The Diversity of Dusty AGN Tori: Results from the VLTI/MIDI AGN Large Programme

Leonard Burtscher[1]
Konrad R. W. Tristram[2]
and the MIDI AGN LP team*

[1] Max-Planck-Institut für extraterrestrische Physik, Garching, Germany
[2] Max-Planck-Institut für Radioastronomie, Bonn, Germany

The molecular gas and dust surrounding the central engine of active galactic nuclei (AGN) plays a fundamental role in understanding their physics. Due to the small angular size of this torus, direct studies of its properties require very high angular resolution. The VLTI/MIDI AGN Large Programme aims at characterising a statistical sample of AGN tori for the first time by resolving their dust emission in the mid-infrared interferometrically. Measurements of 23 sources show that most tori are very compact with sizes of 0.1 to 10 pc and emission from a two-component structure. The morphology of the torus differs significantly between individual objects and does not show the expected dependency on viewing angle (edge-on *vs.* face-on). The torus is thus significantly more complex than typically pictured, requiring new models and imaging interferometry on milliarcsecond scales to decipher the physics.

Motivation

The Mid-Infrared Interferometric Instrument (MIDI) at the Very Large Telescope Interferometer (VLTI) is unique worldwide in resolving what is commonly referred to as the torus in active galactic nuclei (AGNs; see Meisenheimer et al., 2008). This torus is considered to be responsible for the type 1 (broad-line) / type 2 (narrow-line) dichotomy in AGNs and perhaps plays a crucial role in feeding of the central supermassive black hole (e.g., Schartmann et al., 2009).

*The MIDI AGN LP team:
K. Meisenheimer (P.I.)[1], L. Burtscher[2], K. R. W. Tristram[3], W. Jaffe[4], S. F. Hönig[5], R. I. Davies[2], M. Kishimoto[3], J.-U. Pott[3], H. Röttgering[4], M. Schartmann[3,6], G. Weigelt[3], S. Wolf[7]

[1] Max-Planck-Institut für Astronomie, Heidelberg, Germany
[2] Max-Planck-Institut für extraterrestrische Physik, Garching, Germany
[3] Max-Planck-Institut für Radioastronomie, Bonn, Germany
[4] Sterrewacht Leiden, Universiteit Leiden, the Netherlands
[5] Dark Cosmology Center, University of Copenhagen, Denmark
[6] Universitäts-Sternwarte München, Germany
[7] Institut für Theoretische Physik und Astrophysik, Universität zu Kiel, Germany

