Chapter 1

Introduction

1.1 Goals of this thesis

Active Galactic Nuclei (AGN) are fascinating objects. They emit more energy from an area as small as our solar system to rival the energy output of an entire galaxy. All AGNs are powered by matter accreting into the super-massive black hole at the centre of the galaxy. This much they have in common, and many are the observed differences between the types of AGNs. Some are highly variable, and some stable. Some show the accretion disk, and for some it is obscured, to name but a few of the differences. The number of different types of AGNs depends on one’s classification system, but in any case it is more than a handful. Fortunately, there is theory which unites the different properties of AGNs. Known as the ‘AGN unification model’, or ‘standard model’, it declares all the observed differences between AGNs in the same class to be an effect caused by looking at the same object but from a different angle. Specifically, in the case of ‘radio quiet AGNs’ the unification model holds that an obscuring torus-shaped structure of dust surrounds the accretion disk and broad line region. Since the obscuring structure is torus-shaped, and therefore possesses a ‘hole’, it can be viewed either face-on or side on, thereby hiding or revealing the physical processes which take place on smaller scales. The main goal of this thesis is to verify to what extent this simple model is true, by use of interferometric observations in the mid-infrared which directly probe the obscuring torus. Our main goal is to take advantage of the unprecedented spatial resolution in the infrared which the interferometer offers in order to establish via direct measurements the physical properties of the torus, such as size and temperature, and related these properties to the expectations of the unification models.

1.2 Active Galactic Nuclei

There is now considerable evidence that at the centre of every galaxy resides a supermassive black hole (SMBH). In most cases, such as the case in our own galaxy, the SMBH is in a quiescent state, i.e. it does not accrete matter, except on occasion.

Accretion onto a compact object such as a black hole is the most efficient way of producing energy known to men, with a mass to energy efficiency factor of \( \eta \sim 10\% \) (i.e. \( E = \eta mc^2 \)). When there is a stable stream of matter accreting into the SMBH, the resulting release of energy makes the nucleus very bright, emitting across the electromagnetic spectrum. In those cases, the galaxy is called ‘active’, and its nucleus is an ‘AGN’. Some of the main component of an active nucleus, which are relevant to this
Figure 1.1 — A cartoon showing the main components of an AGN, along with the basic idea behind the unification schemes (Urry & Padovani 1995). The white labels describe the different AGN components. The green labels note some of the different AGN types, and the arrows show how these different types are named differently depending on the observer’s line of sight. For example, the differences between Seyfert galaxies type 2 and type 1 are attributed here to viewing the AGN either from the side of the obscuring torus (type 2), or through the opening (type 1). The different types of AGN are discussed in §1.2.5.
work are:

1.2.1 The dusty torus

This component is the main concern of this work. Although it is discussed in more detail in section 1.4, a brief description is needed to put the rest of this section in context.

The dusty torus, also referred to as the ‘obscuring’ torus, surrounds the central engine and the broad line region. Since it has a ‘hole’, it allows for the central engine and broad line region to be seen if the hole is viewed face-on (an ‘unobscured’ AGN), and blocks our view if positioned edge-on. In the standard, simple, picture of an AGN, the properties of the torus, i.e. size, orientation, temperature, etc. are closely coupled to those of the other elements of the AGN (Antonucci & Miller 1985). Thus, by measuring the properties of the torus, and then comparing them to the predictions of the model, we are able to gain more knowledge on the validity of the standard model.

1.2.2 The central engine

The central engine (CE), also known as the ‘accretion disk’, is where most of the energy of an AGN is produced. When visible, it appears on the sky as a bright point-source, as its size is too small to be resolved even by interferometers. The accretion disk emits light across the entire spectrum, from radio to X-rays. In the context of this work, the accretion disk does not play an important role, since emission from thermal dust dominates the mid-infrared, where we observe. The most common use we make here of the accretion disk is to use its luminosity in order to estimate the expected inner radius of the dusty structure which surrounds it. Other circumstances which required us to examine emission from the CE are when the object is variable (the CE being the main source of variability), or when debating whether a bright unresolved source we (or others) have observed is in fact the accretion disk, or compact emission from hot thermal dust.

1.2.3 Broad and narrow lines regions

All AGNs show narrow emission lines in the optical regime, with line widths < 1200 km/s. In some AGNs broad emission lines are detected as well. The broad lines are broader since the matter emitting them is moving at larger velocities, and hence is situated closer to the black hole. The narrow lines are then emitted from a region further away from the central engine.

It was early discovered that the broad lines are only seen together with the accretion disk (Antonucci 1984), which led to the natural suggestion that both the broad line region and the accretion disk are surrounded by an obscuring structure.

The narrow lines are often found in cone-shaped structure, the ‘ionization cone’. The shape of the cone indicates that it is also bounded by a toroidal distribution of obscuring matter (Wilson & Tsvetanov 1994). This structure was termed ‘the obscuring torus’.

In this work, we make two uses of the broad and narrow lines, both in chapter 3. First, we compare the shape of the ionization cone in the galaxy NGC 1068 with the
shape of the dust distribution we observed (i.e. the obscuring torus), as it is a consequence of the above statement that the two structured are related. Second, in NGC 1068 (an obscured galaxy), broad lines were discovered in reflection. Thus, for this specific object we already know that it harbours an un-obscured nucleus, and hence for this object the standard model holds. This knowledge allows us to determine that the dust distribution is inclined mostly edge-one, and its size is therefore and estimation of its thickness.

