High-resolution infrared observations of active galactic nuclei

Jörg-Uwe Pott
Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
E-mail: jpott@mpia.de

Abstract. Interferometric resolution at IR wavelengths offers for the first time the possibility to zoom into the nuclei of galaxies beyond the circumnuclear stellar structures and spatially resolve gas and dust in the innermost regions (0.05-5pc), dominated by the central black hole. Ultimate goal is to reveal new aspects of AGN feeding, and interaction with its host galaxy. After first successes of resolving AGN with infrared interferometry (VLTI, Keck-IF), the second generation of high-resolution interferometric imagers behind 8m class telescopes is currently being built. I will summarize current aspects and successes of the field, and present our activities to provide extended capabilities for VLTI-MIDI and -Matisse, LBT-Linc-NIRVANA and Keck-Astra to study a larger sample of AGN in greater detail.

1. Which AGN questions can be (partially) answered by IR observations at interferometric resolution?

Besides nuclear fusion in stars, accretion of matter onto super-massive black holes in active galactic nuclei (AGN) is the second dominating source of radiative energy in the universe. While we already attempt to use nuclear fusion on Earth, the details of the physics in an AGN are much less understood, and a fascinating area of research. High-angular resolution (HAR) infrared (IR) observations help to reveal the involved physical processes in the outer (red) parts of the black hole’s accretion disk, as well as its immediate surroundings. The structure and kinematics of the broad and narrow emission line regions (BLR resp. NLR), as well as the distribution and content toroidal obscuration region (TOR aka torus) are being studied. Their properties are connected to feeding the accretion process and how it feeds back to the surroundings. While typical linear torus sizes are well suited for the resolution of current long baseline interferometers, like VLTI and KI, line reverberation mapping observations suggest that resolving the broad line region, being located inside of the dusty torus, requires even higher angular resolution.

Apart from measuring their direct properties, the interaction of the AGN with its host galaxy is an active field of research. The feeding material, finally settling in the accretion disk, might originate in circumnuclear star burst outflows, star formation next to an AGN is often observed. On the other hand, AGN feedback has possibly a significant impact on regulating the star formation in the galaxy. Such host-AGN interaction scenarios require sensitive spectroscopic observations, which typically cannot be provided by interferometric arrays, which, due to their limited collecting area, are optimized to observe the brightest and compact details. However, AO-assisted narrow-band imaging or IFU observations, combined with Fizeau interferometry (LINC-NIRVANA), can trace the observations of such AGN-host interaction.
A third area of research, related to HAR-observations of AGN, uses AGN and their properties as tracers for galactic evolution. HAR observations are particularly adequate to study the merger of galaxies in the latest phases. Imaging traces galaxy mergers by resolving distorted shapes of the host. In a few cases, even two AGN are observed, which trace the black hole mass build up via merging.

In this article, I will concentrate mostly on the interferometric observation of AGN physics, using the highest resolution available, provided by Michelson interferometric arrays. The last section will contain a brief outlook to instruments of the next generation interferometers, in the construction of which I am currently involved, and examples of their potential impact on extragalactic HAR observations.

2. Exploring the immediate AGN environment

Given IR broad-band fluxes, and the sizes between 0.1-10 pc, the thermal continuum radiation of dusty clouds of AGN tori can be observed with modern telescope arrays. The last decade has seen quite some groundbreaking work in this field.

First AGN fringes at NIR [Swain et al.(2003), Wittkowski et al.(2004)] and MIR wavelengths [Jaffe et al.(2004)] have been observed, showing the general existence of resolvable dust structures so close to the AGN. The measured sizes are are an order of magnitude smaller than smooth torus models, and can only explained by dusty clumps [Nenkova et al.(2010)]. First interferometric observations of dust heated by an Advection Dominated Accretion Flow (ADAF) in CenA [Meisenheimer et al.(2007)]. While originally several emission mechanism have been proposed to explain the NIR bump in AGN SEDs, interferometric confirmations of the size-luminosity relation [Kishimoto et al.(2009), Kishimoto et al.(2011), Tristram et al.(2009), Tristram & Schartmann(2011)], together with optical-to-NIR reverberation measurements [Suganuma et al.(2006)] strongly support a dusty, thermal origin of the NIR radiation. [Pott et al.(2010a)] pioneered the interferometric version of the dust reverberation measurement, showing suprisingly different results than the spatially unresolved version [Koshida et al.(2009)]. As discussed by the former authors, the interferometrically derived dust size scale is a more robust measurement of the average location of the emitting dust, while, as typically for reverberation measurements, the latter method is sensitive to the innermost dust. Burtscher presented at this conference the first sizeable, systematic, interferometric AGN survey of 14 AGN suitable to probe for differences between the dust morphology in type 1 and type 2 AGN [Burtscher et al.(2012)].

