic sources.

Because the thermal emission from the torus essentially remained unresolved in single-dish observations, only upper limits to its extent could be given and its true size remained unclear for a long time, with sizes up to hundreds of parsecs proposed. The first size measurement of an AGN using infrared interferometry was hence a surprise. Using the Keck Interferometer, the K-band emission of the Seyfert 1 nucleus of NGC 4151 was found to be "unexpectedly compact", being only marginally resolved with a size of ≤ 0.1 pc.[2] As a consequence, the emission was interpreted as mainly originating from the central accretion disk instead of hot dust close to sublimation (see Sec. 7). Shortly after, measurements of the Seyfert 2 galaxy NGC 1068 with the commissioning instrument VINCI at the VLTI, found larger sizes. Taking into account K-band speckle measurements,[47] the data was interpreted in the form of a two component structure with a compact core of < 0.4 pc and emission from larger scales on the order of 3 pc.[3]

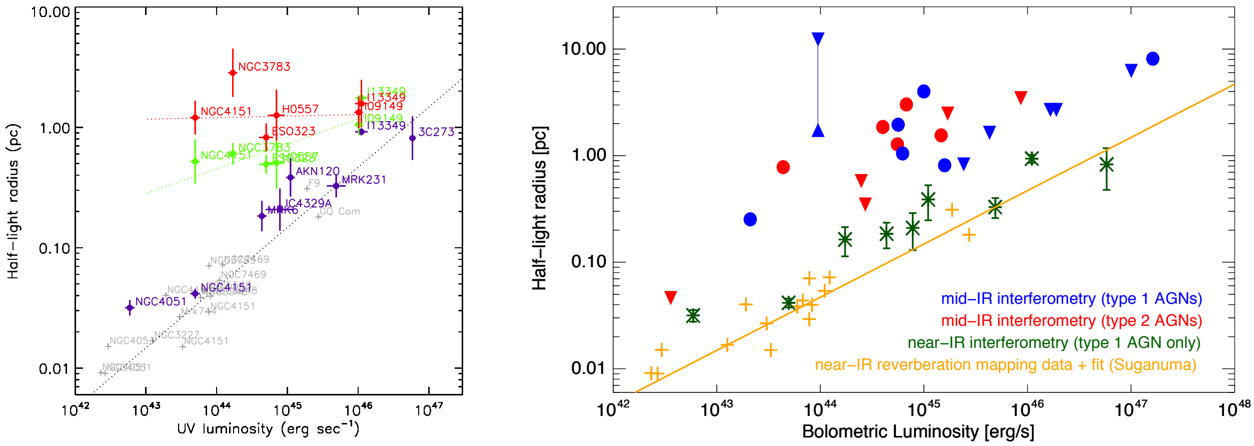

Figure 1. Size luminosity relations for the thermal emission around AGN from Refs. 18 (left, type 1 AGN only) and 23 (right): Reverberation sizes in grey (left) and orange (right);[48] K-band ring fit sizes in violet (left) and dark green (right). In the left panel the half light radii at 8.5 and 13 μm are plotted for several type 1 sources; in the right panel the half light radii for both type 1 (blue) and type 2 (red) AGN.

In the following years several size estimates for the dust emission could be obtained both in the K-band[13,16,18] as well as in the N-band between $\lambda = 8\,\mu$m and $13\,\mu$m.[11,17,23] Similar to what has been done for disks around Young Stellar Objects,[49,50] the sizes can be plotted as a function of the intrinsic luminosity of the AGN, or rather a proxy for the latter such as the hard X-ray luminosity or the optical V-band luminosity in the case of unobscured type 1 objects. Examples from Refs. 18 and 23 are shown in Fig. 1. The K-band sizes show a relatively tight relation with $L^{1/2}$, where L is the AGN luminosity, as expected for centrally heated dust close to the sublimation radius. The K-band sizes actually seem slightly larger than the sizes obtained from reverberation mapping, and the ratio of the two can be used as an approximate probe of the radial distribution of the material.[16]

In the mid-infrared, probing cooler dust further out, the picture is less clear: there are both claims that also the cooler dust roughly follows the $L^{1/2}$ relation[11,17] as well as claims that there is essentially no dependency on luminosity for the sizes at $\lambda = 13\,\mu$m (see left panel of Fig. 1).[18] The latter is interpreted as a sign of steeper dust distributions for more luminous sources. The most complete size-luminosity relation for the mid-infrared shows a general trend following $L^{1/2}$, with the mid-infrared sizes 4 to 30 times larger than the relation determined by reverberation mapping.[23] The large scatter implies that AGN tori are dominated by intrinsic differences in their dust structures. Most notably these differences are much large than the differences expected between type 1 and type 2 sources.

