Mid-infrared Interferometry of Active Galactic Nuclei: an Outstanding Scientific Success of the VLTI

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Active Galactic Nuclei (AGN) are powered by accretion onto a supermassive black hole. The unified scheme for strongly accreting AGN postulates that the central engine is enshrouded by a doughnut-shaped structure of gas and dust – the so-called torus. We report observations with the MID-Infrared Interferometric Instrument (MIDI) at the VLT Interferometer, which resolve the tori in the nearest Seyfert 2 galaxies, and suggest a complex structure, consisting of a compact inner disc embedded in a patchy or filamentary outer torus. The prominent nearby radio galaxy Centaurus A, however, shows little sign of a torus. Instead, its mid-infrared emission is dominated by non-thermal radiation from the base of the radio jet. Thus, not all classes of AGN contain a thick torus.

The *unified scheme* for Active Galactic Nuclei (AGN) explains various types of AGN by a line-of-sight effect: it postulates that the central engine – an accreting supermassive black hole – is embedded in a doughnut-shaped torus of gas and dust. Thus, the hot accretion disc and the surrounding Broad Line Region (BLR) is only visible when looking along the torus axis. This is the case in Seyfert 1 galaxies, the optical spectra of which are characterised by a blue continuum and broad emission lines. In an edge-on case, however, the direct view onto the core is blocked by the dusty torus and only narrow emission lines from regions above and below the torus are visible. The object then appears as a Seyfert 2 galaxy. Spectropolarimetric observations of Seyfert 2 galaxies, showing broad lines in scattered light, support this idea (see review by Antonucci, 1993). The UV-optical light which is trapped by dust in the torus should heat the dust to a few hundred Kelvin, and the dust should re-radiate in the mid-infrared. Indeed, the Spectral Energy Distributions (SEDs) of both Seyfert 1 and Seyfert 2 galaxies display signatures of AGN heated dust between $\simeq 3\lambda$ and 30 μm. It is an open issue whether dust obscuration plays a similar role in radio galaxies.

Before the advent of the VLT Interferometer (VLTI), the size, shape and internal structure of the torus remained unknown, although the mid-infrared spectra located the dust within a few parsec of the core. Single 8-m-class telescopes cannot resolve mid-infrared structures of this size. Even in the *L*-band (3.6 μm) a diffraction-limited 8-m telescope is limited to 93 mas resolution (Full Width at Half Maximum, FWHM). At the distance of nearby Seyfert galaxies, such as NGC 1068 and NGC 4151 (14 Mpc), this corresponds to 6.5 parsec.

The situation changed dramatically in December 2002, when MIDI, the MID-Infrared Interferometric Instrument, became operational at the VLTI. MIDI observes in the *N*-band (wavelengths 8 to 13 μm). Using the widest telescope separation (UT1–UT4) of 125 m, the width of the point-spread function at 8 μm is only 7 mas, or 0.5 parsec at the distance of NGC 1068. But at the start of MIDI's operations two major questions remained: first, would MIDI be sensitive enough to reach extragalactic targets? Second, would observations with a handful of baselines allow us to reconstruct the dust distribution in the torus and thus provide scientifically meaningful insights? This article demonstrates that today both questions can be answered unequivocally: yes!

Mid-infrared interferometry with MIDI

MIDI operates as classical stellar interferometer of the Michelson type. It combines the beams of two telescopes at a time (Leinert et al., 2003). The sensitivity required for most AGN observations (correlated flux $F_{corr} \leq 1$ Jy in the *N*-band) can only be reached by the combination of two Unit Telescopes (UTs) of the VLTI. The highest sensitivity for detecting and tracking the interferometric *fringes* is obtained by inserting a prism into the interferometric beams, that spectrally disperses the *N*-band light with a spectral resolution $\simeq 25$. For brighter objects a grism with a higher resolution of 250 can be used. In both cases MIDI delivers two spectra (phase-shifted by 180 degrees) onto its detector, containing spectral and interferometric information at the same time. A special analysis pipeline is needed to extract this information. We use the *Expert Work Station* (EWS) pipeline developed in Leiden by Walter Jaffe.