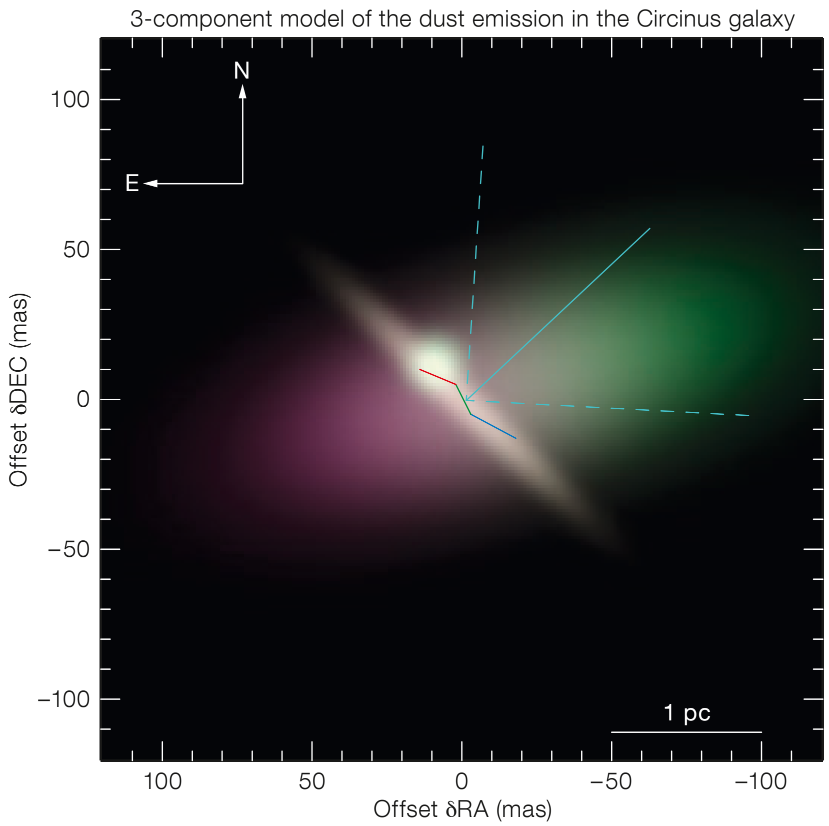

Figure 1. Colour image of the three-component model, describing over 150 individual MIDI measurements of both the visibility amplitude and differential phase from the Circinus galaxy (Tristram et al., A&A, 2013). The model components are: (1) an unresolved component; (2) a highly inclined disc, offset with respect to component (1), whose major axis is perpendicular to the ionisation cone (cyan lines) and which is coincident in orientation with water maser emission (red–green–blue line); and (3) an extended emission region roughly elongated in the polar direction with an increase of the silicate absorption towards the south-east (purple–green, with purple representing deeper silicate feature).

By interferometrically combining light from two of the large Unit Telescopes (UTs), AGNs with mid-infrared (MIR) fluxes as faint as ~ 100 mJy can be studied, and structures as small as ~ 5 milliarcseconds detected. The two brightest extragalactic southern sources in the MIR wavelength range (8–13μm) — NGC 1068 and the Circinus galaxy — have now been observed in great detail and reveal complex morphologies on (sub-)parsec scales (see Figure 1).

Although these two prominent sources have much in common, they also show marked differences. Most notably, hot dust (T ~ 800 K) on parsec scales has only been detected in NGC 1068, while the Circinus galaxy, where a similar spatial resolution is reached, seems to contain only warm (T ~ 300 K) dust. Until a couple of years ago, only a few other extragalactic objects had been studied with MIDI, but it was clear that a much larger sample was needed to build a more coherent view of the nuclear dust structures of AGNs.

This statistical sample has now been assembled by the first VLTI Large Programme (PI: K. Meisenheimer) together with two accompanying programmes and data from the archive. The questions that this programme set out to answer include:

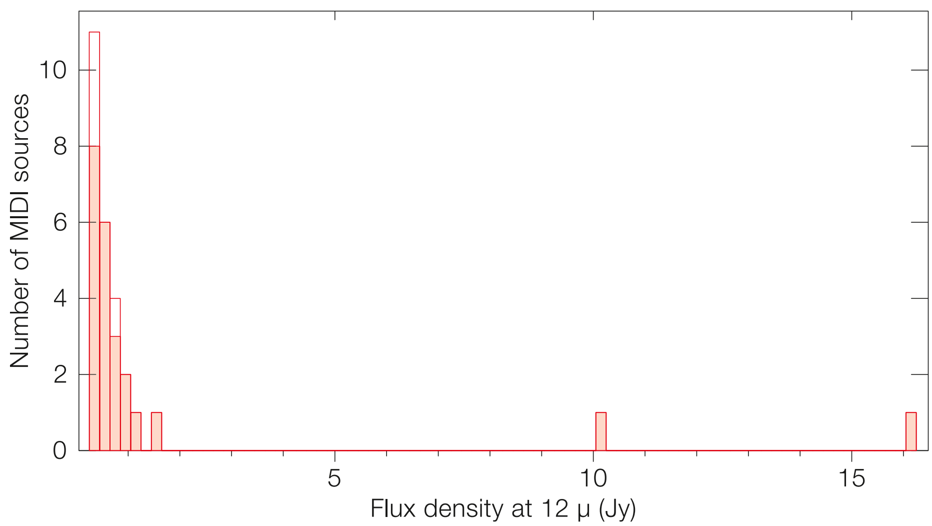

Figure 2. Histogram of mid-infrared fluxes of AGNs that have been interferometrically detected with MIDI (open bars); filled bars are for sources studied in Burtscher et al. (2013), and discussed in this article. In order to increase the sample beyond the two brightest sources, the sensitivity had to be increased by more than a factor of ten.