1.2.4 The Jet

The precise mechanism which produces jets in AGN is not yet established. The current prevailing view (Blandford & Payne 1982) is that magnetic field lines in the inner accretion disk wrap around until they are ‘locked’ in a double-helix configuration which causes charged particles to accelerate to velocities close to the speed of light. The emission mechanism of jets is synchrotron radiation, which has a power-law spectrum. The emission from the jet is highly beamed, and can therefore appear very bright. There are two main ways in which jets are relevant for this work. The first is that jets also emit in the infrared. In some cases emission from the base of the jet dominates over other emission mechanisms. This is the case in the galaxy Centaurus A, and chapter 7 discusses the spectral properties of the jet at microwave wavelengths. The second is that the orientation of the jet is related (normally perpendicular) to the angular momentum of the inner accretion disk. The accretion disk’s angular momentum is related to the angular momentum of the captured (accreting) material. Thus, the orientation of the jet is determined by the sum of the angular momenta of individual accreted
1.3. Unification models

Table 1.1. The main differences between the different AGN types

<table>
<thead>
<tr>
<th>Type</th>
<th>Narrow lines</th>
<th>Broad lines</th>
<th>X-rays excess</th>
<th>UV excess</th>
<th>far-IR excess</th>
<th>Radio loud</th>
<th>variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seyfert 1</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>some</td>
<td>yes</td>
<td>no</td>
<td>some</td>
</tr>
<tr>
<td>Seyfert 2</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Quasar</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Blazar</td>
<td>some</td>
<td>no</td>
<td>yes</td>
<td>some</td>
<td>no</td>
<td>some</td>
<td>strong</td>
</tr>
<tr>
<td>BL LAC</td>
<td>no</td>
<td>some</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>strong</td>
</tr>
<tr>
<td>OVV</td>
<td>some</td>
<td>some</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>strong</td>
</tr>
</tbody>
</table>

material. This orientation may be compared to the orientation of the dusty structure we observe in the infrared. In chapter 3 we show that the position angles of the jet and of the inner part of the dusty torus we observe are not what one would normally expect, i.e. they are not perpendicular. This is a strong hint that this particular AGN had a rather complex accretion history, with the current accreting material possessing a different angular momentum than that of the material captured at earlier times. This would also imply that the accretion disk itself is highly warped. An example of a jet of M87 is shown in Fig.1.2.

1.2.5 AGN Types

The major division between different types of AGNs starts with ‘radio loud’ AGN vs. ‘radio quiet’ AGN, the two main AGN classes. In radio loud AGN the most dominant emission source is the jet, while with radio quiet AGNs the jet is relatively weak and the other components of the AGN dominate the emission. The main types of AGN along with a summary of their main properties are listed in Table 1.1. In the AGN unification models, the differences between the different AGN types (belonging to the same class) comes from the differences in our line of sight to the objects, and are not intrinsic to the objects. Thus, there are two components which break the symmetry of the AGN structure: the obscuring torus, which could be viewed either from the side or through the ‘hole’; and the jet, which could be pointed towards the observer (Blazars), away (Seyferts), or point directly at the observer’s line of sight (optically violent variables, OVVs).

The bulk of this thesis is concerned with radio-quiet AGNs, with the exception of chapter 7 which is concerned with Centaurus A, a radio-loud object. The distinction between Seyfert 1’s and Quasars is somewhat arbitrary and is made for historical reasons. Quasars are Seyfert 1 objects that are very luminous and for that reason they were discovered first and given a particular name. The differences and types of AGNs are further explained in the next section.

1.3 Unification models

When first encountering an unknown, diverse phenomena, the first step to understanding it is classification. Next, an attempt is made to use this classification in order
to get better insight into the physical nature of the phenomena. In the case of AGNs, the classification presented in the previous section forms the basis of the unification models (Antonucci 1993). These models attempt to explain the diversity of AGNs by a combination of orientation effects and luminosity effects, i.e. objects are essentially the same, only viewed from different lines-of-sight, and with different luminosities resulting from different accretion rates and black hole masses. Although attempts have been made to attribute all observed differences between AGN types to orientation effects (e.g. Barthel (1989)), these have not proven successful. Most notably, radio-loud and radio-quiet AGNs cannot be united in such a way. As a result, unification models now concentrate on unifying AGNs within the same class. Since this work is mainly concerned with the unification of Seyfert galaxies, which are radio quiet, the rest of the discussion will concentrate on unification of radio-quiet AGNs. We already know from direct observations of the existence of a linear, beamed jet in most AGNs. The jet is an obvious source of asymmetry, and the orientation of the jet with respect to the observer’s line of sight is naturally expected to affect the properties of the object as we see it. The other source of asymmetry, the obscuring torus, is not as evident as the jet, being much smaller in size. For a considerable time, it was considered putative, since all the evidence in favour of the torus have been indirect (see §1.4.1). The main idea is that there is a torus-shaped structure made of dust, which surrounds the central engine and the broad line region. The ‘hole’ in the torus is the second source of asymmetry. When viewed edge-on, it hides the central engine and the broad line region, and we name the object a Seyfert 2. When viewed face-on, we see the central object and the broad line region through the ‘hole’, exposing the central engine and the high energy photons produced there. In this case the AGN would appear as a Seyfert 1. By considering different combinations of the orientation with respect to the jet or the torus, combined with luminosity dependent effects, the differences between radio-quiet AGNs are explained.

The unification models are indeed very simple. Despite that, they do remarkably well in explaining the AGN phenomena, in particular the relationship between Seyfert galaxies. The obscuring torus, which lies at the heart of the unification of radio-quiet AGNs, is the subject of the next section.