Observations of the scientific target have to be complemented by standard star observations obtained with an identical instrumental set-up. The essential result of the pipeline analysis is a spectrum of the (calibrated) correlated flux $F_{corr}(\lambda)$ in the range 7.8 to 13.2 μm (see Figure 1b, c, d). $F_{corr}(\lambda)$ corresponds to the *Fourier Transform* of the source emission evaluated at a coordinate (called '*uv*-point' or 'baseline') given by the projected separation between the telescopes as viewed from the source. Spatial information about the source structure can be obtained comparing $F_{corr}(\lambda)$ at different *uv*-points. To the actually measured *uv*-points can be added the total flux $F_{tot}(\lambda)$ registered by a single telescope, essentially equivalent to an observation with zero baseline (see Figure 1a). Different baselines can either be realised by using different telescope combinations or by observing the target during its movement across the sky with a fixed telescope combination.

As evident from Figure 1, the AGN spectra between 8.5 and 12.5 μm are often dominated by a broad absorption trough, caused by silicate dust grains. The exact profile of this 'silicate feature' depends on the chemical composition, size and crystalline structure of the grains. Thus the *N*-band interferometry of an AGN not only resolves the spatial structure of the nuclear dust but also can give insight into the dust properties within the inner few parsecs.

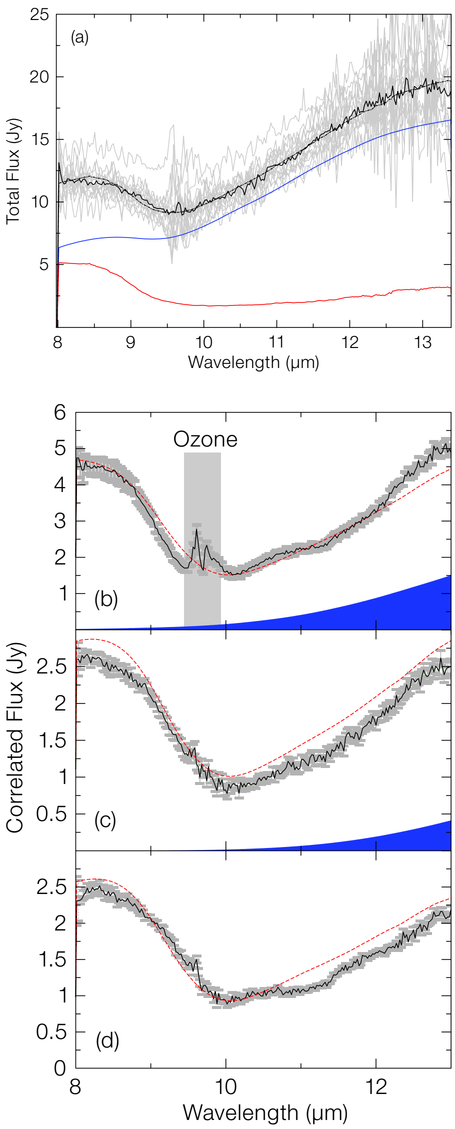

Figure 1. Results of MIDI observations of NGC 1068. (a) Total flux $F_{tot}(\lambda)$: the contribution of the hot component is shown in red, that of the extended component in blue. (b) Correlated flux $F_{corr}(\lambda)$ obtained with a 40-m baseline orientated along position angle P. A. = 36°. The red dotted line gives the model fit and the blue shaded area shows the contribution of the extended component. (c) $F_{corr}(\lambda)$ for 52 m baseline along P. A. = 112°. (d) $F_{corr}(\lambda)$ for 97 m baseline along P. A. = 36°. The comparison between (b) and (c) shows that the hot component is more extended (better resolved) in SE–NW direction.

The dust torus in NGC 1068

The first AGN observed with MIDI was the prototypical Seyfert 2 galaxy NGC 1068. It is the brightest extragalactic *N*-band source in the southern sky. At its distance of 14.4 Mpc, one parsec corresponds to an angular scale of 14 mas, i.e. parsec-scale structures can just be resolved with MIDI at the VLTI.

The earliest MIDI observations of NGC 1068 were obtained half a year after MIDI became operational, during VLTI *Science Demonstration Time* (SDT). Jaffe et al. (2004) demonstrated for the first time that a compact, geometrically thick dust structure – as expected for the dust torus – indeed exists in Seyfert 2 galaxies. Essentially only two visibility points were observed at that time. The correlated fluxes were best modelled by two components, a small, relatively hot one ($T > 800$ K, diameter about 1 pc), embedded in a larger component of 320 K and about 3.5 pc diameter.