– What are the morphology and the size of the nuclear structures? Are type 1/2 sources intrinsically different on parsec scales? These phenomenological questions are directly addressable from the interferometric data and are the focus of this article (see Burtscher et al., 2013);
– What are the elongations of the dust structures and how do they relate to the other axes in these systems? Is the dust chemistry of the nuclear structures different to that on larger scales?
– Is there a connection between nuclear star clusters and the genesis of the torus? This more far-reaching question will be addressed using a combination of observational data (with an important constraint from the MIDI observations reported here) together with hydrodynamical simulations (Schartmann et al., 2010).

Observations

Due to the specific distribution of MIR target brightnesses (Figure 2), enlarging the sample was only possible by observing targets that were at least ten times fainter (and much more distant) than the two initially studied AGNs. NGC 1068 and the Circinus galaxy are among the closest AGNs with distances of 14 and 4 Mpc respectively. The most distant object that

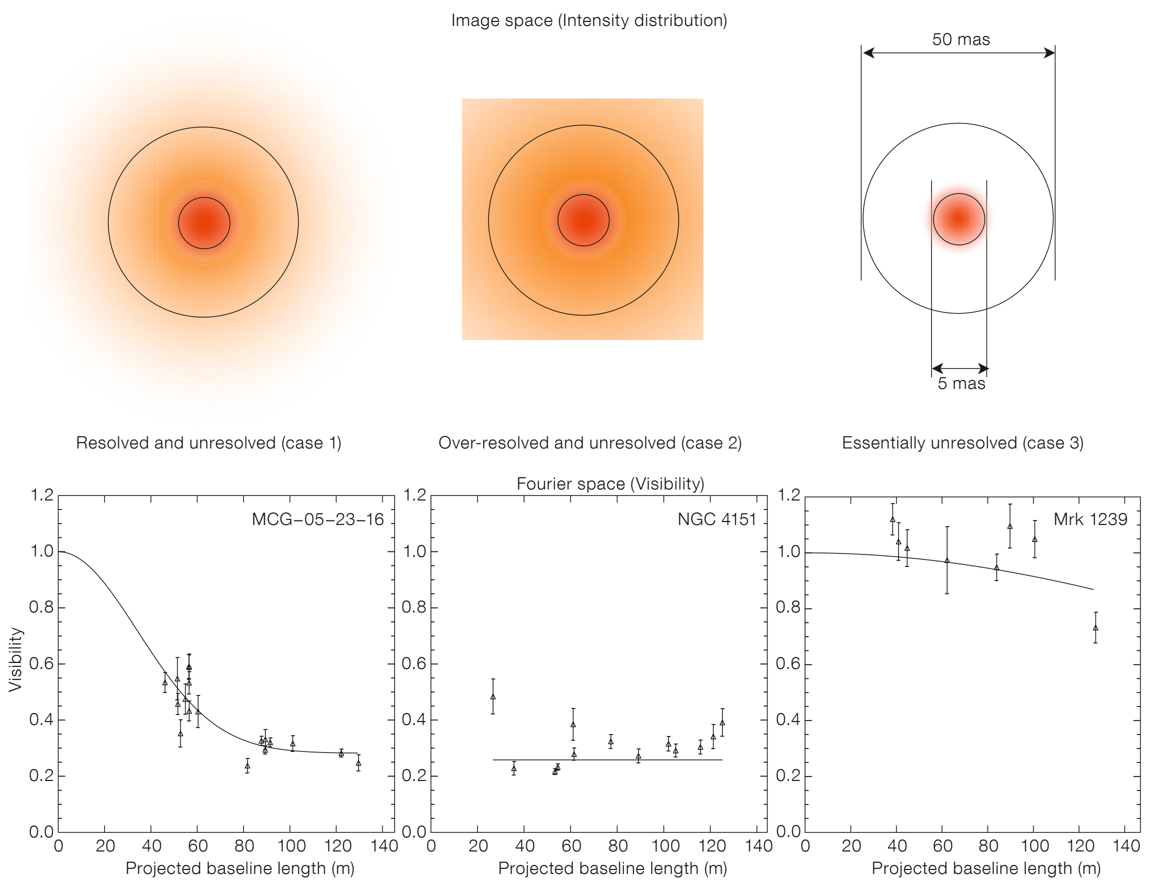

Figure 3. Nuclear morphologies of AGNs in the MIR revealed by MIDI. Left: resolved source with an additional unresolved component (visibility decreases with baseline length, but is always > 0); middle: over-resolved source with an additional unresolved component (visibility is ~ constant with baseline length and < 1); right: essentially unresolved source (visibility is ~ 1 on all