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DUST IN NEARBY MERGER-REMNANT RADIO GALAXIES

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June 2016

A dissertation submitted in fulfilment of the requirements for the Degree of Doctor of Philosophy
in the Department of Physics
UNIVERSITY OF JOHANNESBURG

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Abstract

Radio galaxies are clear evidence of relatively recent activity in the nuclei of their host galaxies. Most radio galaxies are giant gas-poor early-type galaxies, and some host active galactic nuclei (AGN) and contain significant amounts of dust in their central regions. Such dust is likely of external origin, injected during recent infall of low-mass gas-rich galaxies. Mergers might be a necessary condition for triggering AGNs, injecting dust, forming the radio sources and supermassive black holes, and ejecting radio lobes in such galaxies. The central regions of these radio galaxies therefore contain information about their recent activities and the interstellar medium content. Mid-infrared images are valuable tracers of the relatively recent (< 1 Gyr) history of the galaxies, both in terms of star formation and AGN activity, as well as the distribution of dust. Submillimeter images likewise reveal the content and the dust distribution of the interstellar medium.

In this thesis, stellar and dust properties of five merger-remnant radio galaxies of the southern hemisphere have been studied in the mid-infrared and submillimeter parts of the electromagnetic spectrum, using WISE imaging (3.4 μm, 4.6 μm, 12 μm, 22 μm; labeled W1 to W4), Spitzer spectroscopy (IRS 5.12 μm - 39.90 μm) and imaging (IRAC 3.6 μm, 4.5 μm, 5.8 μm, 8 μm and MIPS 24 μm), and APEX-LABOCA imaging (870 μm) data. The radio-loud NGC 1316 (Fornax A) and NGC 612 were studied in both the mid-infrared and submillimeter, and the compact-cored radio galaxies NGC 5078, NGC 7172 and IC 5063, in the mid-infrared. The WISE and Spitzer data were retrieved from the NASA/IPAC Infrared Science Archive (IRSA) database and the LABOCA data from observations made for this study. The properties of the dust and stars in these galaxies have been investigated using photometric measurements of the galaxies reported herein for the first time.

The stellar mass of the galaxies ranges from 75.8×10^{10} M_{\odot} for NGC 1316 to 0.8×10^{10} M_{\odot} for IC 5063. NGC 612 appears small in angular extent, but it is quite a massive galaxy with stellar mass of 40.7×10^{10} M_{\odot}, which is more than a half that of the giant NGC 1316. Of the galaxies, NGC 1316 has the lowest star formation rate of 0.7 M_{\odot} yr^{-1} compared to the 19.4 M_{\odot} yr^{-1} of IC 5063. The interstellar medium of IC 5063 is currently being converted to stars at a higher rate. The star formation rate of the lenticular galaxies (i.e., NGC 612, NGC 5078, NGC 7172 and IC 5063) is proportional to the amount of neutral hydrogen (H I) gas measured therein. The nucleus of NGC 1316 is currently dormant and the galaxy is likely to evolve into a passive elliptical. However, the lenticular galaxies (especially IC 5063
and NGC 612) are potentially growing larger disks as well as sustaining gas accretion into their central black holes.

A LABOCA 870 \(\mu\)m map of NGC 1316 is presented including its neighbour NGC 1317 (with a flux of \(34.0 \pm 13.0\) mJy). The flux within the central 2′ of NGC 1316 is \(113 \pm 17\) mJy. NGC 612 has also been detected as a point-like source (35.2 \(\pm 4.9\) mJy) with LABOCA, unresolved due to its distance. The NGC 1316 870 \(\mu\)m map shows a good agreement with the HST image; the northern and the southern dust concentrations coincide. Two-temperature model fits to homogenized flux density measurements from the near-infrared to the submillimeter band yielded dust mass estimates of \(5.3 \times 10^6\) M\(_{\odot}\) at 21.9 K and \(8.3 \times 10^5\) M\(_{\odot}\) at 55 K for NGC 1316; and \(5.3 \times 10^7\) M\(_{\odot}\) at 25.4 K and \(5.3 \times 10^8\) M\(_{\odot}\) at 59.6 K for NGC 612. A cooler dust component dominates in the both galaxies. NGC 612 has warmer dust compared to NGC 1316 due to the relatively high radiation field caused by the current star formation and the AGN activity.