New observations with MIDI (Raban et al., 2008b) cover the *uv*-plane much better: 15 visibility points were obtained with the telescope combinations UT1–UT3, UT1–UT4, and UT2–UT3. An additional measurement with the orthogonal baseline UT3–UT4 proved essential for the following results. To study the details of the silicate absorption profile, the higher ($R \simeq 230$) resolution grism was used.

Even with this more complete *uv*-coverage, direct image reconstruction is not possible because MIDI observes only two telescopes at a time and rapid atmospheric phase shifts cannot be recovered by *phase closure* techniques. The measured $F_{corr}(\lambda)$ spectra for different baselines still have to be interpreted by simple models. Remarkably, a model of two components with Gaussian brightness distribution and black-body spectrum describes the correlated flux data reasonably well. With the inclusion of the longest VLTI baselines UT1–UT3 and UT1–UT4, the measurements perfectly constrain the size, shape and orientation of the hot, inner component of the dust torus: major axis 20 mas (1.4 pc FWHM), oriented along P. A. = 138°. It is rather elongated, with an axis ratio of 0.25, indicating a geometrically thin (disc-like?) structure. Only a lower limit, $T > 800$ K, can be set to its temperature. The lack of short baselines, < 50 m in the East-West direction makes the determination of the overall size and shape of the more extended 'torus component' uncertain. Its diameter is about 3.5 pc, but its exact shape remains to be determined by shorter baselines along the East-West direction.[1]

The major axis of the hot component is perfectly aligned with a spur of water masers extending about 20 mas towards NW from the (radio-)core, although the relative astrometric position cannot be determined. Surprisingly, the orientation of its minor axis (P. A. = 48°), which might mark the symmetry axis of an inclined disc, does not fit well to the source axis as determined from outflow phenomena. The inner radio jet points almost exactly North (P. A. = 2°), while the ionisation cone opens between P. A. ≃ −5 – −30°. For the standard torus scenario this is a puzzle: the open funnel which allows the ionising UV-photons to escape should be caused by the angular momentum barrier and thus be aligned with the rotation axis of the gas distribution. How could a tilted disc form out of this gas? Perhaps the hot inner component is not a rotationally supported structure (disc) but rather a filament or hot channel.

Further insight into the dust properties can be inferred from the depth of the silicate feature. In the total flux, which is

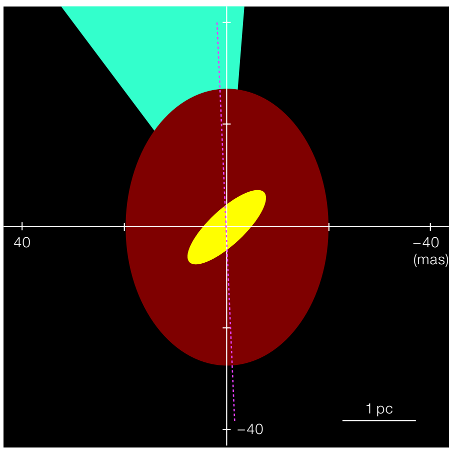

Figure 2. Observational model of the dust torus in NGC 1068. A hot component (yellow) is embedded in an extended cooler component (brown). The orientation of the radio axis is indicated by a purple dotted line and the blue wedge gives the opening angle of the ionisation cone, observed on 100-pc scales.

[1] Such baselines are provided by the Auxiliary Telescopes (ATs). A MIDI observation programme with the ATs is under way and has already detected fringes from NGC 1068.

dominated by the outer component (Figure 1a), the absorption optical depth at 10 µm is moderate, ≃ 0.4, whereas the depth towards the inner component is almost five times larger at ≃ 1.9 (Figure 1b, c, d). Obviously, most of the dust column is located in the outer component.

The dust torus in the Circinus galaxy

The Circinus galaxy at a distance of 4 Mpc is the closest Seyfert galaxy. It shows all signs of a classical Seyfert 2: narrow allowed and forbidden emission lines, strong silicate absorption and a heavily absorbed X-ray spectrum. An extended cone of emission line gas and the presence of broad lines in the polarised optical flux (caused by scattering) provide direct evidence that the central engine is hidden from our direct view behind a substantial amount of dust. Circinus is a spiral galaxy seen almost edge on. Thus, several magnitudes of visual extinction might be caused by the dust lanes in the spiral disc, behind which the nuclear region is located.