baselines with only a shallow decrease). Top row: intensity distribution in image space; bottom row: radial visibility profiles of representatives of the three different nuclear MIR morphologies observed in the MIDI AGN Large Programme: MCG-05-23-16, NGC 4151 and Mrk 1239.

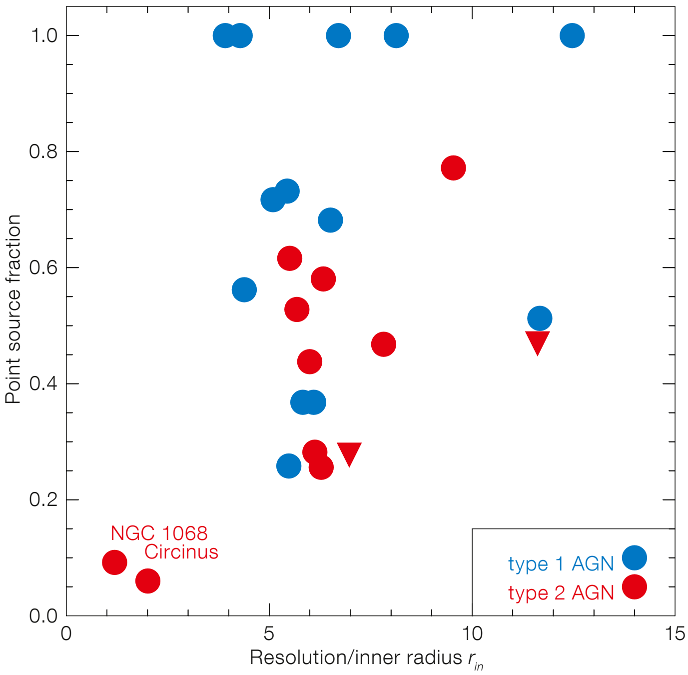

Figure 4. Point source fraction (~ minimum observed visibility) as a function of resolution. Type 1 AGNs are plotted in blue, type 2 AGNs in red; triangles show limits. To overcome resolution / distance effects in our flux-limited sample, we normalise the resolution to the inner radius of dust r_{in} (using the empirically derived relation between bolometric luminosity and r_{in}). If all tori were equal, the point source fraction would only depend on this "intrinsic resolution" — which is clearly not the case. Type 1 sources show higher levels of unresolved flux than type 2 sources (but are nonetheless statistically of the same size).

is observed with MIDI is the quasar 3C 273 at a redshift $z = 0.158$. It is marginally resolved.

To scientifically exploit these observations, a substantial effort was started to better understand the data reduction of the weak objects; correlation losses (that appear when the signal-to-noise ratio is very low) and calibration uncertainties were quantified (Kishimoto et al., 2011; Burtscher et al., 2012). This allowed us to consistently analyse the newly acquired data as well as all previously published archive data on AGNs with MIDI. While not complete by flux or volume, we also did not find any obvious biases in this sample.

