Mid-infrared imaging of dust in galaxies
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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2011

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Introduction

Galaxies are the building blocks of the universe. Held together by gravity, stars, dust and gas clouds are the main components of galaxies. When dust and gas clouds collapse under their own gravity new stars form. The mapping of dust, gas and stars and their kinematics across galaxies is thus vital for understanding their formation and evolution. Besides stars, dust and gas, galaxies host supermassive black holes. These black holes are located in the nuclei of almost all galaxies. Interestingly, their mass scales with the mass of their surrounding spheroids. This fundamental connection shows that the supermassive black hole and its host system must have formed in concert. A small fraction of galaxies have a very bright nucleus, with in some cases an energy output that exceeds the amount of radiation from all the stars in the galaxy. This energy is believed to arise from the accretion of matter onto the supermassive black hole. The complex central regions of active and inactive galaxies are thus an ideal laboratory for a study of the evolution and formation of galaxies.

In this thesis we try to gain a better understanding of dust — its occurrence and nature, spatial distribution, and temperature — in the central regions of galaxies within the context of galaxy evolution. To this end we obtained near- and mid-infrared images of 24 nearby early-type spiral galaxies with the space-based instruments IRAC and MIPS at Spitzer and high resolution mid-infrared images of 27 low redshift radio galaxies with the VISIR instrument at ESO’s VLT. These images can also be used to study the stellar emission of cool photospheres. In this Introduction we discuss dust as a tool to study star formation and active galaxies. Subsequently, we discuss different formation and evolution scenarios of galaxies. Finally, we give an outline of this thesis.
1.1 Star formation from interstellar matter

The space between the stars is not entirely empty. It is filled with a dilute gas, composed of hydrogen and helium, and dust grains, mostly silicates and hydrocarbons. Denser concentrations of this gas and dust, interstellar clouds, play an important role in the evolution of galaxies. The material in these clouds is the material that is expelled by dying stars and becomes the birthplace of new stars and planets.

1.1.1 Interstellar clouds

Although the dust grains in interstellar space are small in size and number, they are very effective in blocking light from objects behind it (Draine & Li 2001; Li & Draine 2001). The dust grains absorb and scatter the light that crosses their path. This process is called extinction; being wavelength-dependent it produces reddening. Interstellar cloud Barnard 68 is a good example of how strong extinction can be (Fig. 1.1). The dust density distribution map constructed from the near-infrared colours of the background stars shows that this interstellar cloud is a self-gravitating, isothermal sphere in hydrostatic equilibrium (Alves et al. 2001). The mass of this cloud is estimated to be $2 \, M_\odot$ and the cloud is 100 times bigger than the solar system. Next to absorbing stellar light, dust grains reemit this light. This emission can be detected at infrared to millimeter wavelengths. The spectrum of the reemitted light depends on the size of the particles and the heating source. The dust grains in Barnard 68 are very cold (10 K) and as a result their emission peaks at submillimeter wavelengths (Lada et al. 2003).

Dust grains are primarily formed when heavy stars explode, known as supernovae, or when giant stars blow off their outer layers. The fusion reactions in stars determine the chemical composition of dust in the interstellar clouds. In fusion, light elements collide and fuse into heavier elements, and release tremendous quantities of energy. The most common fusion reaction involves hydrogen burning into helium (Burbidge et al. 1957). In the biggest and heaviest stars ($M_* > 8 \, M_\odot$) the central temperature is higher, and the nuclear burning of heavier elements can occur in the following sequence: helium, carbon, neon, oxygen, silicon, magnesium and iron. Fusion reactions into other elements are rare. Condensation of the cooling gas around the dying stars creates tiny grains, nano- to micrometers in size, mostly silicates, like sand particles, and carbonaceous material, like coal or soot. That these two kinds of grains are the most common is known from absorption and emission features in the spectra of interstellar clouds, and from the fact that the gas emission lines for abundant heavy elements silicon, magnesium and iron are much weaker than they would be without depletion onto grains (e.g. Draine & Li 2007).