The high southern declination of Circinus ($\delta = -65°$) makes it an almost ideal target for the VLTI: it can be observed for up to 12 hours during long winter nights, thus allowing the projected baseline orientation between each of two UTs to swing by up to 180° due to the earth's rotation. In five observing runs during the MIDI *guaranteed time observation* programme, we have been able to collect 21 visibility points, most of them with the shortest VLTI baselines UT2–UT3 and UT3–UT4 (Tristram et al., 2007). They provide the most complete *uv*-coverage obtained for any extragalactic target so far.

As in NGC 1068, at least two components with Gaussian brightness distribution are required to model the correlated fluxes: a compact component (major axis 0.4 pc and axis ratio 0.2); and an almost round extended component (FWHM 1.9 pc, see Figure 3). Contrary to the case of NGC 1068, the colour temperatures of the inner and outer components both lie around 300 K, differing by less than 50 K. However, the outer component does not seem to be smoothly filled with dust at a constant temperature. Comparing its average surface brightness with that of a black body leads to a covering factor of only 20 %. Moreover, the observed correlated flux values are poorly reproduced by the smooth Gaussian model, but rather seem to 'wiggle' around it when plotting them as function of baseline orientation. In order to test whether a patchy brightness distribution could improve the fit, we modified the smooth Gaussian distribution by a foreground screen of randomly distributed variations in transmission. A thousand different screens were realised, the images were Fourier-transformed, and compared with the observed correlated fluxes. Indeed, we found several patchy screens which reproduce the observations much better than the smooth model. The best-fitting model is displayed in the right panel of Figure 3. Interestingly enough, it shows a bright patch on the axis of the ionisation cone. We regard this as evidence that our interferometric data contain hints for the existence of hotter dust close to an open funnel which confines the ionising radiation.

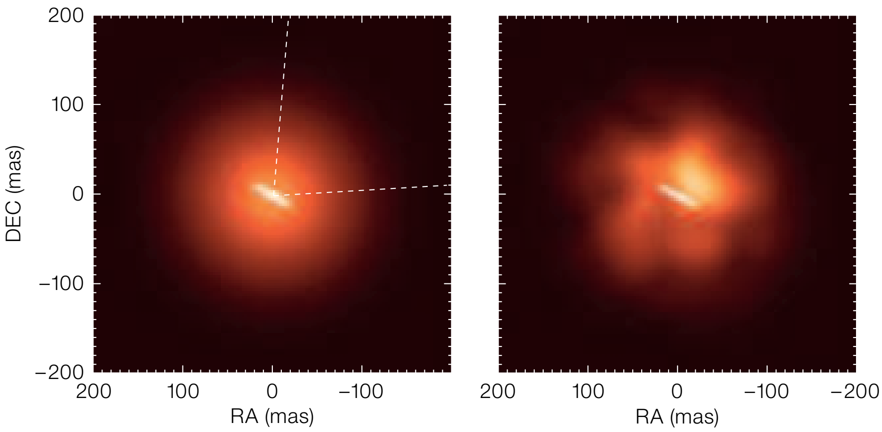

Figure 3. The dust torus in the Circinus galaxy. The left panel shows the smooth model (composed of two Gaussian brightness distributions, the right panel visualises the best-fitting patchy model. Dashed lines indicate the opening angle of the ionisation cone.

The size and orientation of the inner, disc-like component again fit very well to the known disc of water masers which show a Keplerian rotation pattern (Figure 4). Although the location of the dust emission with respect to the maser disc cannot be determined by our MIDI observations, it is very likely that both discs are co-spatial: in this case the inner dust component would also have to be interpreted as a rotationally supported disc.

It is worth noticing that the depth of the silicate absorption towards the dust components in Circinus shows a different behaviour than that observed in NGC 1068. In Circinus the depth of the silicate feature towards the inner component is shallower than towards the outer component. Obviously the dust column through the outer dust component is not very high and the absorption trough is partly filled by silicate *emission* from the dust disc.

