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1.1. A bit of history.

The discovery of Active Galactic Nucleus (AGN) in the cores of many Galaxies occurred early in the twentieth century, when Fath [1909] analyzed the photographic spectra of several 'spiral nebulae' and found that some of the objects in his sample, such as NGC 1068, showed high excitation lines and some peculiar OIII/Hβ ratios which are not tipically observed in stars. Similar findings or confirmations were later reported by Slipher [1917].

Years later, the systematic study of galaxies with nuclear emission lines began with the work of Seyfert [1943]. Carl K. Seyfert obtained spectrograms of galaxies with nearly point-like nuclei showing emission lines superimposed on solar-type spectra. The emission-line profiles differed from line to line and from object to object, but several patterns emerged, that were to prove typical of this class of galaxies. Firstly, all showed high excitation lines in their spectra. Secondly, several showed very broad permitted Hydrogen lines with widths that correspond to speeds of $\approx 8,500 \text{ km/s}$. And thirdly, several objects showed spectra with less broad forbidden lines (with widths corresponding to $\approx 3000 \text{ km/s}$) which matched the cores of hydrogen lines. Galaxies with high excitation nuclear emission lines are now called 'Seyfert galaxies'.

The next major advance for the study of AGNs was triggered by the developments of radio astronomy. Jansky [1933] conducted a study at $\lambda = 14.6 \text{ m}$ and concluded that significant radio emission came from the entire disk of the Milky Way, being strongest in the direction of the Galactic center. Reber [1944] additionally noted that the ratio of radio radiation to optical light was significantly larger for the Milky Way than the sun, suggesting a different mechanism for the emission at the nucleus of the Milky Way.

Years later, Matthews & Sandage [1963] and Schmidt [1963] reported observations of 3C 48 and 3C 273, respectively. These objects showed broad emission lines at unfamiliar wavelengths that could not be identified with known objects. Photometry showed rapid variability changes and an excess of ultraviolet (UV) emission compared with normal stars. Such objects came to be known as quasi-stellar radio sources (QSRS), quasi-stellar sources (QSS), or quasars. The observed similarities between Seyfert galaxies and QSOs suggested a common physical phenomenon. The discovery of the quasar 3C 273 at a redshift $z = 0.16$ implied an enormous luminosity for this object. The large redshifts of QSOs immediately made them potential tools for the study of cosmological questions.
From that time, astronomers have raised questions about the nature of the energy source, the nature of the continuum source and emission-line regions, and the factors that produce an AGN in some galaxies and not others.

1.2. The unified model of AGNs

Several explanations for the observed properties of the Active Galaxies were postulated in early years. Woltjer [1959] postulated a separate region of fast moving, possibly gravitationally bound gas to produce the broad Balmer line wings of Seyfert galaxies. The picture of broad lines from a small region of dense, fast moving clouds (Broad Line Region or BLR) and narrow lines from a larger region of slower moving, less dense clouds (Narrow Line Region or NLR) found support from photoionization models [Shields, 1974].

As for the energy source, explanations including a chain reaction of supernovae in the galactic nucleus [Burbidge, 1961], collisions and tidal encounters in dense star clusters [Spitzer & Saslaw, 1966], and starburst models [Terlevich & Melnick, 1985] were proposed in the early years. But the most accepted and current explanation for the heating engine of AGNs comes from gravitational energy released during accretion onto a Super Massive Black Hole (SMBH) [e.g. Salpeter, 1964; Zel’dovich, 1964]. The explanation for the quasar energy production involved some kind of turbulent transport of angular momentum, allowing the matter to move closer to the hole, which would grow in mass during the accretion process. The thermal radiation expected in a disk of gas orbiting a black hole would naturally lead to photoionization and broad line emission. The radio emission arises from magnetic and particle acceleration that we still partially understand.

Observations of AGNs showed a diversity of spectral features that could be explained by using different physical components for every object. But despite their differences, some classes of AGNs showed unexpected similarities. This was most dramatically demonstrated by the detection of polarized broad lines in 3C 234 [Antonucci, 1984] and NGC 1068 [Antonucci & Miller, 1985]. The polarized spectra, most probably caused by electron scattering, revealed the existence of a broad line region (BLR) in objects with dominating narrow lines in their spectra. In order to find a simplified explanation for the diversity of observed spectra for AGNs, about 20 years ago Antonucci [1993]; Urry & Padovani [1995] proposed a unification scheme. In such unification scheme, all AGNs should share the same properties, which means they all should have a similar heating engine, but their observed differences, such as the presence or absence of broad emission lines, are determined by obscuration effects.
1.2 The unified model of AGNs

Although there are some exceptions, the standard model states that the nuclear environment of an AGN includes the following components:

- **The super massive black hole (SMBH) and the accretion disk.** The strong gravity around the central black hole attracts matter, some of which finally disappears into the black hole. The enormous release of gravitating energy from the accretion process is emitted at optical/UV/X-ray wavelengths generating the famous Big Blue Bump (BBB) characteristic of AGNs.