Results

Out of the 36 galaxies for which observations have been attempted with MIDI, 27 are interferometrically detected (23 are part of this work); the few observed, but undetected galaxies either contain only feeble AGNs or were observed as backup targets during bad conditions. Furthermore, all of the detected sources have been successfully observed on the longest VLTI-UT baseline of 130 metres — there was no galaxy that was only detected on short baselines with MIDI. In MIR-bright AGNs, therefore, a substantial fraction of the nuclear 12 μm emission must originate from very compact (0.1–10 pc) scales, that are only partially resolved even on the longest baselines with MIDI.

This finding was somewhat unexpected, since scaling relations, derived from near-infrared (NIR) dust reverberation mapping and interferometry, predicted more extended dust structures if based on the bright sources that had been initially studied with MIDI. Instead most AGNs were only partly resolved with median visibility well above 50 %. The visibility is a measure of how well resolved a source is: unresolved sources show a visibility of 100 % and resolved sources show very low visibilities.

On the one hand, high visibilities are easier to observe and are the reason for the success we had in observing AGNs with MIDI; on the other hand, the high visibilities imply that fainter AGNs are largely unresolved and therefore their substructure (see Figure 1) is not revealed. But even at these high visibility levels, we were able to discriminate three different morphologies (see Figure 3):

1. Resolved sources, where the visibility decreased with baseline length;
2. Over-resolved sources, where the visibility was less than 100 %, but no change of visibility with baseline or position angle was observed; and
3. Essentially unresolved sources.

Most of the resolved (case 1) and all of the over-resolved (case 2) sources show clear signs of a two-component structure, where the larger component is (at least) several tens of milliarcseconds in size (about 1 pc in the nearest galaxies — 30 pc in the most distant ones) and the compact, unresolved point source is less than about 5 milliarcseconds in size.

The low-resolution spectra obtained with MIDI generally show an almost featureless continuum with only the broad silicate feature imprinted in absorption or emission. Here we show only the visibilities at 12 μm (Figure 3) since the sources are best resolved at this wavelength.

A large sample of (partly) resolved AGN tori

Apart from the generally high level of visibility in the weak sources, another surprising result was the large diversity in morphology among the sources. This is most readily seen when looking at the lowest visibility measured for each source (we call this the "point source fraction"). If the tori in the sources were all of equal size, we would expect that the point source fraction depends only on the resolution with which the source is observed. This is clearly not the case, as Figure 4 demonstrates. Except for the two bright sources (NGC 1068 and the Circinus galaxy) that are more highly resolved than all of the faint sources, no clear trend between resolution and point source fraction can be seen.

Since the radial profiles of most sources show that they are composed of at least two components (perhaps they correspond to the extended component and the disc in the well-resolved sources?), we derive a half-light radius to characterise the extension of the entire nuclear emission in a single number. This radius can then be compared to the inner radius of dust as derived with dust reverberation mapping and NIR interferometry. For this inner radius of dust, it is now well