1.4 The obscuring torus

The obscuring torus in the main subject of this thesis. We now give a more detailed description of the historical background and of the known properties of the torus, including some discussion of its origins and dynamical state.

1.4.1 Indirect Observational evidence

The obscuring torus has a central role in unification models for AGN. However, until recently (Jaffe et al. 2004), no direct evidence (i.e. a direct observation of its toroidal shape) for its existence was available. This is due to the compact (pc-scale) size of the torus, too small to be resolved by even the largest of the single-dish telescopes.

Nevertheless, even without direct observations, there is a considerable body of indirect evidence supporting the existence of the torus. Below is an overview of the most
suggestive discoveries.

1.4.1.1 The infrared bump

Many AGN show an excess in their infrared emission (Barvainis 1987). The infrared spectra of $\sim 60\%$ of all Seyfert galaxies are dominated by thermal ‘bumps’. These were interpreted as emission from dust heated by the nucleus. However, these observations could not tell exactly where the dust is located with respect to the nucleus, or what shape the dust structure must have.

1.4.1.2 Spectropolarimetry

Perhaps the most compelling evidence in favour of an obscuring structure comes from spectropolarimetric observations of Seyfert 2 galaxies. These observations showed that the broad lines characteristic of Seyfert 1 galaxies are also seen in the polarised spectrum of the Seyfert 2 galaxy NGC 1068 (Antonucci & Miller 1985). Later, the same was found for other Seyfert 2 galaxies. The discovery of the hidden broad lines has important consequences. It establishes the existence of a hidden Seyfert 1 nucleus inside a Seyfert 2 nucleus, thereby unifying the two type of AGNs. It also places the obscuring material between the narrow line region and the broad line region. Finally, it suggests a thick distribution of the obscuring matter.

1.4.1.3 The Seyfert 1/2 ratio

The discoveries mentioned in the previous sections strongly suggest the existence of a thick (and therefore torus-like) body of dust which occupies the space between the narrow and broad lines regions. The question remains exactly how thick the structure is. Assuming that obscuration is solely responsible for the differences between Seyfert galaxies (as unification models do), the relative number of Seyfert 1’s vs. Seyfert 2’s would be indicative of the (average) opening angle of the structure. If $f_2$ is the fraction of type 2 sources, then it is related to the angular width $\sigma$ of the torus by $f_2 = \sin \sigma$. Schmitt et al. (2001) find that $f_2 \approx 70\%$, and hence $\sigma \approx 45$ degrees. In contrast, Hao et al. (2005) find the ratio to be $50\%$, hence $\sigma \approx 30$ degrees. In any case, the torus is thick.

1.4.1.4 The conical shape of the ionisation cones

Cones of ionised matter are often seen in the nuclei of active galaxies. An example of the ionisation cone of NGC 1068 is shown in Fig.1.3. Such cones can result from collimation in the emission of the ionising photons, or by absorption. In the case of absorption, the absorbing matter must then be distributed in the torus-shaped structure (Wilson & Tsvetanov 1994). The opening angle of the cone, which can be measured directly, should match the opening angle of the putative torus. This scenario is sketched in Fig.1.3. Note, however, that once again this consideration cannot constrain the size of the torus.
Chapter 1. Introduction

Figure 1.3 — Left: A sketch showing the relation between the ionisation cone and the dusty torus (Evans et al. 1993). Right: The ionisation cone of NGC 1068, as seen by the Hubble Space Telescope (Macchetto et al. 1994)

1.4.1.5 The ‘receding torus’

The ‘receding-torus’ refers to the fact the the fraction of obscured AGN decreases with the bolometric luminosity of the AGN (Lawrence 1991; Simpson 2005). This fact strongly implies that the obscuring structure is thick: as the luminosity of the AGN increases, the dust reaches sublimation temperature further away from the nucleus, thus increasing the opening angle of the obscuring structure which in turn makes the appearance of unobscured AGNs more common. It is also possible to determine how changes in the fraction of (un)obscured sources depends upon the assumes shape of the torus. The most simple geometry is that of a torus with a constant height. In this case, the AGN type is related to the luminosity by (Simpson 2005):

\[ f_1 = 1 - (1 + 3L/L_0)^{-0.5} \]  

(1.1)

where \( f_1 \) is the fraction of type 1 sources, and \( L_0 \) is the luminosity at which the numbers of type 1 and type 2 sources are equal, i.e. an opening angle of 60 degrees. A schematic representation of the receding torus model is shown is Figure 1.4 along with a comparison between the fraction of type 1 sources as a function of luminosity and the expected relationship from Equation 1.1. It can be seen that Equation 1.1 does indeed follow the general shape of the data, but is not an exact fit. Differences can result from a number of factors, one of them being the oversimplified geometry which is assumed. Nevertheless, the data does strongly support the basic assumptions of the receding torus model.
1.4. The obscuring torus

Figure 1.4 — Left: A schematic representation of the receding torus model (Simpson 1998), showing how the opening angle increases with luminosity. Right: The relationship between the fraction of type 1 sources versus the luminosity of the AGN. The solid line represents the expectations from the geometry of the sketch on the left, which assumes that $h$ is constant with $r$ and is the same for every AGN (Simpson 2005).

1.4.2 The 10$\mu$m spectral feature

At the mid-infrared there are two spectral features (lines) which are associated with dust, at wavelength of 9.7 and 18$\mu$m. These lines are caused by Si-O stretching and O-Si-O bending modes. They are therefore commonly named 'the 10$\mu$m silicate feature' and 'the 18$\mu$m silicate feature', since they are lines associated with silicate dust.