- **Relativistic jet.** A jet is a phenomenon in astrophysics, where particles are accelerated to speeds almost as great as the speed of light and form a stream typically divided in two narrow beams along the axis of rotation of the black hole. The highly beamed stream of matter propagates from the vicinity of the black hole out to parsec, kiloparsec and, in some objects, megaparsec distances. Because the medium in the accretion disc is highly ionized, the charged particles that are accelerated along the jet (due to magnetic fields) produce synchrotron radiation. The trapped magnetic field is capable in the accretion process to ultimatly give rise to the radio jets.

- **The Broad Line Region (BLR).** Surrounding the accretion disc, there is a region composed of high density ($\sim 10^{10} \text{ cm}^{-3}$) and highly ionized gravitationally bounded gas clouds with a column density of $\sim 10^{23} \text{ cm}^{-2}$. Due to their
proximity to the accretion disk, the clouds have typical velocities of order of 3000 km s\(^{-1}\) and it is reflected in the observed widths of the emitted emission lines. Because of the high density, forbidden lines are weak or absent.

- **The dusty environment.** At a few tenths of a parsec the strength of the radiation from the central engine drops down sufficiently that the dust can survive. The dust grains absorb the optical/UV radiation produced by the accretion disc and then re-emit the energy at infrared wavelengths, producing the typical observed infrared bumps in the spectral energy distributions (SEDs) of AGNs, which accounts for roughly half of the bolometric luminosity. Additionally, because the dust acts as an obscuring entity in the optical/UV regime, the dusty environment plays a significant role in the classification of AGNs.

- **Narrow Line Region (NLR).** Outside of the broad line region and extending out to a few parsecs, we find a region composed of clouds with low column density ($\sim 10^{20}$ cm\(^{-2}\)) and with a particle density of about $10^4$ per cm\(^{-3}\). The observed spectrum of this component includes intense forbidden lines, because of the low densities. These lines shift the cooling balance in such a way that the semi-forbidden and permitted lines are relatively weaker. Another group of lines that are predicted to be intense in the innermost part of this region are coronal lines, produced by fine-structure transitions and observed mostly in the infrared.

1.2.1. **The AGN family**

Although many subdivisions exist, the primary classification of AGNs is based on the extent to which the nuclear region is visible. The current classification of AGN includes a diverse number of sub-groups, but the typical division for the sub-groups can be summarized as follows:

1.2.1.1. **Type 1 AGNs**

The spectra of Type 1 objects show broad (1000 – 20,000 km s\(^{-1}\)) permitted and semi forbidden emission lines and a bright, non-stellar, central point source visible at all wavelengths. Almost all low to intermediate luminosity type 1 AGNs show strong, high ionization narrow emission lines, many of which are forbidden lines, while narrow emission lines are missing from the spectrum of many high luminosity type 1 AGNs. Additional sub-division (1.5, 1.8, and 1.9) exist inside this group, most of them based on the relative intensity of the broad and narrow components of the Balmer lines. Objects with broad Paschen lines, usually referred as intermediate objects, are referred to as type 1i. Some of the distinctions of these sub-groups might
not be caused by intrinsic differences in the central engine but they could also be caused by variability effects or obscuration from the host galaxy.

The high-luminosity type 1 objects, where the nuclear light outshines the surrounding galaxy, are often called Quasi-Stellar Objects (QSO’s) or quasi-stellar radio sources (quasars). The lower-luminosity objects are called Seyfert 1 galaxies.

1.2.1.2. Type 2 AGNs

This type of objects show strong narrow (300-1000 km $s^{-1}$) NIR/optical/UV emission lines that clearly show indication of photo-ionization by a non-stellar source. The absence of optical/UV continuum emission in Type 2 objects is in agreement with the idea that the dust obscures the BBB from the accretion disc. Typical strong lines are [O III] $\lambda 5007$, [N II] $\lambda 6584$, [O II] $\lambda 3727$, [O IV] $\lambda 25.9\mu m$, [Ne V] $\lambda 3426$, [C IV] $\lambda 1549$ and the hydrogen Balmer and Lyman lines. Type 2 AGNs are further divided into two subgroups: 1) Hidden type 1 sources with broad emission lines seen in polarized light and 2) ‘true type 2’ AGNs, although this class is less well defined. The latter subgroup members shows similar width and excitation narrow lines but no detectable broad lines and little X-ray absorption. Their mean luminosity is below the luminosity of the type 2 objects with hidden broad lines.

