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Resolving the dusty cores of nearby AGN with mid-infrared interferometry

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Abstract. We observed the mid-infrared cores of nearby AGN with the interferometric instrument MIDI at the VLTI. In the two closest Seyfert 2 galaxies, NGC 1068 and Circinus, our interferometric measurements resolve the emission to a large degree. In both nuclei we find parsec-sized, clumpy disk-torus configurations which are aligned in the same direction as water maser disks. While in the Circinus galaxy the dust structure is oriented perpendicular to the ionisation cone and outflow, the dust structure in NGC 1068 is misaligned with respect to the jet and the ionisation cone. In the radio galaxy Centaurus A, about half of the emission is unresolved. It is interpreted as synchrotron radiation from the foot of the jet. In a snapshot survey, several other AGN have been observed with MIDI. While the AGN at the largest distances from us remain unresolved, those closest to us are slightly resolved with sizes of their dust distributions on the order of a few parsecs. From this we conclude that toroidal dust distributions as postulated in the unified picture of AGN indeed exist and that they are relatively compact.

Key words. galaxies: active, galaxies: nuclei, galaxies: Seyfert, radiation mechanisms: thermal, techniques: interferometric

1. Introduction

The nuclear distribution of gas and dust, which surrounds the central engine of AGN on parsec scales, plays an important role for the diversity of AGN types. Different theoretical concepts for the dust distribution, such as clumpy dusty tori – either supported by radiation pressure (cf. Krolik, these proceedings) or by supernova explosions (cf. Schartmann et al., these proceedings) –, disk winds (cf. Elitzur, these proceedings) or warped disks, are being discussed. These essentially axisymmetric dust distributions aim at explaining the type 1 / type 2 dichotomy of AGN by an orientation effect.

A part of the energy from the central engine is absorbed by the dust, which in turn reradiates it in the thermal infrared. Due to the small size of the infrared emitting region, interferometric observations are the only tool to directly investigate the spatial distribution of the dust: the infrared emission is unresolved in almost all AGN, even for 10 m class telescopes.

We used the MID-infrared Interferometric instrument (MIDI) at the Very Large Telescope Interferometer (VLTI) to investigate the nu-

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Table 1. List of all AGN which were successfully observed by us with MIDI at the VLTI. The columns include the AGN type, the distance *D*, the fluxes at 11.9 μm and the relevant publication of the MIDI results. The fluxes are from Raban et al. (2008) and were obtained with TIMMI2, except for the fluxes of NGC 1068 and NGC 4151 where the values were derived from Mason et al. (2006) or Roche et al. (1991), respectively.

Name	Type	D [Mpc]	$F_{11.9\,\mu\mathrm{m}}$ [Jy]	Publication of MIDI results
NGC 1068	Sy 2	14	12.50	Raban et al. (2008)
Circinus	Sy 2	4	9.70	Tristram et al. (2007)
Centaurus A	FR I	4	1.22	Meisenheimer et al. (2007)
NGC 4151	Sy 1	14	1.20	resolved (paper in prep.)
NGC 1365	Sy 1.8	18	0.61	Tristram et al. (2008)
MCG-05-23-016	Sy 1.9	35	0.65	Tristram et al. (2008)
IC 4329A	Sy 1	65	0.35	Tristram et al. (2008)
NGC 7469	Sy 1	65	0.41	Tristram et al. (2008)
Mrk 1239	Sy 1	80	0.64	Tristram et al. (2008)
3C 273	Quasar	650	0.35	Tristram et al. (2008)

clear mid-infrared (MIR) emission in a set of nearby AGN. MIDI is a Michelson-type interferometer which combines the light of two telescopes of the VLTI to produce spectrally dispersed fringes in the N-band (8 to 10 μm). The longest baselines of the interferometer provide a resolution down to 7 mas. Because of the low UV coverage that can be achieved with the VLTI in a reasonable amount of time and because of the lack of absolute phases, the possibility to reconstruct images from the data is very limited. Therefore, the interferometric data were modelled in order to extract physical properties of the sources.