The radio galaxy Centaurus A

The radio galaxy Centaurus A (= NGC 5128) plays a key role in extragalactic astronomy: at a distance of only 3.8 Mpc it is the closest large *elliptical galaxy*, the closest *galaxy merger* and the closest

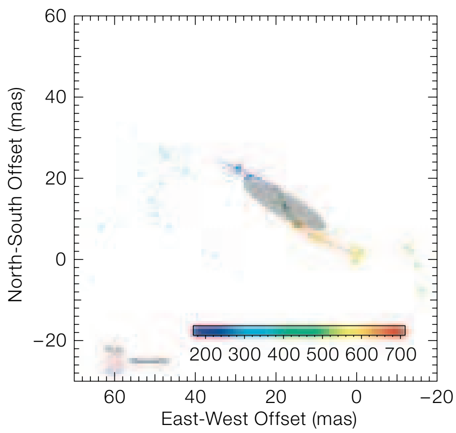

Figure 4. Overlay of the compact dust component in Circinus over the location of the (warped) disc of water masers (from Gallimore et al., 2004).

violent AGN. At its distance, 1 pc corresponds to 53 mas. The radio source can be traced over seven orders of magnitude in angular scales, from the VLBI jets (a few mas) to the outer lobes (several degrees). Extinction in the dust lane of the merging spiral galaxy severely obscures our view towards the nucleus of Centaurus A. Thus observations at infrared wavelengths are mandatory (see Meisenheimer et al., 2007, and references therein for more details).

Centaurus A was observed in 2005 with MIDI using two telescope combinations: UT3–UT4 and UT2–UT3. With both combinations two visibility points were obtained, separated by about two hours. The projected baseline with UT3–UT4 was orientated roughly perpendicular to the parsec scale radio jet, while UT2–UT3 was aligned with it (Figure 5). We found that the mid-infrared emission is marginally resolved perpendicular to the jet axis with a 60-m projected baseline, whereas it remains unresolved along the jet axis. Accordingly, we conclude that the 8 to 13 μm emission from the core of Centaurus A is dominated by an unresolved point source (FWHM < 6 mas), which contributes between 50 % and 80 % of the total flux at 13 μm and 8 μm, respectively. The extended component is tiny (FWHM ≃ 30 mas), and seems elongated perpendicular to the radio axis (see sketch in Figure 5). However, a better *uv*-coverage (including longer baselines) will be required to constrain the size, shape and orientation of this extended component more accurately. We interpret the extended component as dust emission from a small, inclined disc (diameter about 0.6 pc). The unresolved component is identified with the non-thermal 'synchrotron core' of Centaurus A, since we find that – after correcting for the foreground extinction of $A_V = 14$ mag (derived from the depth of the silicate absorption) – its flux level and spectrum lies perfectly on the extrapolation of the power-law spectrum observed at millimetre wavelengths. Together with photometry at shorter wavelengths (from HST and the AO camera NACO at the VLTI) the flux of the unresolved point source fits perfectly to a canonical synchrotron spectrum: it is characterised by a rather flat power-law $F_\nu \propto \nu^{-0.36}$, cutting off exponentially at a frequency $\nu_c = 8 \times 10^{13}$ Hz. We interpret

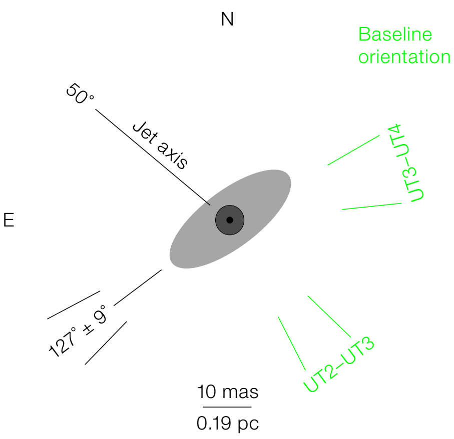

Figure 5. Sketch of our model for the *N*-band emission from the central parsec of Centaurus A. An unresolved point source is surrounded by a faint dust disc.

this 'synchrotron core' as the base of the radio jet (for details see Meisenheimer et al., 2007). Our interferometric results on Centaurus A demonstrate that mid-infrared radiation processes are not restricted to thermal dust emission.

The thermal dust emission from the core of Centaurus A is very feeble, more than 20 times weaker than that of the Circinus galaxy at the same distance. We think that *both* a lack of dust in the inner parsec and the absence of a sufficiently strong heating source are responsible for this. Certainly, Centaurus A neither contains a torus which severely blocks our line of sight nor a UV-optically bright central accretion disc. Most likely, the accretion onto its black hole happens via an *advection dominated accretion flow* (ADAF), which is very inefficient in converting accretion power $\dot{m}c^2$ into radiation.