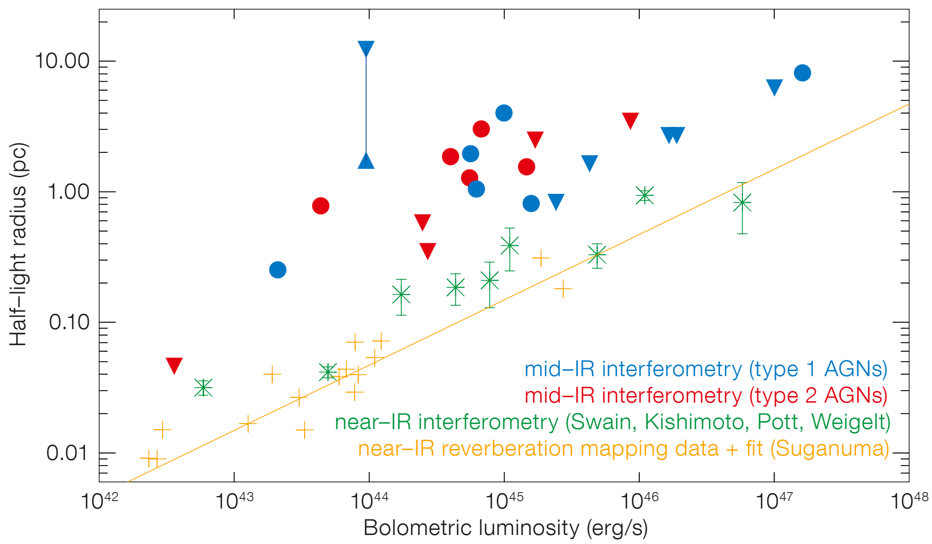

Figure 5. Size–luminosity relation for AGNs probing different regions of the torus: blue/ red points are MIDI measurements from the MIDI AGN Large Programme + archive for type 1/type 2 sources (statistical errors are smaller than symbol sizes); green crosses are NIR interferometry with both the Keck-Interferometer and AMBER/VLTI; orange pluses are from NIR dust reverberation mapping. Filled triangles show limits. Taking both the limits and the determined half-light radii into account shows that the mid-infrared size is less strictly correlated with luminosity than the innermost radius of dust that is seen in the NIR.

accepted that it scales with $\sqrt{L}$ where L is the bolometric luminosity of the AGN. For the MIR, due to the small and biased samples that were available prior to the MIDI AGN Large Programme, such a relation was claimed from some early data (Tristram et al., 2009), but later Kishimoto et al. (2011) found the relation to be essentially flat at 12 μm. With the large sample available now, we show that the torus does scale with luminosity roughly as $\sqrt{L}$, but we also find that this relation shows more scatter than the NIR relations (Figure 5), possibly because of the two-component structure discussed above.

In our sample, there are about the same numbers of type 1 and type 2 sources. The type 1 sources are at greater distances, i.e., have higher luminosities in our flux-limited sample. Otherwise, the two populations are indistinguishable. This is in contradiction to expectations from clumpy torus models, in which type 2 tori are expected to appear larger than type 1 tori. It shows that torus orientation cannot be the only factor in creating the different optical characteristics of AGNs.

Further results and future perspective

So far we have used only simple axisymmetric models for the brightness distribution, although the best-studied sources (NGC 1068, Circinus galaxy, NGC 424, NGC 3783) show considerable elongations in their dust distributions. While these axisymmetric models provided good fits to all faint targets, the residuals for some of the weak sources (see Burtscher et al., 2013) show indications for elongations. This, as well as an analysis of the full spectral information, is ongoing work.

In conclusion, the MIDI AGN Large Programme (+ archive) provides a sample of 23 (partially) resolved AGN tori, analysed in a uniform way. It has shown that the differences that were already known between the two MIR brightest AGNs are not a peculiarity of these sources, but indicative for the whole population. Even at more or less constant intrinsic resolution, AGN tori appear very diverse.

On the other hand, a two-component structure of the nuclear MIR morphology seems to be a common trait in most AGNs. We found both a very compact (< 0.1 pc in the most nearby sources) and a more extended component in the majority of sources. While all torus models predict that type 2 tori appear larger than type 1 tori, we cannot find such a dichotomy in our sample of 23 (partly) resolved AGN tori. This calls for a new set of torus models to explain the now well-studied nuclear dust morphologies in a large sample of active galaxies.

VLTI/MIDI observations have shown how complex the nuclear dust morphologies of AGNs are. In the near future, the second generation VLTI instruments GRAVITY and MATISSE will allow interferometric observations on six baselines at a time and provide both high signal-to-noise visibilities and phases. This will allow us to reconstruct real images of the torus from the inner edge to the main body with resolutions of a few milliarcseconds that are needed to decipher the physics at work.

Acknowledgements

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