One issue when determining sizes from visibilities is that typically a specific model for the brightness distribution must be assumed, especially if there are only very few measurements at different spatial frequencies and visibilities are close to 0 or 1, the latter being the case for most K-band measurements. For the K-band, mainly ring fits were performed, while in the mid-infrared often Gaussian or $r^{-\alpha}$ brightness distributions are assumed. The choice of the model can lead to significantly different size estimates. Only when the visibilities cover the range of $V \sim 0.5$, the model-independent half-light radius can be determined.

4. CONTINUUM MORPHOLOGIES

From the previous section it becomes clear that a better understanding of the radial distribution of the emission in AGN would be highly desirable. After first claims of a possible common brightness distribution following a r^{-2} powerlaw,[9] it now rather seems that AGN tori are dominated by intrinsic differences in their dust structures.[23] Moreover, many sources seem to possess a two component structure in the mid-infrared. For 18 out of 23 sources studied in Ref. 23, two nuclear components can be distinguished in radial fits: a compact component often appearing unresolved even on the longest interferometric baselines, as well a more extended well resolved component. Surprising is the relatively high level of unresolved flux and its large scatter. The median "point source fraction" is 70% for type 1 and 47% for type 2 AGNs meaning that a large part of the flux is concentrated on scales < 5 mas ($0.1 - 10$ pc). For sources observed with similar spatial resolution, the unresolved flux varies from $20\% - 100\%$, confirming once more that there are large intrinsic differences in the dust structures.

Going one step further in complexity, we can ask if the radial distribution is the same in all position angles, or more simply speaking if the emission is elongated in a certain direction. Indeed from classical models of the dusty torus or a thick disk this is expected: for type 2 systems with a highly inclined torus, the infrared emission is anticipated to be elongated in the equatorial direction, barring radiative transfer effects, while for type 1 systems with an almost face-on torus no significant elongation is anticipated. But here comes the probably biggest surprise of extragalactic infrared interferometry: this seems not to be the case.

To securely make any statement on the elongation of the emission, the source must be resolved to a significant fraction and the measurement uncertainties must be small enough to be able to unambiguously constrain an elongation. Furthermore a sufficient uv coverage has to be reached, covering a wide range of position angles. Due to these requirements, measuring elongations has so far only been possible for a few sources with the mid-infrared beam combiner MIDI[51] at the VLTI.

The first indications for an extension in polar direction on parsec scales came from the modelling of the interferometry data of the Seyfert 2 nucleus of NGC 1068,[10] where the extended emission component was found to be extended in the direction of the nuclear jet. This was followed by the detection of polar dust in another type 2 source NGC 424[21] and then also in the type 1 nucleus of NGC 3783.[22] A more systematic search for elongated emission using all MIDI data, resulted in clearly elongated structures in five out of seven sources where the uv plane was sufficient to constrain an elongation.[27] From these five sources, three are type 2, two type 1. The observed axis ratios are typically around 2 and the elongations were found to be more or less (but not exactly) in the polar direction as inferred from ionisation cones or polarisation. The remaining two sources, both Seyfert 2 nuclei, are consistent with the emission being radially symmetric. Recently a further type 1 source, ESO 323-G77, has been confirmed to show strong polar elongation.[30] That is the warm dust emission is polar extended in 3 out of 4 sources. In fact deep single-dish observations reveal that the mid-infrared emission is extended in polar direction out to 100 pc scales.[37,52]

The physical origin of the polar emission is still unclear, but first models have been proposed, suggesting that the emission comes from a dusty polar wind or a hollow outflow cone, possibly driven by radiation pressure.[53,54] An increased modelling effort as well as further interferometric measurements will be necessary to fully pin down the origin of the thermal emission and its relation to the physics of the torus. It may well be that the dusty torus of the unified scheme is the basis of the wind extending out to galactic scales and hence forms part of the AGN feedback process.