Models of the torus

The concept of a doughnut-shaped 'torus', continuously filled with gas and dust, is an oversimplified geometrical picture. Already 20 years ago, Krolik & Begelman (1988) pointed out that it must consist of a large number of individual clouds orbiting around the AGN core. However, frequent cloud–cloud collisions would make such a system very unstable: within a few orbital timescales it should settle into a geometrically thin disc. Other arguments for a clumpy sub-structure of the torus include the widely spread and continuous distribution in X-ray absorbing hydrogen column densities between Seyfert 1 and Seyfert 2 galaxies and several cases in which an AGN changed its broad line spectrum, indicating a change in central obscuration. Radiative transfer calculations of 'clumpy' torus models showed that another problem of the continuous torus models – namely their prediction of a strong silicate emission in Seyfert 1 galaxies, which is rarely observed – can be solved by shadowing effects in a clumpy structure (Nenkova et al., 2002). In a recent study we demonstrate by fully 3D radiative transfer calculations (Schartmann et al., 2008) that a wide variety of cloud distributions is able to reproduce the observed mid-infrared spectra. Moreover, when simulating interferometric observations of such a clumpy torus, we find similar 'wiggles' in the correlated fluxes to those observed in Circinus.

Despite the success of radiative transfer models in explaining the infrared SEDs of AGN, they cannot solve the stability problem pointed out by Krolik & Begelman: how could the geometrically thick distribution of clouds be maintained? To address this question a hydrodynamical model is required that simulates a realistic mass injection into the torus and follows the evolution of the gas clouds. We are currently developing a torus model for Seyfert galaxies that starts from a number of assumptions. The centre of the galaxy harbours a massive young stellar cluster (age between 40 and 100 million years). Stellar mass loss via planetary nebulae and stellar winds injects gas and dust into the system, while frequent supernova explosions stir up the gas. Locally the gas gets compressed and the subsequent cooling instability leads to the formation of dense and cool filaments (see Figure 6). In between the filaments cavities of very hot plasma form overpressured regions, which expand radially along the density gradient. Thus the cool filaments also become radially stretched. The cool gas and dust streams inwards along the filaments and accumulates in a very dense turbulent disc with a few parsec radius.

In a second step, the radiative transfer through the simulated density distribution

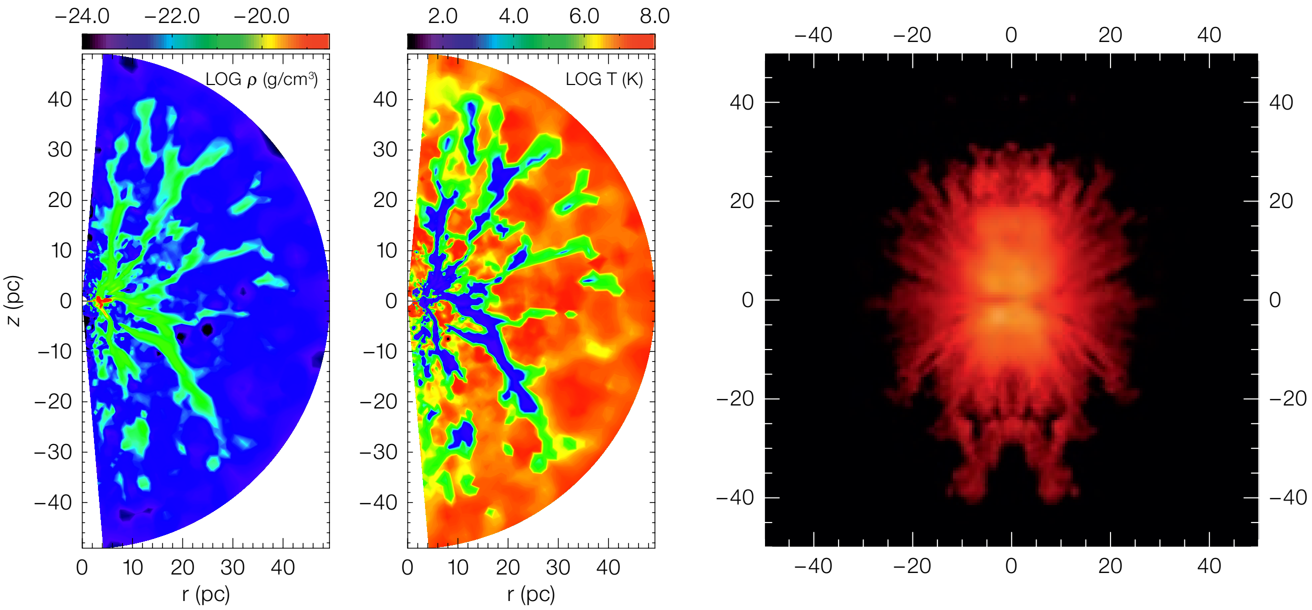

Figure 6. Hydrodynamical torus model. The left and middle panels show the gas density and temperature in a meridional slice. The right panel displays the image at 12 μm which would be observed from an edge-on view onto this torus. The simulations refer to an AGN that is about five times more luminous than NGC 1068.