3. What is required to go beyond shear torus size estimates?

Now we search for ways to go into the details of the circumnuclear dust. There is several paths to go forward.

- multi-wavelength studies to identify large-scale structure
- high-precision measurements to identify the small scale structure (clouds)
- spatially resolved multi-λ reverberation measurements to understand the heating throught the entire torus
- spectro-astrometry of the broad-line region.

Currently, it is not clear if the dust structures seen at 2 μm and 10 μm are the same, and physically connected. Multi-wavelength campaigns are rare, and have just started, since typically the interferometric AGN observations have been carried out in different hemispheres: 2 μm with the more sensitive Keck interferometer on Mauna Kea, and the 10 μm observations with the MIDI beamcombiner of the VLTI on Cerro Paranal in Chile. However, recent advances with the VLTI instrumentation will allow for more efficient NIR-AGN observations and facilitate future multi-wavelength studies (ESO press releases ann11031 & ann11021).
Direct detection of small scale structure in the torus (like dusty clouds) will require high-precision measurements. Current MIR visibility measurements suffer from the difficult photometric measurements in the large thermal background. Upcoming NIR instrumentation and fringe tracking possibilities at the VLTI will offer to combine measurements of a few percent precision of the correlated flux with good uv-coverage. Ultimately, the 2nd generation instruments like GRAVITY and MATISSE will provide the tools to distinguish clumpy structure and warps in the dust morphology.

Interferometric NIR imaging of the broadline region would require 0.1 mas resolution, or baselines of order 1 km, at the sensitivity of todays arrays. No currently built or planned array provides these performance numbers. However, spectro-interferometric astrometry has proven on sky to deliver differential astrometric precision up to 3 \( \mu \)as for bright stars [Pott et al.(2010b)]. A few tens of micro-arcsec would be enough to astrometrically resolve the kinematic properties of the BLR with respect to the continuum radiation. We currently work to upgrade the KI-ASTRA spectroscopy [Woillez et al.(2010)] to allow the spectroscopic observation of the brightest AGN.

4. What to expect from the next generation of instruments?

![Image of graphs and data plots]

**Figure 1.** First results from commissioning the PRIMA-FSU as MIDI fringe tracker, showing that the MIDI group delay can be controlled to better than \( \lambda/10 \).

MPIA contributes to the next generation of infrared high-angular resolution technology. Here, I will briefly report on three of our interferometric instrumentation initiatives for the next years.
As discussed above, the VLTI/MIDI precision is currently limited to typically 5-10%, which is not sufficient to resolve fine-structure details in the dust morphology of AGN surroundings. In collaboration with ESO, we work on commissioning the PRIMA-FSU K-band fringe tracker as external fringe tracker for the MIR measurements. First results are very encouraging ([Müller et al.(2010)]). Key of the fringe sensing unit (FSU) is that low-dispersion fringes are recorded in K-band. Spectrally dispersed FSU fringes allow to distinguish the water vapor seeing from the dry air fringe position, which is a prerequisite to precisely predict the mid-infrared fringe position [Koresko et al.(2006)]. This technology will allow both to improve on the precision and the sensitivity of MIDI. While the precision is important for fine structure, the sensitivity improvement is needed to enlarge the number observable targets, and be able to detect significant differences between different type of AGN. This remains difficult, since also within a class the detailed properties of each AGN can be quite different, depending on several physical parameters of the accretion process.