5. SUBSTRUCTURES IN INDIVIDUAL SOURCES

For the two brightest and best resolved AGN in the mid-infrared, the Seyfert 2 galaxies NGC 1068 and the Circinus galaxy, interferometric measurements with MIDI allowed us to obtain a more detailed understanding of the brightness distribution. For both sources, a large number of uv points, 152 for the Circinus galaxy and 40 for NGC 1068, were obtained using both the Unit Telescopes as well as the Auxiliary Telescopes of the VLTI.

Both sources reveal a clear two component structure composed of an inner disk-like component as well as extended emission perpendicular to it on scales of 2 to 3 pc (see Fig. 2). Also in several other aspects the results for these two galaxies are very similar: The dust emission is not directly concentrated along the system axis as defined by the ionisation cone, but rather trace one of the cone edges. A strong gradient in the 13.0 μm silicate absorption feature is observed in direction of the system axis and in agreement to the larger scale structures such as the one-sided ionisation cones (the other cones being obscured). The dense disk-like components only contribute to about one fourth of the total mid-infrared emission coming from the nuclei; the majority of the emission comes from the extended components. Furthermore the disk-like components in both galaxies match water maser disks in orientation and size. On the other hand there are also a few subtle differences: While in NGC 1068 the temperature $T \sim 700$ K of the disk-like component is significantly higher than that of the extended

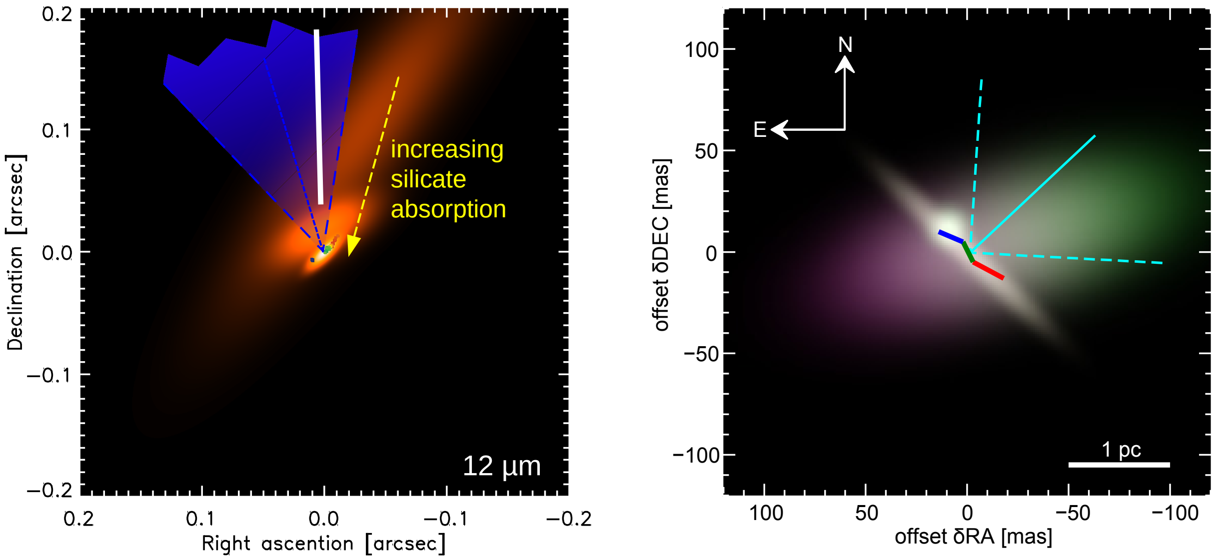

Figure 2. Model images for NGC 1068 (left) and the Circinus galaxy (right) from Refs. 26 and 25, respectively. The image for NGC 1068 shows the model brightness distribution of the mid-infrared emission at 12 μm. To set the dust emission in context, the coloured points in the very nucleus delineate the nuclear water maser disk, the thick white line indicates the direction of the nuclear jet and the blue cone represents the direction and opening angle of the ionisation cone on arcsec scales. The depth of the silicate absorption increases in the three components from North to South. The image for the Circinus galaxy is a false-colour image of the model brightness distribution. The colours red, green and blue correspond to the model at 13.0 μm, 10.5 μm and 8.0 μm, respectively. The colour gradient of the extended component is due to the increase in the silicate depth towards the south-east. Also plotted are the opening angle of the one-sided ionisation cone as well as the trace of the water maser disk: the blue and red parts trace the approaching and receding sides of the maser disk respectively.