1.1.2 Star formation

The densest regions in the interstellar cloud Barnard 68 will eventually collapse under their own gravity and form new stars (Shu et al. 1987). The dust grains in interstellar clouds that are forming new stars, like in the Orion Nebula (Fig. 1.1), are heated by...
1.1 Star formation from interstellar matter

Figure 1.1: Left: BVIJK imaging of interstellar cloud Barnard 68. Obscuration by the cloud diminishes with wavelength. Credit: Alves et al. (2001) and ESO. Right: an UV-optical composite image of the Orion Nebula, the most nearby starforming region. Credit: ESO and I Chekalin.

Figure 1.2: Left: the spectral energy distribution at mid-infrared wavelengths of stellar light, star formation, and active nuclei. The IRAC photometric bands are shown at the bottom of the figure. Warm dust emitting in the PAH lines, and active nuclei, both appear red in the IRAC bands, while stellar light appears blue. The presence of CO absorption in the 4.5 µm band also results in cool, late-type stars having a bluer color [3.6]–[4.5] than earlier-type stars like Vega. Right: a schematic spectral energy distribution of starburst galaxy M 82, extending from the near-ultraviolet to the submillimeter. Credit: Fazio (2005); Kennicutt et al. (2003).

the proto-stars to temperatures of a few 100 K and their emission peaks at mid- to far-infrared wavelengths. This makes dust emission a good tool to trace star formation in galaxies (Kennicutt 1998, Calzetti et al. 2005, 2010). Especially, since at optical and UV wavelengths the star formation that gets absorbed by dust is untraceable. However, an advantage of UV emission is that it directly traces the emission from young and massive stars (> 5 M⊙). A complication is that these stars stay bright at UV wavelengths for a rather long time period (100 Myr). Optical emission lines (e.g. Hα, [O II]) do trace recent star formation: only stars with masses of > 10 M⊙ and lifespans of < 20 Myr contribute significantly to the ionizing flux. The disadvantage
of emission line and UV star formation tracers is, besides that dust extinction plays a role, that it requires an estimation of the initial mass function, the mass distribution of the newborn stars.

Three main components of dust emission contribute to the infrared spectrum of star forming regions and galaxies (Fig. 1.2). The first comes from polycyclic aromatic hydrocarbons (PAHs), which give a mid-infrared spectrum that rises with wavelength up to 13 µm and shows emission features that are associated with the heating of these particles. PAHs are large molecules, a few Ångström in diameter, consisting mainly of carbon atoms (Leger & Puget 1984). The second component is a steeply rising continuum longwards of 10 µm, arising from very small grains (VSGs) with sizes < 10 nm, that are heated to temperatures of ∼ 30 K and peak at far-infrared wavelengths. The third is a near-infrared bump, associated with hot dust particles with temperatures between 150 to 1 700 K, and which has to do with strong star formation or active galaxies.

Of these three components mid-infrared star formation tracers are the most reliable (Calzetti 2008). At far-infrared wavelengths dust from evolved stellar populations can contribute and make an accurate determination of the star formation rate difficult. Another problem is that in the far-infrared a broad spectral energy distribution should be sampled. The near-infrared bump is only related to sites of extreme star formation. Mid-infrared radiation is the best star formation tracer since it shows a good correlation with ionizing photon emission. The 24 µm emission and a linear combination of the 24 µm and Hα emission provide robust star formation tracers with uncertainties of a factor two. The 8µm emission is less reliable as a star formation tracer, since it traces the regions around rather than inside ionized regions, and depends strongly on variations in metallicity and stellar population mix.

1.2 Dust in galaxies

Galaxy evolution in the early universe is dominated by a combination of collapse of the first matter (Eggen et al. 1962) and the merging of the first galaxies (Toomre 1977). This evolution is thought to happen fast and violently, and result in two classes of galaxies: elliptical and lenticular galaxies on the one hand, and spiral and irregular galaxies on the other. Spiral galaxies consist of a flat disc with spiral arms surrounding a bulge of stars, resembling a small elliptical galaxy. Ellipticals are thought to be the result of the merging of several smaller or larger clouds of gas and stars followed by a period of intense accretion onto a black hole (e.g. Hopkins et al. 2008). This merging results in a very dusty galactic nucleus where stars are formed at a very high rate (10–100 M⊙/yr), known as a starburst or ultraluminous infrared galaxy (ULIRG). At the same time the black holes in the centre of these galaxies merge and start to grow rapidly, known as the quasar or active galactic nucleus (AGN) phase. This phase is thought to be related at first with extreme galactic winds of dust and gas, caused by supernovae and black hole accretion. Then, as the dust settles in the galaxy, a very bright optical nucleus plus relativistic jets in certain types start to dominate the galaxy light. When the star formation and quasar phase have ceased,
an elliptical galaxy is the end product.