2. Results

We targeted a total of 13 AGN with MIDI. For most of these 13 AGN an interferometric signal could indeed be recorded. Only for two sources (NGC 3281 and NGC 5506) no observations at all were possible with MIDI because the adaptive optics systems, preprocessing the light of the interferometer, failed to close the loop. In one object (LEDA 17155 = IRAS 05189-2524) the interferometric signal was too weak to be detected at the time of observation, probably due to a slight misalignment of the two beams. A list of the remaining 10 sources, which were all successfully observed, is given in Table 1. For the three brightest sources, NGC 1068, the Circinus galaxy and Centaurus A, measurements at several different baseline orientations and lengths were obtained. This has allowed us to conduct more detailed studies of these three objects. The results are published in Raban et al. (2008), Tristram et al. (2007) and Meisenheimer et al. (2007) for the three sources, respectively.

The nuclear mid-infrared emission in the two Seyfert 2 galaxies NGC 1068 and the Circinus galaxy is resolved to a large fraction. For both galaxies the data was modelled by two elliptical Gaussian black body emitters. We find that the nucleus of the Circinus galaxy contains a small (0.4 pc) and warm (T = 330 K) dust disk which is oriented perpendicular to the ionisation cone and which matches an H_2O maser disk in orientation and size (see Fig. 1). The disk is embedded in a larger (2.0 pc), slightly cooler (T = 300 K), geometrically thick dust torus with a low scaling factor. The low scaling factor of the extended component, the shallow radial temperature gradient of the two components and the deviations of the measurements from the smooth model give strong evidence for the dust distribution to be clumpy or filamentary.

In NGC 1068, the emission comes from an extended (3.5 pc), warm ($T \sim 300$ K) and geometrically thick torus, as well as from a smaller, hot ($T \sim 800$ K) component, which is

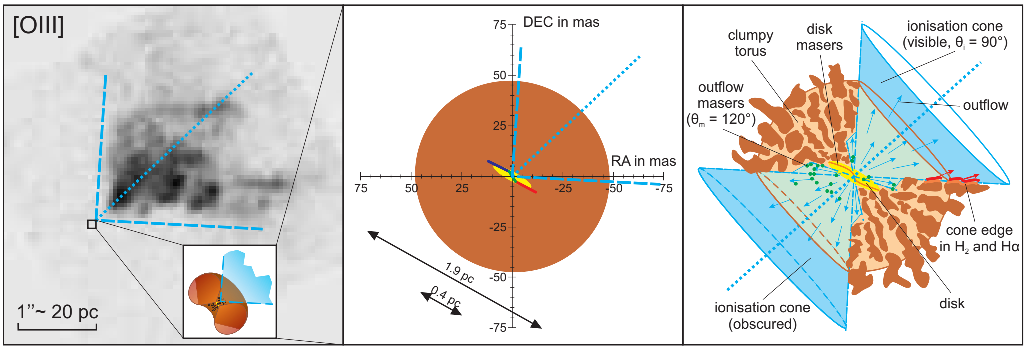

Fig. 1. The dusty torus in the Circinus galaxy. The ionisation cone from Wilson et al. (2000), left panel, is compared to the model fit of the interferometric observations, central panel, and the interpretation in terms of a dust disk and a geometrically thick, filamentary dust distribution, right panel. The rotating maser disk (blue part approaching, red part receding) and the outflow masers from Greenhill et al. (2003) are also plotted.

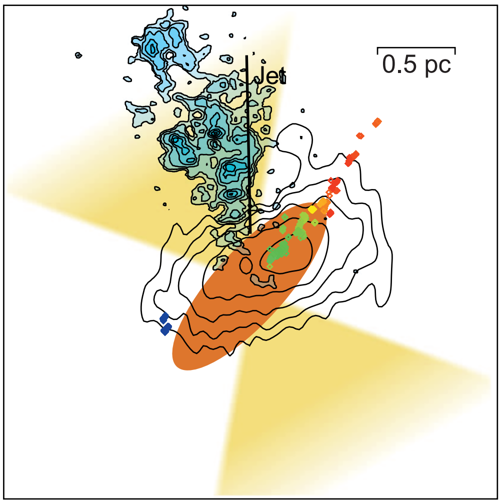

Fig. 2. Structures in the nucleus of NGC 1068: the hot dust component revealed by our interferometric measurements (orange), the free free emission (black contours) and the maser disk (coloured dots), both from Gallimore et al. (2004), the ionisation cone (blue; Evans et al. 1991) and the outflow (yellow; Das et al. 2006). Both the ionisation cone and the outflow are reduced in scale for comparison.