emission with $T \sim 300$ K (as expected for centrally heated dust), this is not the case for the Circinus galaxy. In that galaxy both components have similarly low temperatures of $T \sim 300$ K, somewhat difficult to explain for centrally heated dust. Furthermore the silicate feature of the disk component is significantly deeper towards the disk-like component for NGC 1068, while for the Circinus galaxy the opposite is the case. Full radiative transfer modelling is currently being carried out to better understand the underlying geometry.[55]

A third source, the Seyfert 1 galaxy NGC 3783, is less resolved than NGC 1068 and the Circinus galaxy but nevertheless appears to show a similar two component structure with warm polar elongated dust emission and a compact hot components which is possibly extended in the equatorial direction.

These results are in general agreement to those found for the less resolved sources, assuming that the disk components are not resolved. On the other hand, it may well be that the brighter sources are in some form special. Higher resolution observations of more AGN will be required to verify that there is indeed an inner disk plus a polar extension in most AGN.

6. EMISSION LINES

Apart from the continuum, emission lines can be resolved both interferometrically and spectrally. These are of special interest as they carry kinematic information about the material. Unfortunately, detailed spectro-interferometric studies such as those for e.g. Be stars[56] have not yet been possible for AGN due to the lack of sensitivity.

In the context of AGN, the most promising and also scientifically interesting objective is to study the BLR using the Br γ or (for sufficiently distant and hence redshifted targets) Pa α line in the K-band. This is particularly relevant since variability observations of the BLR are used to determine black hole masses, with the major caveat that the derivation of the masses from these data requires strong assumptions on the geometry and dynamic state of the line-emitting gas. Spectrally and spatially resolved interferometry will remove a large part of these assumptions. Because the BLR is much smaller – on μas scales – than what can be resolved by current interferometers, differential measurements of the visibilities and especially the phases as a function of the wavelength have to be carried out.

A first such measurement was attempted for the Pa α line of the quasar 3C273 using the AMBER[57] at the VLTI. Despite the signal being at the detection limit of the instrument, the measurements suggest a decrease in the differential visibility between the emission line and the continuum as well as a differential phase smaller than $3°$.[20] This would imply a radius of the BLR $\gtrsim 1\,\mathrm{pc}$, which is 3 times larger than the estimates obtained from reverberation mapping.[58]

A second, measurement, also using the Pa α line, was carried out with GRAVITY for PDS456, a quasar at $z = 0.184$.[28] The continuum appears marginally resolved, with a best Gaussian fit FWHM size of 0.3 mas ($\sim$ 1 pc), which is comparable to the size expected for the dust sublimation radius. However, no differential phase or amplitude signature could be detected at the Pa α line, despite a precision of $\lesssim 0.1°$ for the differential phase. This constrains the line centroid displacement to $\lesssim 10\,\mu$as and places an upper limit on the offset of the line emission from the continuum of $\lesssim 150\,\mu$as. Further measurements have been carried out with GRAVITY in the meantime for this source, as well as for a few other targets and a phase signal has been detected for at least one of them.

7. VARIABILITY

Due to the stochastic nature of accretion onto the supermassive black hole as well as instabilities in the accretion flow, the activity of AGN is variably on various time-scales. An increase in the luminosity of the accretion disk will lead to an increase of the emission from the BLR and of the thermal emission from the dust with different delays and time scales. This is used by reverberation mapping to infer the properties of these components.[59,60] More specifically, for an increased luminosity L of the accretion disk, one would expect the radius of the BLR and the dust sublimation region to increase with $r \propto L^{1/2}$. Indeed such size changes have been measured using reverberation mapping although these do not necessarily follow the $L^{1/2}$ relation directly but rather after some delay.[61,62]

While reverberation mapping can only deliver averaged sizes for certain periods of time (100 days for the dust), interferometric measurements allow to determine sizes instantaneously. So far, only one object has been studied in this respect using optical interferometry: NGC 4151. K-band measurements obtained with the Keck Interferometer as well as AMBER at the VLTI between 2003 and 2012 revealed that the size of the near-infrared emission structure does not strictly depend on the respective momentary nuclear luminosity. Instead the radius of the hottest dust seems to correlate with a long-term average of the flux of the central engine over the previous several ($\sim$ 6) years.[14,24] This implies that the destruction and reformation timescale of the innermost dust distribution is on such time scales.