In the nearby universe galaxy evolution is dominated by slow and calm processes (Combes et al. 1990; Norman et al. 1996; Kormendy & Kennicutt 2004). Large galaxies merge with small galaxies leaving the structure of the large galaxies relatively unchanged, or they rearrange their material from outwards inwards through large stellar bars or spiral arms. The mapping of stellar populations, star formation and gas and stellar kinematics across these galaxies is an important tool to study this evolution.

1.2.1 Star formation across the Hubble sequence

The morphological classification scheme of galaxies introduced by Hubble (1936) is still a fundamental method by which astronomers sort and compare galaxies, with only a few minor updates (de Vaucouleurs 1959; Sandage 1961; Kormendy 1979; Buta et al. 2010). This scheme, known as the Hubble sequence or the Hubble tuning fork, divides galaxies into four main classes: elliptical, lenticular, spiral and irregular galaxies. The elliptical galaxies (E) are sub-classified based on the ellipticity that they have on the sky. The spiral galaxies are subdivided in four classes (Sa, Sb, Sc, and Sd), depending on the relative size and brightness of their bulge and the degree of the winding of their arms. Galaxies with very loose arms and a very weak bulge are called late-type spiral galaxies (Sd), while on the other extreme early-type spiral galaxies have a bright bulge and tightly wound arms (Sa). More than half of the spiral galaxies have a bar of stars and gas that extends from the bulge towards where the spiral arms start. Lenticular galaxies (S0) have a bright central bulge surrounded by a weak disc without spiral arms.

The Hubble sequence follows the fundamental distinction between galaxies with and without interstellar starforming regions. Fig. 1.4 illustrates the Hubble tuning fork of galaxies as imaged in the infrared. Each galaxy is shown in three colours: blue, green and red. The blue colour represents the galaxy’s stellar emission at a wavelength of 3.6 $\mu$m, the green and red colour represent emission from dust heated by star formation at 8.0 and 24 $\mu$m. Late-type spiral galaxies are rich in star forming regions, while elliptical galaxies are rich in stars. The $[3.6] - [8.0]$ colour reflects the current star formation rate (SFR) per unit of stellar luminosity. This colour is found to monotonically increase with later Hubble type (Pahre et al. 2004a). This strong trend reflects an underlying trend in star formation histories of spiral discs in galaxies: late-type galaxy discs form stars at a roughly constant rate, while early-type spiral discs are characterized by a currently rapid declining SFR (Kennicutt 1998). Another mode of star formation occurs as circumnuclear starbursts in spiral galaxies, with the highest SFRs in early-type spiral galaxies, and seems related to the presence of a bar, and often co-occurs with an AGN (Kormendy & Kennicutt 2004; Knapen et al. 2006).

There are several ideas about the formation of the bulge. It is possible that the bulge in spiral galaxies is formed by the combination of protogalactic collapse at high redshift and the merging of galaxies, similar to how large elliptical-type galaxies are formed. However, most spiral galaxy bulges are likely to be formed by internal secular processes (Combes et al. 1990; Norman et al. 1996; Kormendy & Kennicutt 2004).
Figure 1.3: Schematic outline of the phases of galaxy evolution involving a major merger. The graphs show the star formation rate (SFR) and accretion activity of the supermassive black hole versus time. Credit: Hopkins et al. (2008).