The lower luminosity type 2 objects, often hosted by spiral galaxies, are called Seyfert 2 galaxies, the higher luminosity types, often hosted by elliptical galaxies and discovered because of their radio emission, are typically Radio galaxies (RGs).

1.2.1.3. Low-Ionization Nuclear Emission-line Region (LINERs)

The spectra of these objects show low ionization, narrow emission lines from gas ionized by a non-stellar source and without presence or a relatively low contribution of high ionization emission lines. Typical strong emission lines in this group are [N II] $\lambda 6584$, [N II] $\lambda 6584$ and [S II] $\lambda 6731$, and the Balmer lines. Similar to Seyfert Galaxies, LINERs can be divided into type 1 LINERs with broad emission lines and type 2 LINERs with only narrow emission lines. Some but not all LINERs show point-like X-ray and UV sources and UV and X-ray variations [Maoz, 2007; Hernández-García et al., 2013].

1.2.1.4. BL Lac Objects

These are relatively low luminosity galaxies showing extremely high surface brightness, rapidly variable emission. These are interpreted to be AGNs viewed directly into their relativistic jets, which are responsible for the bright emission.
1.3. Investigating the dusty environment

As discussed in the previous section, dust is one of the main components of the unification theory of AGNs. In the strictest version of this theory, all types of AGNs are surrounded by an optically thick dust torus and are basically the same object but viewed from different lines of sight.

Therefore, the key factors in understanding the structure and nature of AGNs include the determination of the geometry of the nuclear obscuring torus and the obscuration properties of the circumnuclear dust. An accurate knowledge of the dust extinction properties is also required to correct for the dust obscuration in order to reconstruct the intrinsic optical/UV spectrum of the nucleus from the observed spectrum and to probe the physical conditions of the dust close to the nucleus.

Direct evidence for the presence of a dust torus is provided by infrared observations [e.g., Jaffe et al., 2004] but to properly interpret the observed infrared continuum emission and spectroscopy as well as the infrared images of AGNs, we require a good understanding of the absorption and emission properties of the circumnuclear dust. To achieve this goal, we need to know the composition, size, and morphology of the dust in order to compute the absorption and scattering cross sections of the dust from X-ray to far-IR wavelengths, and then calculate its UV/optical/near-IR obscuration as a function of wavelength, and derive the dust thermal equilibrium temperature as well as its infrared emission spectrum. This will allow us to constrain the circumnuclear structure through modeling the observed infrared emission and its spatial structure; which is critical to our understanding of the growth of the central supermassive black hole. However, still many properties of the dust in the circumnuclear torus of AGNs remains undetermined.

1.3.1. Observing the nuclear dusty emission

Although we are able to spectrally isolate the torus emission by observing in the infrared, many studies have shown that the infrared emission generated by the nuclear dust comes from a region of a few parsecs [see e.g., Alonso-Herrero et al., 2011; Asmus et al., 2014]. If we want to answer questions about the geometry of the dusty environment we cannot only rely on low spatial resolution observations. The small angular sizes (a few milliarc seconds) corresponding to the dusty torus are beyond the spatial resolution capabilities of any single telescope.

Neglecting atmospheric or instrumental effects, bigger telescopes produce sharper images. The angular resolution of a telescope is inverse proportional to the diameter $D$ of its aperture, $\theta \sim \lambda/D$, where $\lambda$ is the observed wavelength. Therefore, in order to reach the angular resolution required to resolve the infrared emission from the dusty environment we need single-aperture telescopes with mirrors of about hundreds of
meters in diameter. Building such giant telescopes is currently not feasible, but there is an alternative to this problem. Instead of having one single-aperture telescope with a diameter of hundreds of meters we could replace it with two or more telescopes, with much smaller diameters, separated by a hundreds of meters. By combining the light beams from several small telescopes using interferometry, we synthesize a large aperture and achieve the high resolutions required. A brief explanation on how an interferometer works is given in the following subsection.