is calculated (assuming a standard gas-to-dust ratio in all cells below sublimation temperature). The emerging mid-infrared images (right panel in Figure 6) reproduce the filamentary density structure. They can explain the 'patchy' outer torus observed in Circinus rather nicely. It should be noted, however, that the central turbulent dust disc appears *dark* in our simulations. A set of torus models is generated by varying the mass injection and supernova rates. Observing those under various aspect angles can well account for the wide spread in hydrogen column in Seyfert galaxies (over three orders of magnitude) while the change in silicate depth (from absorption to moderate emission) remains limited.

MIDI observations of distant AGN

In addition to the detailed studies described above, we carried out an AGN snapshot survey during the *guaranteed time observations* of the MIDI consortium. The survey tried to identify all those AGN, which are bright enough in the *N*-band to be observed with MIDI. The preliminary target list was selected from AGN with known *N*-band flux > 1 Jy. Since most of the available *N*-band photometry was obtained in large apertures, it was necessary to observe all targets with TIMMI2 at the 3.6-m telescope (beam size 0.7″) to get the core flux at λ = 12 μm. The final target list (Table 1) contains all southern AGN with S_N(core) > 300 mJy (Raban et al., 2008). 13 of the targets have been observed during the snapshot survey, two more were tried by other observers. From 11 of these 15 targets, MIDI could detect interferometric fringes (column 6 in Table 1). Three of the sources, for which MIDI observations were attempted, could not be observed since their nuclei were too faint for the adaptive optics system MACAO. Only one source, the star burst nucleus in NGC 253, seems too extended to show an interferometric signal.

Most targets have been observed only with the shortest baseline UT2–UT3, and remain unresolved within the errors (which are dominated by the measurement of the total flux F_{tot}). Additional observations with longer baselines will be required to determine the size and flux of their dust tori (if present). Despite its northern declination (+40°), we recently managed to observe the nearest Seyfert 1 galaxy, NGC 4151 with the VLTI. It is clearly resolved at 10 μm with a 60-m baseline. But seen from the VLT, the *uv*-coverage of this Seyfert 1 galaxy will always remain very limited. The closest southern Seyfert 1 galaxy which is bright enough for MIDI observations, NGC 3783, is three times more distant than NGC 4151. In order to obtain a direct comparison, more distant (and luminous) Seyfert 2 galaxies have to be studied as well.

Synthesis

At the first sight, our results for the dust structures in the Seyfert 2 galaxies NGC 1068 and Circinus look quite similar: they both contain an elongated inner component which is embedded in a larger dust distribution, heated to about 300 K. The observed difference in torus size is expected from the fact that NGC 1068 is about 10 times more luminous than Circinus. In both sources the inner component is aligned with the location of water masers.

On the other hand, one might argue that the differences between both objects are even more significant: only in NGC 1068 do we find dust heated to almost the sublimation temperature, while in Circinus any strong temperature gradient between the innermost dust and outer parts of the torus is absent. Moreover, the elongation of the hot dust component in NGC 1068 appears significantly tilted with

Name	Type	z	Scale [mas/pc]	S_N (core) [mJy]	MIDI	Remarks
*NGC 1068	S2	0.00379	14.0	15000	X	well observed (16 visibility points), see text
NGC 1365	S1.8	0.00546	11.0	610	X	marginally resolved in snapshot survey
IRAS 05189-2524	S2	0.0425	1.0	550		AO correction with MACAO failed
MCG-5-23-16	S1.9	0.00827	5.7	650	X	done in snapshot survey
Mrk 123	S1	0.0199	2.5	640	X	done in snapshot survey
NGC 3281	S2	0.01067	4.4	620		AO failed on nucleus, nearby star not used
*NGC 3783	S1	0.00973	5.0	590	X	observed by Beckert et al. (in prep.)
NGC 4151	S1	0.00182	14.0	1400	X	resolved in snapshot survey
Centaurus A	RG	0.00332	53.0	1220	X	first results with short baselines, see text
IC 4329A	S1	0.01605	3.1	420	x	fringes detected
*Mrk 463	S1	0.0504	1.0	340		not yet tried
Circinus	S2	0.00145	50.0	9700	X	well observed (21 visibility points), see text
NGC 5506	S2	0.00618	8.0	910		AO correction with MACAO failed
NGC 7469	S1	0.01631	3.1	410	x	fringes detected
NGC 7582	S2	0.00539	9.0	320		not yet tried
3C 273	QSR	0.1583	0.3	350v	X	two interferometric measurements
NGC 253 core	LE	0.00080	57.3	1100	–	no fringes detected (Hönig, priv. comm.)