These lines play a vital role in our understanding of the physical conditions which produce the mid-infrared emission from AGNs, and observing and detecting these lines is the major tool by which the mid-infrared properties of AGN are investigated. The two physical processes which govern the appearance of a spectral feature are line-emission and self absorption. In now briefly discuss the conditions for the appearance an absorption or emission feature.

1.4.2.1 Absorption feature

Based on the geometry of the dust distribution with relation to the central heat source and its optical thickness, the features can appear either in absorption or emission. An optically thick medium with a uniform temperature can never produce an emission or absorption feature. In this case, self-absorption and emission are perfectly balanced, producing a featureless Planck function. For an absorption feature to appear, two conditions must be satisfied:

1. A decreasing temperature profile (towards the observer).
2. The dust must be optically thick.

Optically thick dust is needed in order to allow some of the radiation to propagate, while still maintaining a temperature difference, from hot regions towards colder regions. Thus, the colder regions absorb the photons which originated from the hotter regions, and this absorption is not compensated by emission from these regions since they are colder. Therefore, the detection of a feature in absorption is a clear indication of the presence of optically thick dust with a temperature profile which decreases to-
wards the observer. Furthermore, the strength of the absorption feature is then related to the temperature profile of the dust. A large temperature gradient will produce a deeper absorption feature.

1.4.2.2 Emission feature

The conditions for the appearance of an emission feature are less strict. An emission feature can appear for dust at a single temperature if the dust is optically thin. In the general case, an emission feature is observed when looking at optically thin dust with a temperature profile which increases towards the observer, or when the illuminated surface of the dust is directly visible.

1.4.3 Implication on unified models

From the above discussion, it is clear that for nuclei where the obscuring torus is observed edge-on, the spectral features should appear in absorption, while for nuclei which are observed face-on, the features should appear in emission. This is one of the main predictions of unification models.

In the case of Seyfert 2 galaxies, the silicate feature is well detected in absorption. However, in the case of Seyfert 1 galaxies, a featureless continuum is commonly observed. This can be seen in Fig. 1.5, which shows Spitzer spectra for a sample of Seyfert galaxies. Currently, more and more type 1 objects showing the silicate feature in emission are found. This progress is mostly due to the shift towards space-based infrared telescopes, e.g. the Spitzer space observatory. However, in the general case of type 1 objects, the feature is still not detected. This non-detection of the silicate feature in emission poses a challenge to unification models.

Currently, the main approach into solving this problem is by looking for physical mechanisms which will suppress the emission feature. One such mechanism is the introduction of a clumpy medium for the distribution of the dust in the obscuring torus (Nenkova et al. 2002).

With MIDI, we are able to obtain a high-resolution correlated flux in the wavelength range of 8-13 µm. We therefore have an opportunity to detect the 10 µm silicate feature in emission/absorption. For type 2 objects, the feature in absorption is well detected in the case of the Seyfert 2 galaxy NGC 1068. Unfortunately, there happens to be no nearby type 1 AGNs which are as bright as NGC 1068, a coincidence which limits out capacity to observe type 1 sources, and hopefully detect the elusive emission feature.

This lack of prominent bright Seyfert 1 galaxies did not deter us from still attempting to use the superior resolution of MIDI in order to shed light on this issue. We have therefore attempted to observe the brightest Seyfert 1 galaxy NGC 4151, although its declination is northern (+39), and our observing facilities are situated in the southern Hemisphere, and therefore the object is barely observable. The results, presented in chapter 4, clearly detect the silicate emission feature in our correlated flux, and constrain the location of the silicate emitting region to within the central ∼ 2 pc of the galaxy. This is an improvement of a factor ∼ 15 over the current limit of the size of the silicate emitting region (Mason et al. 2009). Furthermore, the emission feature is tentatively detected as well for several other type 1 objects, although not as clearly as in NGC
Section 1.4. The obscuring torus

Figure 1.5 — Infrared spectra of a sample of AGNs from Buchanan et al. (2006) displaying the strong absorption feature seen at 10µm for Seyfert 2 galaxies, and the same very weak (at best) feature in emission in the case of Seyfert 1 galaxies.
1.4.4 The dust L-r-T relation

The circum-nuclear dust in AGNs is heated by absorbing UV radiation from the central engine. Naturally, the further the dust is from the UV source, or the less powerful the UV source is, the lower the temperature of the dust is expected to be. This is expressed in the following relationship between the dust temperature $T$, the bolometric luminosity of the AGN, $L$, and the distance from the energy source $r$, which we label ‘the dust $L - r - T$ relation’. The quantitative relations in this section are based on the discussion of Nenkova et al. (2008).

\[
r \simeq 0.4 \left( \frac{L}{10^{45} \text{ erg s}^{-1}} \right)^{1/2} \left( \frac{1500 K}{T} \right)^{2.6} \text{ pc}
\]  

(1.2)

or, alternatively

\[
T(r,L) \simeq 680 \left( \frac{L}{10^{44} \text{ erg s}^{-1}} \right)^{0.2} \left( \frac{1 \text{ pc}}{r} \right)^{0.38} \text{ K}
\]

(1.3)

The bolometric luminosity of an AGN may be directly measured or derived. The dust temperature and the its spatial scale may also be derived from MIDI observations. We are therefore in a position to test this relation.