1.3.2. Infrared interferometry

An interferometer combines two or more separate parts of the wavefront in order to produce an interference pattern. Since the telescopes are located at different distances, the light will not reach all the telescopes at the same time. Corrections to make the path lengths equal are applied so that the interferometric fringes are visible. These corrections are usually done by making the light to travel longer distances before combining the light. The crude part of this correction is to allow observations of objects all over the sky, not just those which are directly overhead. This is achieved by delaying one beam which allows to steer the interferometer. Additionally, due to atmospheric changes the length of the path that the light travels changes rapidly and randomly a few tens of microns. To compensate for such changes an allow the
integration of the light for long periods, a fringe tracking system is typically needed. The fringe tracking can be done on the scientific target or on a nearby reference star. Nevertheless the ability to track fringes is a difficult requirement and will usually set the limiting magnitude of the interferometer.

When we observe a distant object in this way, we see an interference pattern or interference fringes. These fringes arise because of the wave nature of light and they contain information about the object being observed. The signal recorded after combining the light is nothing else than the Fourier transform of the sources brightness distribution. The normalized value of the spatial coherence function $V$ is then equal to the normalized Fourier transform of the sky brightness distribution, $I$, this is formally written as

$$V(u, v) = \frac{\iint I(l, m) e^{-2\pi i (ul + vm)} dl \, dm}{\iint I(l, m) dl \, dm}, \quad (1.1)$$

where, $u$ and $v$ are the components of the baseline vector measured in wavelengths and projected onto the plane perpendicular to the incident wavevector, and $l$ and $m$ are angular co-ordinates on the sky. In interferometry, 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 visibility of fringes is a number between zero and one which measures the fringe contrast. It is defined as $V = (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}})$. If the fringes have a visibility of one we say the object is unresolved. If $V = 0$ there are no fringes and the object is completely resolved.

1.3.2.1. The MIDI instrument

Observations presented in this thesis as well as the data compiled from previous publications, were all observed with the MID-Infrared Interferometric Instrument [MIDI, Leinert et al., 2003] at the European Southern Observatory’s (ESO) Very Large Telescope Interferometer (VLTI) located on Cerro Paranal in Chile. For many years, the MIDI instrument probed to be the best and only option to resolve the infrared emission from AGNs.

The very large telescope interferometer (VLTI) is composed of four 8.2 m unit telescopes (UTs), and several 1.8 m auxiliary telescopes (ATs). The light received by the telescopes travels trough the tunnels 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 zero, the delay lines are equipped with mobile retroflector carriages which are able to move with a precision of a micron.

After the beam combiner, the beams pass thorough a dispersive element to generate a spectrum. Two available dispersive elements can be used in MIDI: 1) The low resolution *Prism* with spectral resolution $R \equiv \lambda/\Delta\lambda \sim 30$ and the *Grism* with
1.3 Investigating the Dusty Environment

Figure 1.3: Principle of the MIDI instrument. Image courtesy of ESO.

R = 230. As most of the AGNs observed with the instrument MIDI are quite faint, the Prism was used for all of them except for a few observations of NGC 1068.

For planning out the observations presented in this work we used the techniques and knowledge developed during previous AGN observations. For a very detailed explanation about the observing strategy, data reduction process, and analysis of the data we referred to Burtscher et al. [2012]. The reduction of the data was performed with the interferometric data reduction software MIDI Interactive Analysis and Expert Work Station [MIA+EWS\(^1\), Jaffe, 2004] which implement the method of coherent integration for MIDI data.

1.3.3 Dusty models

Because current interferometric observations do not provide true images of the infrared emission we need to build brightness distribution functions that suits the observed visibilities. This can be done by using known brightness distribution functions, such as Gaussians distributions, or build complex brightness distribution functions using radiative transfer methods. For this work we used both simple functions and images computed from complex dusty structures.

\(^1\)EWS is available for download from: http://home.strw.leidenuniv.nl/~jaffe/ews/index.html.
Current radiative transfer models of AGN tori are built using arbitrary prescriptions for the distribution of the dust in the model space and a broad family of numerical radiative transfer models has been developed [Schartmann et al., 2005; Dullemond & van Bemmel, 2005; Hönig et al., 2006; Schartmann et al., 2008; Nenkova et al., 2008a,b; Stalevski et al., 2012]. Despite the use of different assumptions or prescriptions, in general, AGN torus models share some fundamental similarities. These similarities are summarized in Figure 1.4. The model space is usually delimited by an inner radius $R_{\text{in}}$ and an outer radius $R_{\text{out}}$, where the inner radius is typically determined by the sublimation radius. The distribution of the dust in radial direction is typically defined by a radial power law distribution, $n(r) \sim r^{-\alpha}$ where $\alpha$ is the power-law index that defines compactness or shallowness of the dust or dust-cloud distribution. The typical geometrical thickness of the models which can go from homogeneous vertical distributions with a cut-off height or scale-height to Gaussian or power-law distribution functions. The absolute density or dust mass in the model space is defined by specifying one of these two quantities or by defining an optical depth value along a preferred line-of-sight as a normalization.