Table 1. Target list and results of the AGN snapshot survey carried out during MIDI guaranteed time observations (GTO). Targets marked by * were released from the GTO list early. A cross in the column 'MIDI' indicates successful MIDI observations (X: complete interferometric measurement, x: fringes detected, but unstable weather conditions prohibited complete observation).

respect to the source axis as defined by the radio jet and the ionisation cone, whereas the dust disc in Circinus seems to fit perfectly into an axisymmetric torus model. The outer torus in Circinus appears patchy or filamentary as predicted by hydrodynamical models. The low absorption depth in the silicate feature towards the inner component indicates that our line of sight onto the dust disc is not severely blocked by the outer structure and most of the large hydrogen column towards the X-ray core must be located *within* a radius ≃ 0.2 pc. In contrast, NGC 1068 exhibits a huge dust column towards the hot component. Here most of the absorbing gas and dust is located *outside* a radius of ~ 1 pc.

From these differences it seems evident that the torus in the Circinus galaxy is not just a scaled-down version of that in NGC 1068. Thus the question arises: is there such a thing as the standard torus in Seyfert galaxies? In any case, the 'torus' possesses a complex structure, which not only *appears* different (due to line-of-sight effects) but may *differ intrinsically* between individual AGN. This is not necessarily in conflict with the essential assumption of the unified scheme: it is still possible that Seyfert 1s and Seyfert 2s are intrinsically the same class of objects. In order to verify this generic assumption, one has to prove that similar tori, as in NGC 1068 and Circinus, also exist in Seyfert 1 galaxies. The detection of an extended component in NGC 4151 with MIDI marks a promising first step in this direction. Finally, our results on Centaurus A demonstrate that the absence of broad emission lines cannot always be explained by an obscuring torus. Intrinsic properties of the accretion flow onto the black hole might be equally important.

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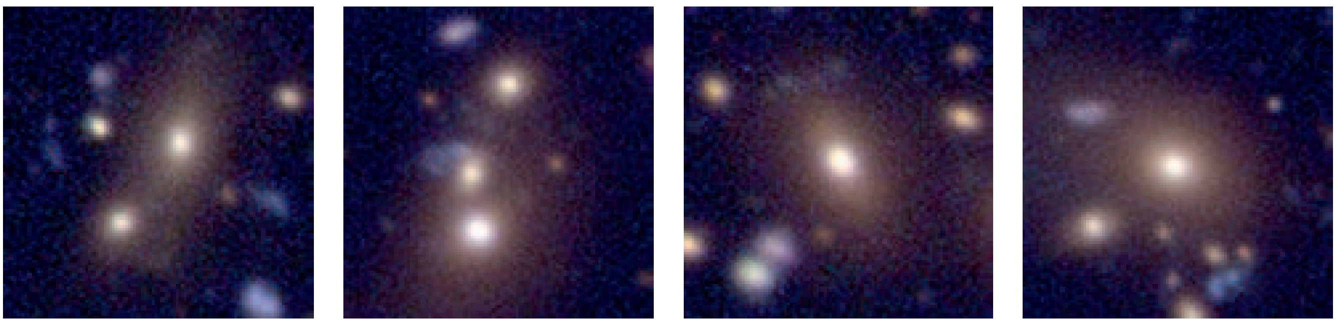

Colour images of the brightest galaxies in four galaxy groups at redshift ~ 0.36, formed by combining VIMOS *B*, *V* and *R* band images (20″ × 20″ sections shown). The galaxies are ordered from left to right in increasing stellar mass, i.e. a rough time sequence. The brightest galaxies in the left two images have gravitationally bound bright companions. See ESO Science Release 24/08 for more details.