Figure 1.4: The Hubble tuning fork in the mid-infrared. Credit: Spitzer Science Center.
Bars, oval distortions, spiral structures or nuclear black holes could bring matter from the disc inwards in isolated galaxies, that are undisturbed by mergers, and slowly build up bulges. The existence of almost bulge-less, late-type spiral galaxies are a clue that undisturbed galaxies exist. AGN, for which matter needs to flow into the centre, are uncommon in bulgeless spiral galaxies, and common in galaxies with bulges (Ho 2008). Apparently, as spiral galaxies get older their bulges and nuclear supermassive black holes are increasingly fed by material from the disc. This can be tested further by studying stellar populations of the disc and bulge, which in a secular evolution scenario would be similar. Bulges might have an additional component of fresh star formation due to gas flowing into the central region. Unfortunately, dust extinction, star formation and the relatively low surface brightness of spiral galaxies make it difficult to observationally study the nuclear activity, kinematic properties, and the stellar ages, and thus build-up, of the bulges and discs of galaxies.

1.2.2 The link between stellar populations and kinematic properties

In the first part of this thesis we focus on the star formation in early-type spiral galaxies. The sample we study is part of the SAURON sample of Sa galaxies. This is a well-studied sample of nearby galaxies and also includes lenticular and elliptical galaxies (de Zeeuw et al. 2002). It has been very well characterized at optical wavelengths using the SAURON integral-field spectrograph (Bacon et al. 2001) and the Hubble Space Telescope (HST). A wealth of information is available on the kinematics of stars and gas, stellar populations, dust and gas in the central regions of these galaxies (Falcón-Barroso et al. 2006; Peletier et al. 2007). This makes it an ideal sample to study in the near- and mid-infrared.

The SAURON studies of spiral galaxies have provided intriguing results. The kinematic maps reveal that more than half of the Sa galaxies have so-called sigma dips, i.e. local minima in their stellar velocity dispersions, in their centres. The data further show that this phenomenon is due to central stellar disks that are rich in gas and dust. These discs contain young stellar populations and often contribute most of the light in the central regions, implying that they are the objects that (Kormendy & Kennicutt 2004) call pseudobulges. These kind of bulges probably have had a different formation history, where the bulge is built from disc material via secular evolution. In this process material is funnelled into the central regions by bars. When the bulge becomes massive enough, the bar is destroyed, and the process starts again (Norman et al. 1996). In this way, one expects exponential bulge surface brightness profiles, the presence of cold/warm ISM, and young stars in the inner regions. Without spirals and bars, bulges can also form and even more quickly: simulations show that gas-rich discs will become clumpy and that these clumps will coalesce and produce pseudobulges through dynamical friction (Combes 2009).

The early-type lenticular and elliptical system have analogous central substructures; however this population is more diverse, containing not only stellar discs but also central components that are misaligned from the rotation in the main galaxy (McDermid et al. 2006). These kinematically decoupled components (KDCs) can be subdivided into large KDCs, generally found in non-rotating ellipticals without young
stellar populations, and smaller KDCs in fast-rotating ellipticals and lenticulars with young stellar populations (Kuntschner et al. 2006, 2010). A comparison with the mid-infrared images of this sample (Shapiro et al. 2010) reveals that in some of the fainter galaxies in which star formation is widespread across the central region, it is associated with counterrotating components and is thus likely due to minor mergers. In other, massive galaxies the star formation is concentrated into well-defined disc or ring morphologies, outside of which the host galaxies exhibit uniformly evolved stellar populations. This and the ubiquitous presence of corotating inner stellar discs implies that these star formation events are due to secular evolution. Despite this star formation, the galaxies show tight scaling relations between stellar velocity dispersion and optical and near-infrared colours ($V$–[3.6] and [3.6]–[4.5]) that trace stellar emission (Falcón-Barroso et al. 2011; Peletier et al. 2011). More massive galaxies are bluer in [3.6]–[4.5] colour. This can be explained as being due to CO absorption in the 4.5 $\mu$m band of cool, late-type stars with respect to stars like VEGA. Massive galaxies have more late-type metal-rich stars.

1.2.3 Circumnuclear dust in active galaxies

The amount of energy arising from the unresolved nucleus of an active galaxy is as large as the energy emitted by all of the stars in a galaxy. In extreme, rare cases, in quasars, the nuclear source is even a factor of a hundred or more luminous than the stars. Early attempts to understand the physics of these galactic nuclei (Woltjer 1959) still hold today: the emission comes from a very small region ($< 1$ pc$^3$), the black holes become dormant for some time, and their mass must be very high ($10^6 – 10^9 M_\odot$). It is now almost certain that most of this radiation is coming from the accretion of matter by a supermassive black hole. This is a very small region of space from which nothing, not even light, is able to escape. The matter that accretes towards the black hole gets compressed and rotates very fast, causing the highly energetic radiation, generally known as accretion disk. Circumnuclear dust plays a major role in the classification of the different types of active galaxies.