To separate and characterize the stellar, AGN and dust contributions to the mid-infrared WISE emission of the galaxies, GALFIT (a two-dimensional image analysis programme) was first used to model the stellar component (W1) in NGC 1316 as a single and double Sérsic profile, and in NGC 612 as a Sérsic and Sérsic + Exponential disk profile. The AGN was modeled by point spread functions of the respective bands using an iterative procedure. The dust component in the W3 and W4 was modeled in two ways, namely through; (i) GALFIT and (ii) a scaling method. In the GALFIT method constrained two-dimensional fits were performed to the W3 and W4 images to model and subtract the starlight component, leaving the dust (together with the AGN) component. In the scaling method the W1 images were simply scaled by appropriate derived factors and subtracted from the W3 and W4 images, having been smoothed and adjusted to their respective angular resolutions. Due to the poor resolution, the W4 images are useful for global measurements, but not for detailed analysis such as the GALFIT modeling.

The dust distributions revealed by both the GALFIT and scaling methods are analogous to the dust emission in the respective optical images of the galaxies. The extra-nuclear W3 GALFIT and scaled dust emission of NGC 1316 coincides with two dusty regions north-west and south-east of the nucleus seen in extinction in the optical images, where molecular gas is known to reside. For NGC 612 the dust emission seen in the infrared comes from a warped disk and coincides with the dust lane visible in the optical images of the galaxy. The dust distribution suggests a recent infall onto NGC 1316 and disruption of one or several smaller gas-rich galaxies, but a smoother accretion in NGC 612. There is an eruptive activity in the nucleus of IC 5063. Notwithstanding, gas accretion into the lenticular galaxies are smoother. Spitzer spectroscopy shows that the 7.7-to-11.3 \(\mu\)m PAH line ratio is significantly lower in NGC 1316 than in NGC 612, an indication of nuclear activity intensity in the galaxies.

The GALFIT method of components separation works better in nearby (\(\leq 20\) Mpc) sources for unveiling the residual and dust maps in such nearby sources, but not distant ones. The scaling method is a better option. The galaxies represent interesting challenges to models of formation and evolution of galaxies and AGNs.


# Acknowledgements

The research included in this dissertation could not have been possible if not for the assistance, patience, and support of many individuals. I would like first and foremost to extend my deepest gratitude and a heartfelt thanks to my supervisors, Prof. Cathy Hovellou, Prof. Tom Jarrett and Prof. Hartmut Winkler, for the patience, motivation, inspiration, encouragement and the continuous support during my PhD study and related training programmes. I appreciate their vast knowledge and skills in many areas, which have added so much to my graduate experience. A very special gratitude to Dr. Michelle Cluver for the hospitality during my regular study visits to Tom at the University of Cape Town, and also for taking time out of her busy schedule to read through the entire manuscript of the dissertation.

Thanks to Zolt Levay and Paul Goudfrooij for making their HST image of NGC 1316 (Fornax A) available to me. and Chien Peng and Lauranne Lanz for their initial help with the GALFIT program. I sincerely thank Adrian Snyman of the Information and Communication Systems Department (ICS) at the University of Johannesburg for helping to address some of my software installation and computer challenges.

I acknowledge funding from the SKA (Square Kilometre Array) Africa Postgraduate Bursary Programme. This research would not have been possible without the financial assistance from the SKA Bursary Programme. I also acknowledge MIDPREP, an exchange programme between two European Institutes (Chalmers University of Technology in Sweden and ASTRON in the Netherlands) and three South African partners (University of Stellenbosch, Rhodes University and University of Cape Town), for sponsoring one of my annual study visits to Cathy at the Onsala Space Observatory in Sweden.

A big thank you to Prof. Roy Booth for introducing me to the SKA Africa Postgraduate Bursary Programme, and also for the encouragement during some challenging moments. I will not be able to convey my appreciation fully, but I owe Dr. Bernie Fanaroff, Ms Kim de Boer, Ms Rose Robertson and Ms. Deborah Letteka eternal gratitude for the different roles they played during the study period and also for facilitating the extension of my bursary duration for another year when it became necessary.

I am very grateful to Prof. Edward Akaho, Prof. Benjamin Nyarko, Prof. Shiloh Osa, Prof. Dickson Adomako, Mr. Felix Adeku, Mrs Margaret Ahiadek, Auntie Diana Djirackor and Mr. Eric Aggrey all of Ghana Atomic Energy Commission (GAEC), for the selfless and diverse help, supports, encouragements and parts played in seeing me through the doctoral
study.