1.4×0.5 pc in size. As in the Circinus galaxy, the latter component matches an H_2O maser disk in orientation and size (see Fig. 2). We interpret it as the hot inner funnel of the torus. The hot component, however, neither lies perpendicular to the radio jet, nor to the ionisation cone (Evans et al. 1991), nor to the outflow modelled by Das et al. (2006). This misalignment may be caused by a warped accretion flow. As for Circinus, a non-homogeneous distribution of the dust is needed to explain the deviations of the interferometric measurements from the smooth model.

The mid-infrared emission in the nucleus of the radio galaxy Centaurus A is significantly less resolved. The emission comes in about equal parts from an extended component and from an unresolved core. The extended component can be interpreted as a thin dust disk with a size of 0.6 pc. The axis of the disk is consistent with being aligned with the radio jet (see Fig. 3). The flux of the unresolved core fits to a synchrotron spectrum ranging from the radio to the near-infrared. We hence identify the unresolved emission with the foot of the jet.

The other seven successfully observed sources were observed in the context of the MIDI AGN snapshot survey. The main goal of this survey was to ascertain which galaxies are best suited for further study with MIDI (Tristram et al. 2008). Hence only one or two measurements were carried out per target. The closest galaxies, namely NGC 1365, MCG-05-23-016, NGC 4151 and to some degree also NGC 7469, appear to be partially resolved by our interferometric measurements. The sizes derived for the respective dust distri-

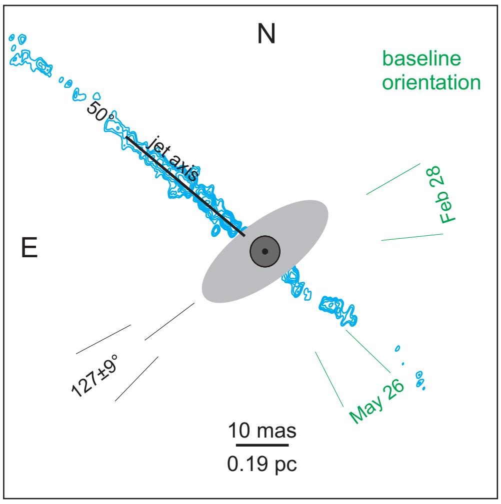

Fig. 3. Sketch of the nuclear mid-infrared emitters in Centaurus A: the dust disk (light grey) and the unresolved mid-infrared emission (dark grey, with the size corresponding to the beam size of the interferometer during our observations) which is identified with the VLBI core (black dot) at the foot of the jet. Also shown is the jet from Horiuchi et al. (2006) in blue.

butions are on the order of 1 to 2 pc, that is, of the same size as in the Circinus galaxy and in NGC 1068. The more distant targets Mrk 1239, 3C 273 and IC 4329A essentially remain unresolved. Only an upper limit for the size of mid-infrared emitters can be derived for these cases: $\lesssim$ 10 pc for Mrk 1239 and IC 4329A and $\lesssim$ 100 pc for 3C 273.

3. Conclusions

Our interferometric observations of the Circinus galaxy and NGC 1068 confirm that indeed geometrically thick dust distributions exist in Seyfert 2 nuclei. Our observations also show that these dust distributions are clumpy. Although the dust distributions in these two nuclei agree in many respects, there are also significant differences. The most notable are the different temperature distributions of the dust and the different orientations of the individual components of the nuclei with respect to each other. Hence, neither the Circinus galaxy nor NGC 1068 seem to be the typical prototype of a Seyfert 2 galaxy. Several fainter and more distant Seyfert galaxies also seem to contain parsec-scaled dust distributions. This is in particular also true for Seyfert 1 galaxies, indicating that the two types of objects are indeed the same. The radio galaxy Centaurus A, on the other hand, shows no evidence for a geometrically thick torus. Whether this implies that radio galaxies truly contain less dust in their nuclei remains unanswered.

We are continuing to study nearby AGN with MIDI, first by increasing the UV coverage for the three brightest objects in order to better characterise the details of the dust distribution, and second by more detailed observations of the sources of the snapshot survey. Together with full hydrodynamic modelling of dusty tori, such as presented by Schartmann et al. (these proceedings), these observations will greatly advance our understanding of the dusty cores of AGN.

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