1.4.4.1 Derivation

The spectral infrared luminosity ($L_{\nu}$) of a single grain with temperature $T$, size $a$, and absorption coefficient $Q_{\nu}$ is given by:

\[
L_{\nu} = 4\pi a^2 Q_{\nu} B_{\nu}(T) \text{ ergs s}^{-1}\text{Hz}^{-1}
\]

(1.4)

When exposed to a UV radiation field on energy density $u_{\nu}$, an equilibrium state will be reached when the energy absorption rate equals the rate at which it is radiated:

\[
\pi a^2 \int u_{\nu} c Q_{UV} d\nu = \int L_{\nu} d\nu
\]

(1.5)

where $Q_{UV}$ is the ultraviolet absorption efficiency of the grains. Eqs. 1.2, 1.3 are a solution to the last equation.

Given the elementary physics involved, it is clear that if the L-r-T relation is found inaccurate, there are basically just three options:

- Dust grains are wither smaller or bigger than expected
- $Q_{\nu}$ is different
- $Q_{UV}$ is different.
1.4.4.2 Empirical evidence in favour of relation

Let us consider the evidence in favour of Eqs. 1.2, 1.3. To the best of our knowledge, empirical evidence for the \( L - r - T \) relation comes from measurements of the time-delayed responses of the K-band flux variations to the V-band flux variations in a sample of nearby Seyfert 1 objects (Suganuma et al. 2006). The K-band emission originates from the putative torus, while the V-band emission from the accretion disk. The time lag between the two, if indeed found, is then an estimation of the inner radius of the torus. The results of this study show that the above mentioned time-lag, \( \Delta t \), is proportional to the square root of the luminosity, i.e. the same relation between \( r \) and \( L \) as expressed Eq.1.2.

1.4.4.3 significance of the relation

From the discussion above we can see that the \( L - r - T \) relation is another form of representing the way UV radiation interacts with the dust grains. It therefore has implication on every field in Astronomy where centrally heated dust is concerned. This includes studies of galactic objects such as proto-planetary disks, for example. Any information we obtain using MIDI about the \( L - r - T \) relation therefore might apply to different physical environments as well.

1.4.5 Masers

Masers are molecules such as OH and H\(_2\)O, which have undergone a population inversion and emit stimulated emission. The radiation is emitted at a single wavelength corresponding to the transition between the levels in question. Masers are very similar to man-made lasers in principle, but they do not employ resonant feedback as lasers do. Masers require a pumping mechanism to supply the energy input and stimulate the emission.

Masers in AGN are usually referred to as ‘megamasers’ due to their exceptional isotropic luminosities. Masers are a very useful tool in astronomy. They can be used to measure distances, determining very accurate rotation curves, and may reveal the geometry of the disks they occupy.

Masers require specific astrophysical conditions to be formed (Elitzur 1992), and can only be formed where the density and temperature of the interstellar material falls within a certain range. For water masers, for example, a temperature of 300-900 K is needed.

For this reason, it was early speculated that masers are related to the dusty torus, as dust clouds are a fertile environment to maser formation (Claussen & Lo 1986). However, the high resolution data necessary to confirm this was not available. Now, after the successful operation of the VLTI, we have managed to prove the relation between the masers and the dust distribution in two galaxies: Circinus and NGC 1068 (chapter 3). In both cases, the masers are distributed in a ring with an orientation and size matching those of the dust structure we observe. The geometrical properties of the maser ring in NGC 1068, and its edge-on inclination, both provided substantial support to the interpretation of our finding in NGC 1068.
1.4.5.1 Our findings

As discussed, MIDI observations let us directly test the $L - r - T$ relation if we can estimate a size and a temperature for the dust emitting region, providing the bolometric luminosity of the AGN is known. We consistently find that the $L - r - T$ relation is not properly scaled. i.e. while the size of the dust is still proportional to the luminosity, the dust is nevertheless found to be cooler than Eq.1.2 predicts. We attribute this difference to either larger grains, or to the existence of dust species which absorb less UV than normal dust.

1.4.6 Outlook to the future: 3D radiative transfer models

The observational effort to detect and measure the properties of the torus is accompanied by a theoretical effort to constrain its physical properties with the help of state-of-the-art 3-D computer simulations. The first such simulations where relatively simple and only considered a smooth distribution for the dust.

During the last decade, more complicated radiative transfer models have been introduced. These models now enable us to consider clumpy distributions for the dust. The handling of clumpy media was pioneered by Nenkova et al. (2002), and there are now several groups who are busy perfecting their models, each with a different approach.

Most such radiative transfer models make several assumptions about the optical depth of the individual dust clouds. The clouds are then distributed in an arbitrary manner which would nevertheless provide toroidal obscuration, and the resulting images and SEDs as a function of the model parameters and its inclination are compared to available data. As an example, Fig.1.6 shows images of the torus model of Hönig et al. (2006) as a function of its inclination and cloud arrangement.

Most models, however, still do not address the issue of how the dust clouds ended up in their locations, or what is the dynamical state of the clouds. An exception is the work of Schartmann et al. (2009) who attempt to use stellar feedback processes to explain the dynamical state of the torus. The temporal evolution of the torus density from their latest models is shown in Fig.1.7.

It is safe to say that currently our ability to create complicated models outshines our ability to obtain data which would constrain such models. The data presented in this work is the most extensive of its kind. And yet, to fully constrain the models with this data, a much higher resolution is needed. The true impact of the radiative transfer models will take place in the future, when better instruments are available.

1.4.7 Origin and dynamical state

As stated before, the dynamical state of the torus is still unknown. Still, there are two main scenarios for the dynamical state of the torus: the outflowing and inflowing scenarios, which we will shortly describe. The issues we address in this section are actually not addressed at all in the thesis. The main reason is that the observations, which are the basis for this work, are unable to distinguish between the different scenarios. However, this work is concerned with the torus, so an overview of the current speculation as to its origin and dynamical state is given.
Figure 1.6 — L-band model images of the torus of Hönig et al. (2006) as a function of its inclination, \( i \).