A leap forward regarding the MIR imaging capabilities of the VLTI will be provided by MATISSE, the 2nd generation 4-telescope beam-combiner [Lopez et al.(2008)]. Delivering 6 baselines and 3 closure-phases at a time, MATISSE is dedicated to model-independent interferometric imaging of the dusty environment of AGN. Particularly interesting will be the fact, that MATISSE also offers L/M-band observing capabilities. This will finally close the gap for HAR-AGN observations between 2 μm and 10 μm. This is crucial to get a complete picture of the dust formation in AGN. First light for MATISSE is foreseen for 2016.

A different type of gap will be closed by the Fizeau-interferometric imager at the LBT, LINC-NIRVANA [Herbst et al.(2010)]. This strategic LBT instrument will, from 2014 on, deliver AO-like diffraction limited images of a 23m telescope. While current interferometric arrays already deliver higher resolution, only the complete uv-coverage of such an Fizeau-imager will allow faint images in narrow- and broad-band of the surroundings of AGN at 50-100pc scale. Here, circum-nuclear starbursts, jets, and AGN winds are key targets to investigate the processes of AGN feeding and feedback. LINC-NIRVANA will be the next step in resolution and sensitivity from the current 8m-class AO-imagers towards ELT and JWST science cases.

References
[Swain et al.(2003)] Swain, M., Vasisht, G., Akeson, R., et al. 2003, ApJL, 596, L163
[Wittkowski et al.(2004)] Wittkowski, M., Kervella, P., Arsenault, R., et al. 2004, A&A, 418, L39
[Jaffe et al.(2004)] Jaffe, W., Meisenheimer, K., Röttgering, H. J. A., et al. 2004, Nature, 429, 47
[Meisenheimer et al.(2007)] Meisenheimer, K., Tristram, K. R. W., Jaffe, W., et al. 2007, A&A, 471, 453
[Kishimoto et al.(2009)] Kishimoto, M., Hönig, S. F., Antonucci, R., et al. 2009, A&A, 507, L57
[Kishimoto et al.(2011)] Kishimoto, M., Hönig, S. F., Antonucci, R., et al. 2011, A&A, 527, A121
[Tristram et al.(2009)] Tristram, K. R. W., Raban, D., Meisenheimer, K., et al. 2009, A&A, 502, 67
[Tristram & Schartmann(2011)] Tristram, K. R. W., & Schartmann, M. 2011, A&A, 531, A99
[Pott et al.(2010a)] Pott, J.-U., Malkan, M. A., Elitzur, M., et al. 2010, ApJ, 715, 736
[Burtscher et al.(2012)] Burtscher, L., et al., MIDI AGN Large Programme: A statistical sample of resolved AGN tori, in this conference proceedings
[Nenkova et al.(2010)] Tenenkova, M., Sirocky, M. M., Nikutta, R., Ivezić, Ž., & Elitzur, M. 2010, ApJ, 723, 1827
[Suganuma et al.(2006)] Suganuma, M., Yoshii, Y., Kobayashi, Y., et al. 2006, ApJ, 639, 46
[Koshida et al.(2009)] Koshida, S., Yoshii, Y., Kobayashi, Y., et al. 2009, ApJL, 700, L109
[Pott et al.(2010b)] Pott, J.-U., Wöillez, J., Ragland, S., et al. 2010, ApJ, 721, 802
[Wöillez et al.(2010)] Wöillez, J., Akeson, R., Colavita, M., et al. 2010, SPIE, 7734
[Müller et al.(2010)] Müller, A., Pott, J.-U., Morel, S., et al. 2010, SPIE, 7734.
[Koresko et al.(2006)] Koresko, C., Colavita, M. M., Serabyn, E., Booth, A., & Garcia, J. 2006, SPIE, 6268,
[Lopez et al.(2008)] Lopez, B., Antonelli, P., Wolf, S., et al. 2008, SPIE, 7013,
[Herbst et al.(2010)] Herbst, T. M., Ragazzoni, R., Eckart, A., & Weigelt, G. 2010, SPIE, 7734,