The possibility to determine angular sizes using optical interferometry and physical sizes using reverberation mapping allows us to measure directly the angular-diameter distance to the AGN using the relation $D(\mathrm{Mpc}) = 0.173\,\tau(\mathrm{days})/(\rho(\mathrm{mas})(1+z))$, where D is the distance, τ is the time lag obtained by reverberation measurements and ρ is the angular diameter from interferometry. Originally proposed using the broad emission lines ("quasar parallax"),[63] it was adapted and proven feasible using the hot dust emission ("dust parallax"):[64] using K-band sizes and lags for NGC 4151, a distance of $D \sim 19\,\mathrm{Mpc}$ could be determined, at the same time leading to a more accurate black hole mass estimate. If applied to other galaxies, this geometric-distance method could lead to an improvement in estimates of black-hole masses from reverberation mapping as well as direct distance measurements out to higher redshifts, hence allowing to constrain cosmological properties.

We close with the note, that variability has also been observed in the mid-infrared, with flux changes up to a factor of 2, which could also imply changes in the size of the emitting region by a factor of $\sqrt{2}$. However the interferometric measurements do not seem affected by the flux changes, and it remains unclear from where the flux changes actually originate. Infrared monitoring campaigns and more rapidly carried out interferometric measurements will be required to shed more light on the mid-infrared variations.

8. CONCLUSION AND OUTLOOK

Infrared interferometry of AGN has become mature and provided a breakthrough for the investigation of the centrally heated dust structures in AGN through continuum studies in the near- and mid-infrared. Using the interferometric measurements it could be shown that the innermost, hot dust mainly emitting in the K-band scales with $L^{1/2}$ at radii close to the sublimation radius and only slightly larger than the radii determined from reverberation mapping. Dust destruction and formation timescale in this region are on the order of a few years. The cooler dust dominating the emission in the mid-infrared, is located at ten times larger radii, but still on scales of less than 10 pc with a large scatter interpreted as evidence for substantial intrinsic differences in the dust distributions. In contrast to model predictions for the emission from the dusty torus, the bulk of the emission turned out to be extended in the polar direction. This has triggered new torus models in order to explain the interferometric data.[53,54,65] However the fundamental question still remains open: Where does the main obscuration of the central source and the BLR emission take place and how is is the absorbed energy re-processed.

Spectro-interferometry of AGN is still in its infancy but expectations are that GRAVITY with its exquisite sensitivity and stability will be able to resolve the kinematic structure of the broad line region. The combination of interferometric with reverberation measurements opens the possibility to determine direct quasar-parallax or dust-parallax distances to sources at significant redshift (given that the necessary sensitivities can be reached), obliterating the uncertainties of the cosmic distance ladder.

One limitation of the observations so far have is that it was not possible to reconstruct images for them, less for the near-infrared where the sources are barely resolved, more for the mid-infrared where at best a few sources are well resolved. This will now change with the advent of MATISSE[66] the second generation mid-infrared interferometer of the VLTI. The extragalactic interferometry community is eagerly looking forward to the first true images reconstructed from observations with this instrument expected to be appear at the end of 2018 or early 2019. Additionally, MATISSE will open the so far unexplored L- & M-bands for interferometry.

Sensitivity and resolution remain a challenge for infrared interferometry of AGN. For example, there have been only 2 interferometric facilities so far that were sensitive enough to observe AGN: the Keck Interferometer as well as the VLTI, both with baseline lengths limited to < 130 m. The Center for High Angular Resolution Astronomy (CHARA) is still fighting and once its new adaptive optics is fully commissioned it will hopefully be able to record the faint extragalactic fringes. With baselines up to 330 m this would for the first time allow to also properly resolve the emission from the hot dust at the inner rim for the first time and allow to go beyond measuring ring fit radii.

The main issues for extragalactic interferometry, sensitivity and unresolvedness, will only be overcome with a new array, ideally with kilometer-long baselines. A promising proposal is the Planet Formation Imager (PFI), for which extragalactic science is among the more prominent secondary science cases.[67] Only with such a facility can we expect to fully resolve out the dust and line emission in larger samples of AGN as well as to measure interferometric parallaxes out to cosmological distances.

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