*Left column:* images obtained by averaging model images of \( \sim 200 \) different random cloud arrangements.

*Middle and right columns:* model images for two particular random cloud arrangements. *From top to bottom:* \( i = 90^\circ, 45^\circ, 30^\circ \) and \( 0^\circ \).
Figure 1.7 — Temporal evolution of the density in the model of Schartmann et al. (2009), given in a meridional slice of the torus. Shown are four stages of the torus at 0.25, 1.0, 5.0 and roughly 10.0 global orbits. The scaling is logarithmic.

1.4.7.1 The inflowing scenario

In this scenario, which is the dominant one at the moment, the torus is a somewhat separate entity from the broad line region (BLR). The dust originates from stars in the host galaxy, slowly making their way to the nucleus. Below is a qualitative description for the scenario of Schartmann et al. (2009), which is the most detailed one currently available. This model is not only able to account for the origin of the dust clouds, but is also able to explain its vertical structure.

The main assumption of the model is that a young star cluster exists in those AGN which posses a torus, which was build up during a short duration (40 Myr) starburst period. After the first violent phase of the evolution of the cluster double systems of lower mass stars are able to form, and the rate of supernova type Ia begin to rise sharply. At the same time, planetary nebulae formed by stars in the intermediate mass range (1.5-8 $M_\odot$) begin to inject mass into the interstellar medium. The injection velocity matches the velocity dispersion plus the rotational velocity of the stars. The injected mass begins to cool and loose energy, making its way towards the central engine. The combination of cooling instabilities, shock fronts from supernova explosions and planetary nebula collisions lead to the creation of a geometrically thin, but optically thick and very turbulent disk. As more and more matter falls towards the minimum of the potential, a turbulent and fluffy disk emerges, possessing a very filamentary structure with strings of material in the azimuthal direction, in a torus-like shape. The torus, then, is not a stable structure. It’s height is maintained by constant injection of mass and energy from the nuclear star cluster and supernova explosions. Without this constant mass and energy injection, the torus will collapse to a thin disk. The temporal evolution of the density in this model is shown in Fig.1.7

1.4.7.2 The outflowing scenario

The outflow scenario offers a radically different outlook on the torus. Here, the torus is not an independent entity. Rather, the torus, accretion disk and broad line region
are all basically the same phenomena, with the BLR being a wind of ionized material lifted out of the accretion disk, and the torus being the condensed, molecular part of the wind.

This scenario started to take shape after Blandford & Payne (1982) proposed that energy and angular momentum are removed from the accretion disk by field lines that leave the disk surface, extending to large distances. This idea was originally intended to explain the production of jets in AGN. About ten years later, Emmering et al. considered what happens to the material lifted off the accretion disk in the more extended regions of the disk, which are not directly related to the jet. They proposed that this material is ionised by the AGN, and is seen as the broad line region. Thus, the accretion disk and BLR are united in this scheme, in the sense that if you have an accretion disk, then you have a BLR as well. The next step was to consider what happens to the BLR ionized clouds when they are sufficiently away from the nucleus. If the uplifting force is sufficient, the clouds will eventually condense and become molecular and optically thick, obscuring the nucleus. Thus, in this case, the obscuring torus is not a structure which exists on its own, but is the part of the wind which has condensed. This scheme may be termed the ‘Grand unification theory’ since it requires only a SMBH accreting matter in order to account for the CE, the BLR, and the torus.

1.5 Introduction to Interferometry

Interferometry can be most simply described as the careful combination of light from telescopes placed at distance. The fringe pattern produced due to the wave-like nature of the light contains information on the spatial distribution of the emitter, but with a resolution \( \theta = \frac{2.2 \lambda}{B} \), where \( \lambda \) is the observed wavelength and \( B \) the projected separation between the telescopes. The higher the separation between the telescopes, the higher the resolution gained. The Very Long Baseline Array, for example, has a network of radio telescopes across North America.

While the spatial resolution depends on the distance between the telescopes, the amount of information gained depends mostly on how many different telescopes positions were used in the observation. The distribution of the telescopes (or antennas) is referred to as the ‘u-v plane’, where each point on the plane is the projected position of each telescope. The signal recorded after combining the light is nothing else than the Fourier transform of the source’s brightness distribution. This may be formally written as:

\[
V(u',v') = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(l',m') e^{-2\pi i(u' l' + v' m')} \frac{dl' dm'}{\sqrt{l'^2 + m'^2}}
\]  

(1.6)

where \((l',m')\) are direction cosines measured with respect to the relative position of the telescopes \((u', v')\), \(V(u', v')\) is the visibility for each pair of \((u, v)\) points, and \(I\) the spatial distribution of the source on the sky.

Equation 1.5 is all one needs in order to analyse interferometric data. If enough u-v points were gathered, then one has determined sufficient values of \(V\) in order to use the inverse transform and recover \(I\), the image of the source, as is normally the case with radio astronomy. At shorter wavelengths, such as the infrared, the process...
of collecting and combining the light is more complicated. The practical implication
is that infrared interferometric arrays are very small compared to their radio counter-
parts, and therefore provide considerably less information. In Chapter 3 we present
one of the most extensive infrared interferometric observations to date. These obser-
vations are composed of 16 u-v points, combining the data form only two telescopes
at a time. With this type of data, the direct imaging method described above cannot
be employed. Not only do we not measure enough values of $V$, but we also lose the
phase of $V$ (which is a complex number) and measure only its amplitude.

This lack of information may be overcome by use of either modelling, or by use of
clever ways to reconstruct images from partial data. The next section describes both
methods.