Active galaxy zoo

Active nuclei show extra components alongside the accretion disc, which make it difficult to understand their nature. In Fig. 1.5 a schematic picture of active nuclei is shown. Some of the active nuclei are accompanied by broad line regions very close to the centre. These are clouds that show ionized emission lines that are broadened due to their high velocity ($> 2000$ km/s). At larger radii there is less motion and the lines in these gas clouds are narrow ($< 1200$ km/s). Such narrow line regions are detected in all active galaxy types, and often show a large-scale coneshape. An opaque dust torus, that surrounds the accretion disc and the broad line region, perpendicular to this ionization cone could explain why some active galaxies show the broad central emission lines while others do not. The AGN classification is determined from whether the nucleus is oriented such that it is viewed unobscured (type 1) or not (type 2). Another division exists among AGN that have relativistic jets emitting at radio wavelengths,
1.2 Dust in galaxies

Figure 1.5: The different types of active galaxies can be explained by the orientation angle they are viewed on. The central supermassive black hole is surrounded by an accretion disc, broad line regions and a dust torus. Perpendicular to this torus a jet outflow and an ionization cone of narrow line clouds are other main components. This scheme may be a bit outdated, since FR-I radio galaxies probably lack dust tori. Credit: Urry & Padovani (1995).

so-called radio-loud objects, and AGN that do not, radio-quiet objects (Antonucci 1993). Radio-loud objects are usually found in elliptical galaxies, and radio-quiet objects are hosted by spiral and irregular galaxies.

Radio-quiet active galaxies

A large number of radio-quiet AGN in Seyfert galaxies (Seyfert 1943), are indeed dust-obscured. Since polarized light is a good indicator of AGN light, spectropolarimetric observations of type 2 Seyferts reveal hidden Seyfert type 1 broad line emission via reflection off material situated above the torus opening (Antonucci 1993). These observations suggest that the obscuring material is located between the narrow line region and the broad line region. From source statistics the angular extent of the dust obscuration can be determined. It is shown from a large sample of optical observations of Seyferts that the fraction of obscured AGN decreases with luminosity. For low-luminosity sources the ratio of type 1 and 2 Seyferts is 1:1, while at higher luminosities Seyfert 1 galaxies outnumber Seyfert 2 galaxies (Hao et al. 2005). This fraction \( f_2 \) of type 2 sources indicates that the torus, assuming it is optical thick, has an angular width \( w \) of \( w < \cos^{-1}(f_2) < 30 \text{ degrees} \). However, this optical study does not take into account type 2 sources that do not host a hidden type 1 source. Spectropolarimetric studies of some nearby objects indicate that up to a half of the
Seyfert 2 galaxies do not have a hidden broad line region (non-HBLR) \cite{Moran2007}, leaving 40 degrees for the angular width of the torus.

Direct evidence for torus emission can be found from infrared observations. The obscuring dust torus should reradiate in the infrared the fraction of nuclear luminosity it absorbs. Using infrared interferometry the tori in bright nearby galaxies are found to be small ($< 100$ parsec) and clumpy \cite{Jaffe2004,Tristram2009}. From a large set of infrared observations of Seyfert nuclei it can be inferred that all types, also non-HBLRs, are indeed surrounded by dust tori and that non-HBLRs have a lower activity level than normal type 2 Seyfert’s \cite{Haas2007}. In the most common class of radio-quiet AGN, characterized by low-ionization narrow emission line regions (LINERs\cite{Heckman1980}), both the dust torus and broad line region are absent. This is due to their nuclei being less active than those of Seyfert galaxies (see the review by \cite{Ho2008}).