The advantage of radiative transfer models is their relative simplicity that makes it easy to simulate model grids. However, they do not contain any physical constraints of the environment. In order to study the dynamics of the gas and dust around the black hole in the region of the torus, a number of hydrodynamic models has
been developed with the goal to reproduce the mass distribution self-consistently
[Schartmann et al., 2009; Dorodnitsyn et al., 2011; Wada, 2012; Schartmann et al.,
2014]. Since most of them are computationally expensive, the task of providing
photometric observations or images for a wide range of parameters still needs to be
improved. On the other hand, since both densities and kinematics are predicted, the
models provide a physical basis for studying molecular lines on scales of several to
tens of parsecs.

1.4. This Thesis

In this thesis we study the mid-infrared emission produced by the nuclear dusty
environment of AGNs. We take advantage of the relevant information provided from
infrared interferometric observations to explore the geometry and properties of the
dusty region. Here is a brief summary of the contents of each chapter.

Previous interferometric observations of NGC 1068 revealed the existence of a hot
disc-like structure in the nuclear dusty environment, but its surrounding environment
was not fully revealed due to the lack of low resolution short baseline measurements.
We therefore obtained a new series of interferometric measurements to study the
missing scales. In Chapter 2 we present the observations obtained with the in-
strument MIDI in combination with the 1.8 m Auxiliary Telescopes. We analyze the
nuclear dusty environment of NGC 1068 combining the low and high resolution data.
We model the observed correlated fluxes and differential phases using offset Gauss-
ian distributions and found that at least half of the mid-infrared emission coming
from the central 600 milli arcsecond region is produced at a region at least 7 parsecs
away from the region where the nucleus of the AGN should be. We think that the
warm offset extended emission is consistent with dust heated along the walls of the
ionization cone.

In Chapter 3 we analyze mid-infrared interferometric observations of 23 objects
to retrieve additional geometric information. Individually observed objects have re-
vealed nuclear polar elongated emission attributed to dust instead of the expected
equatorial emission. We investigate our ability to identify elongated shapes with
respect to \((u, v)\) coverage and the signal-to-noise ratio. In 7 of the 23 objects, we
revealed with accuracy their geometrical shape at a first order. 5 objects have elon-
gated mid-infrared emission with its major axis closer to the polar axis of the system
than perpendicular to it. The other 2 objects are less elongated and their shape could
be consider as circular. A polar elongated emission supports the idea of a dusty-wind
environment rather than the classical torus-like structure.

Mid-infrared interferometric observations obtained with the instrument MIDI lack
true phase information. Without the phase information, it is difficult or even impossi-
ble to apply image reconstruction techniques. As an alternative, we use the brightness distributions obtained from 3-dimensional clumpy torus models to retrieve information about the dusty environment. In Chapter 4 we present a statistical analysis of a sample of sources. We find that the differences in type 1 and type 2 objects are too complex to be explained only by inclination effects or statistical variations of the clouds. We are able to explain each Seyfert type separately and the biggest difference between them is in the fraction of volume occupied by the dust. For type 1 objects, the observed interferometric visibilities are better explained by using a low number of clouds. Our findings suggest that at least two possible families of type 1 objects would be required. Although a larger number or a continuous transition between type 1s could also be possible.

In Chapter 5 we analyze in detail the mid-infrared emission of dusty clouds in order to learn more about the role of the optical thickness, the relative location of the clouds and inclination with respect to the observer. By analyzing the mid-infrared spectral index (8–12.5 µm) and the strength of the silicate feature we are able to provide an explanation for the observed differences in Type 1 AGNs. We find a correlation between the spectral index and the average location of the clouds that is hard to explain with an inclination effect. Our results suggest that the observed differences in Type 1 spectra are caused by size variations in the cloud distribution.

In Chapter 6 we investigate if there is any signature in the infrared produced as a response for a recent X-ray variability in the nuclear region of NGC 1068. The observed mid-infrared interferometric signal observed before and during the X-ray variations showed no clear changes. This suggests that the mid-infrared environment of NGC 1068 has remained unchanged for the last 10 years and that the X-ray variation detected with NuSTAR measurements is due to X-ray emission piercing through the dusty region.

In Chapter 7 we present a summary of the work done for this thesis. We present a brief discussion where we place our findings in the context of current research. We additionally discuss the implications of this work and the directions to pursue.