1.5.1 Modelling

Modelling allows us to determine the basic properties of the source, even when a small
number of u-v points are measured. First, a model, often with a few free parameters
for $I$, the source’s brightness distribution, is generated. The values of $V$ for each u-v
point are then determined according to Eq.1.5, while changing the free parameters to
fit the data. Modelling is especially useful when the shape of $I$ is already known. For
example, measuring the diameter of a star is possible using a single u-v point, using a
circular disk model for $I$, which has only one free parameter, its radius.

In cases where there is no a-priori information about the shape of the source, one
must assume a specific shape for $I$. Common shapes used in interferometry include a
Gaussian distribution, a ring, a circular disk etc.

Modelling is in a way a process of clever guessing, since we have to first guess the
basic properties of the source. However, as shown in this thesis, modelling can deliver
a large degree of certainty if enough u-v points are measured, and if the model fits the
data well.

1.5.2 Image reconstruction

In some situations, there is enough information allowing one to reconstruct an image
of the source although some of the data is missing. Suppose we have measured a set
of 10 u-v points, while 30 u-v points are enough to apply the inverse Fourier transform
and generate the true image. In this case, there are many images which might differ
considerably, but nevertheless would fit the measured data points. How does one
choose between them?

The answer is: by making a few other assumptions about the flux distribution. The
first one, and the most straightforward, is that the image we recover must have all posi-
tive values. The second one is less intuitive than the first. Namely, we define a function
called the 'entropy', and select the image for which the entropy is in extremum. The
most simple definition of entropy here is virtually identical to the classical entropy in
thermodynamics: $S = \sum_i P_i \log P_i$, where we sum over the number of pixels and $P_i$ is
the pixel value of the $i$th pixel. In practice, more complicated forms of the entropy
can be used. This method is called 'Maximum Entropy', and in Chapter 3 we employ it for
the first time with such data in order to reconstruct an image of the centre of the active
galaxy NGC 1068 at mid-infrared wavelengths.

1.5.3 Spectro-interferometry

Spectro-interferometry is the technique we use in all the interferometric observations presented in this thesis. The idea is to disperse the light before combining the beams using either a prism or a grism. This way we get not just the visibility $V$, but the visibility for each wavelength we measure, $V(\lambda)$. The direct product of the spectro-interferometer is not the visibility, but the ‘correlated flux’, which is the actual flux which is correlated, and may be thought of as the spectrum of the source measured under an aperture set by the spatial resolution of the interferometer\textsuperscript{1}. The correlated flux is in fact the visibility times the total flux emitted from the source.

Although the common practice is to use the visibility in analysing interferometric data, it is often more useful to model the correlated flux directly, as we have done throughout this thesis. The main reason for this is that in many cases the uncertainties in the visibility are much higher than in the correlated fluxes.

Spectro-interferometric observations pose an additional challenge due to the correlated fluxes being sensitive to the spectrum of the source and to its size. For example, suppose we see that the correlated fluxes rises with wavelength. The rise could be due to the source emitting more at longer wavelengths, or may indicate that the source is more resolved spatially at shorter wavelengths. There is no full-proof method to disentangle the two effects. The approach that we have taken in this work in to apply two models to the data. The first model assumes all the differences in flux arise from the spectral properties of the source, i.e. the source has the same size in every wavelength. The second assumes no relationship between the flux at different wavelengths, i.e. source size (and orientation) may vary with wavelength. By comparing the results of the two models, one may gain some insight into the true nature of the source.

1.6 The Very Large Telescope Interferometer and MIDI

The very large telescope interferometer (VLTI) is composed of four 8.2 meter units telescopes (UTs), and several 1.8 meter auxiliary telescopes (ATs). The telescopes are coupled together by tunnels (the delay lines) designed to carry the photons to a common location, where the beams are combined by the specific instrument used. Since the optical path difference between the telescopes and instrument must be equal, the delay line are equipped with mobile retroflector carriages which are able to move with a precision of a micron. For a successful beam combination, the optical path difference must be controlled with a precision that is better than the shortest observed wavelength, in this case $\sim 2\mu m$. This very high precision needed is the main reason while optical interferometry had to wait to the 21 century, while radio interferometry (with much larger wavelengths) has been practised for half a century. There are several instruments currently coupled to the VLTI with different capabilities. For example the AMBER instrument can simultaneously combine the K-band light from three telescopes.

\textsuperscript{1}In some cases, usually when the source has a sharp ‘edge’, the correlated flux behaves rather differently
For the observations presented in this work, we use the MIDI instrument, which shall be described ext.

### 1.6.1 The MIDI instrument

The Mid Infrared Interferometric Instrument (MIDI) is the instrument we use in all the interferometric observations presented in this thesis. It is also the only such interferometer which routinely observes AGNs. Below is a brief description of the instrument. For a more detailed overview see Leinert et al. (2003)

MIDI is a classical Michelson interferometer, combining the light from two UTs or ATs at a time. To protect the instrument from thermal radiation from the environment,
most of the optics is enclosed in a cryostat cooled at about 40 K (the cold box), while the array detector of MIDI is cooled at 10 K, with pupil-stops inside the cryostat reducing the background radiation and stray-light. In order to adjust the optical path difference, the two beams paths are modulated by moveable mirrors motored by piezoelectric transducers, before entering the cold box. In the cold box, the two beams pass through two stops, designed to block stray light and improve the image quality. The beams then continue to the beam combiner, which is made from a ZnSe plate with a 50:50 coating. After the beam combiner, the beams (now called 'channels') pass thorough a dispersive element to generate a spectrum. Two kinds of dispersive elements are used, a grism and a prism. The Prism provided a spectral resolution of \( R = \lambda / \Delta \lambda = 30 \) and for the grism \( R = 230 \). The dispersed beam is then recorded on a detector, divided into spectral channels. There is a trade-off between the spectral resolution and the number of photons that reach each pixel on the detector. For strong sources, the grism is used, while for weak sources the prism is used since there are less spectral channels and so each pixel on the detector gets more photons.