Radio-loud active galaxies

Galaxies that were discovered since they were very strong emitters at radio wavelengths were found to have rich emission line spectra that are similar to Seyfert galaxies \cite{Bolton1949,Baade1954}. Broad line radio galaxies (BLRGs) and quasars are the radio-loud equivalent of Seyfert 1 galaxies, and narrow line galaxies (NLRGs) the equivalent of Seyfert 2 galaxies. Another class, that of the weak line radio galaxies (WLRGs), is equivalent to LINERs and they probably lack thick dust tori. Besides the viewing angle of the dust torus and accreting power, the orientation and morphology of the jet play an important role in the unification of radio-loud galaxies \cite{Barthel1989,Antonucci1993,Urry1995,Tadhunter2008,Antonucci2011}. When the radio jet has a substantial angle with respect to the observer’s line of sight, the galaxies are classified as radio galaxies (Fig. 1.5). At smaller radio jet angles radio-loud AGN show a steep or a flat radio spectrum plus highly variable emission of the inner jet and the object is classified as a quasar. Next to the optical classification of radio galaxies, they can be subdivided according to whether they have extended radio structures that are edge-brightened (Fanaroff-Riley class II objects) or edge-darkened (FR-I) \cite{Fanaroff1974}. FR-I radio sources have radio powers that are lower than those of FR-II radio sources. FR-I galaxies are dominantly WLRGs, and probably lack dust tori.

1.3 Thesis outline

In this thesis we examine star formation and supermassive black hole accretion in the central regions of galaxies. To this end we obtained near- and mid-infrared images of 24 nearby early-type spiral galaxies, as well as high resolution mid-infrared images of the nuclei of 27 low redshift radio galaxies.
Chapter 2

Star formation in the central regions of galaxies, in particular bulges, can be studied very well with Spitzer near- and mid-infrared broadband photometry. The SAURON sample of Sa galaxies is very suitable for such a study, since it has been very well characterized in the optical: kinematics, stellar populations, dust and gas. These properties can be compared with Spitzer probes of old stars, star formation, and active galactic nucleus emission (e.g. Shapiro et al. 2010; Peletier et al. 2011). We investigate why the spiral galaxies show such a large diversity in star formation and how star formation in the bulge depends on that in the disc.

Chapter 3

For understanding the nature and formation of bulges it is important to understand their properties. If there are two kinds of bulges, named pseudobulges and classical bulges, there should be an easy and straightforward way to classify them. We have studied Spitzer colours, S´ersic indices, SAURON stellar kinematics, ionized gas emission and absorption line indices to define a classification method that can classify pseudobulges in the SAURON Sa sample on a physical basis. We investigate questions like which method is the best. Is secular evolution a common process? Do stars form in central discs and rings for massive early-type spiral galaxies and in extended starburst structures in less massive early-type spiral galaxies, as is the case in the elliptical and lenticular galaxy sample?

Chapter 4

We investigate the nature of galaxy nuclei with a strong near-infrared [3.6]−[4.5] colour excess. Such red nuclei are present in 3/24 of the early-type spiral Sa galaxies from the SAURON sample. We compare the Spitzer colours of the complete set of 24 Sa nuclei with a few well-known nearby active galactic nuclei (M 51, 81, 87 and 104) and present new colour maps. The nearby active nuclei also show a near-infrared excess in comparison to normal nuclei which are dominated by stellar and star formation emission. This gives rise to the interpretation that this excess is related to supermassive black hole accretion. The near-infrared emission of active nuclei can be explained as arising from either hot dust or a power-law spectral distribution. We investigate whether 2-dimensional high resolution near-infrared imaging is an efficient way of finding low-luminosity active galactic nuclei.

Chapter 5

We investigate the quasar – radio galaxy unification scenario and detect dust tori within radio galaxies of various types. Using VISIR on the VLT, we acquired sub-arcsecond (∼0.40 arcsec) resolution N-band images, at a wavelength of 11.85 μm, of the nuclei of a sample of 27 radio galaxies of four types in the redshift range z = 0.006–0.156. The sample consists of 8 edge-darkened, low-power Fanaroff-Riley class I (FR-I) radio galaxies, 6 edge-brightened, class II (FR-II) radio galaxies displaying low-
excitation optical emission, 7 FR-IIIs displaying high-excitation optical emission, and 6 FR-II broad emission line radio galaxies. We find intriguing systematics on the presence of dust tori in relation with the black hole accretion rate and/or efficiency.