The official limiting flux of MIDI is 1 Jy if using the ATs. However, we present here MIDI data for sources with flux as low as 50 mJy. This shows that MIDI as an exceptionally successful instrument, capable of performing observations well beyond its designated limits. In fact, most of the problems which occur when observing very faint sources arise from the other systems of the VLTI, most notably the adaptive optics. The main limitation of MIDI is its lack of phase measurement, as MIDI can only measure Fourier amplitudes. In practice this means that when interpreting MIDI data we cannot distinguish between symmetrical and asymmetrical models.

1.6.2 Observational procedure and data reduction

The observational procedure is described in detail in chapter 6. For reducing the data, we use the Expert Work Station (EWS) data reduction package, developed by Leiden University. EWS uses coherent visibility estimation as the method of data reduction. For a detailed description see Jaffe (2004).

1.7 This thesis

Here is a brief summary of the contents of each chapter.

Chapter 2

Interferometric observations are costly, and observing time is not given easily. We therefore must be sure which objects are worth observing, given the limited time on the interferometer.

In this chapter, we use the 3.6m telescope at La Silla, Chile, to first observe every source which may be a promising MIDI target, a total of 21 sources. We try to determine which sources are bright enough to be observed and for which sources the mid-infrared emission is resolved. Images are also presented when structure is visible.
Chapter 3

In this chapter we present observation of the Seyfert 2 galaxy NGC 1068. For this object we use an extensive $u - v$ coverage composed of 16 different baselines, which is one of the most extensive infrared interferometric observations of an extragalactic object. We were able to fully resolve the dusty structure and measure its main properties such as size and temperature. We also present an image of the source at 8 µm, which was produced using maximum entropy image reconstruction. We find the dust component (the torus) to be co-spatial with the known maser disk and discuss the relation between the dust and the ionisation cone. We also find that the dust is tilted by 45 degrees with respect to the jet, which indicated a complicated history of accretion for this specific object. Due to the side-one position of the torus in NGC 1068, we were able to show that the dust structure we resolve is indeed an inflated torus. The observation of NGC 1068 provide the most convincing case for the obscuring torus, compared with results for other objects.

Chapter 4

In this chapter we present observations which resolve the dust distribution in the Seyfert 1 galaxy NGC 4151. The resolved structure’s size and temperature are comparable with those of Seyfert 2 galaxies, which is a strong indication in favour of the unification models. We compare in detail our findings with interferometric observations at shorter wavelengths, and conclude that the unresolved source seen in those observations cannot be a continuation of the resolved structure seen by MIDI. We detect the silicate feature in emission, albeit tentatively, and discuss how the size and temperature we derive for this source fit into the unification models.

Chapter 5

In chapter 5, we present observations of the Quasar 3c273. This source is unique in our sample because it is not a nearby object, allowing us to test the predictions of the unification models on a high-redshift and very luminous object, as well as to compare our findings for this object with our finding on nearby AGNs. We find a resolved and elongated structure at the core of 3C 273. The size of the structure is consistent with the size predicted by unification models for the dusty torus. Similarly with NGC 4151, we also detect the 10 µm silicate feature in emission tentatively.

These observations, for the first time for such high redshift source, resolve the emission from the dust in the centre of the quasar, and provide the first direct evidence that unification scheme hold for this type of objects.

Chapter 6

In this chapter we present observations of a sample of 10 Seyfert galaxies, a combination of both types of Seyfert galaxies. For each source we obtain between one and three $u-v$ points, which allow us to see whether the target is resolved and to measure basic properties such as the size of the mid-IR emitting regions. For seven targets out of the ten observed, we derive sizes of limits on the sizes of the AGN heated dust. In these cases we find that the size of the mid-IR emitting region is parsec-scaled. Further, the
derived sizes roughly scale with the square root of the AGN luminosity. The 10 micron silicate feature is also tentatively detected either in emission or absorption.

**Chapter 7**

In this chapter we turn our attention away from the obscuring torus and toward the mm and radio emission coming from the jet. Only publicly available data is used, including WMAP data which was obtained for determining the properties of the microwave background radiation. Here, we use WMAP data in order to study the radio emission mechanism of the FR-I AGN NGC 5128 (Centaurus A). We determine the centimeter and millimeter continuum spectrum of the whole Centaurus A radio source and measure at frequencies between 86 GHz (3.5 mm) and 345 GHz (0.85 mm) the continuum emission from the active radio galaxy nucleus at various times between 1989 and 2005. The data shows that the integral radio source spectrum becomes steeper at frequencies above 5 GHz. The SW outer lobe has a steeper spectrum than the NE middle and outer lobes. We find that Millimeter emission from the core of Centaurus A is variable, a variability that correlates appreciably better with the 20-200 keV X-ray variability than with 2 - 10 keV variability. In its quiescent state, the core has a spectral index which steepens when the core brightens. The variability appears to be mostly associated with the inner nuclear jet components that have been detected in VLBI measurements. The densest nuclear components are optically thick below 45-80 GHz. This chapter is an example of how one can use existing and publicly available data to obtain results in a different niche of Astronomy than the data was intended for.