To staff and students at the Hartebeesthoek Radio Astronomy Observatory, Onsala Space Observatory, and the Astronomy Department of the University of Cape Town, I say thank you for assistance during my regular visits. I must also thank colleagues and the staff at the Physics Department of the University of Johannesburg for the support and the bond of friendship that contributed in no small measure to the realisation of my dream.

I am very grateful to the unanimous examiners for the exceptionally thorough reviews, many constructive comments and finally rating my work worthy for the degree.

Finally, I would like to extend my deepest gratitude to Maa Afia, Abena Gyasiwa, Paa Kwasi, Obaapa Akua, Rev. Osei Fordjour and my entire family for the patience, encouragement and prayer support. And a very special thanks goes out to Nompumelelo Priscilla Sambo and Lusito Shongumusa Sambo whose love, support, provisions and understanding saw me through the extremely difficult times, without which I could never have completed this doctoral degree.

And to God Almighty be all the glory, honour and adoration for His faithfulness.
Plagiarism Declaration

I, Bernard Duah Asabere, know the meaning of plagiarism and declare that the work in this thesis is based on research carried out at the Department of Physics at the University of Johannesburg, the Astronomy Department of University of Cape Town in South Africa and the Onsala Space Observatory in Sweden. No part of this thesis has been submitted elsewhere for any other degree or qualification and it is all my own work unless properly acknowledged to the contrary in the text.
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Chapter 1

Introduction

Dust is ubiquitous in the interstellar medium (ISM) of galaxies, constituting about 1% of the total mass of the ISM (Draine 1990, Draine et al. 2007). Fundamentally, interstellar dust in a galaxy absorbs and scatters the galaxy’s short-wavelength starlight in the ultraviolet and optical bands. It subsequently re-radiates a large fraction of the absorbed galaxy’s energy into the mid-infrared, far-infrared and submillimeter parts of the electromagnetic spectrum. Consequently, dust dims and reddens the galaxy’s light in the ultraviolet and optical bands (i.e., it causes interstellar extinction), and enriches the emission in the longer-wavelength infrared and submillimeter regimes (e.g., Spitzer 1978, Blain et al. 2002, Draine 2009a). Notwithstanding the small proportion of dust in the total mass of the ISM, it contributes significantly to star formation, stellar evolution and the evolution of the ISM in total. It is therefore important in the evolution of galaxies (e.g., Alonso-Herrero et al. 2006, Calzetti et al. 2007, Cluver et al. 2014).

More than 30% of nearby massive early-type galaxies associated with galaxy-galaxy gravitational interactions (i.e., merger activities and/or gas accretion) host active galactic nuclei (AGNs), radio sources and significant amounts of gas and dust and some eject radio jets (see Merritt 1993, Kaviraj et al. 2007, Schawinski et al. 2007a,b, Bureau et al. 2011). Such peculiar galaxies have traces of recent (<1 Gyr) star formation (e.g., Yi et al. 2005, Draine et al. 2007, Leeuw et al. 2008, Dale et al. 2012). These studies negate the earlier belief that early-type galaxies were red and inactive with little interstellar medium and old stellar populations devoid of star formation potential and nuclear activity (Faber & Gallagher 1976, Thomas et al. 2005). Such galaxies in the local Universe are good candidates for detailed investigations and studies of dust properties, merger activities, an AGN’s feedback on the ISM, and galaxy formation and evolution.

This thesis aims to investigate the mid-infrared and submillimeter dust properties of a sample of nearby merger-remnant radio galaxies in the southern hemisphere. The properties of the stellar and other emission components (e.g., AGN) from the central regions of the galaxies in the mid-infrared will also be treated in the study.
1.1 Types of Galaxies

Galaxies are the building units of the observable Universe. They are gravitationally-bound systems consisting of gas, dust, stars, possible centrally-located (supermassive) black holes, and poorly understood dark matter and dark energy (Steinicke & Jakiel 2007). There are many isolated field galaxies in the visible Universe, but mostly galaxies are gravitationally bound in pairs, groups, clusters and superclusters. Moreover, galaxies come in a diversity of sizes, shapes, densities, appearances, stellar populations and internal structures, their spectrum being redshifted due to the expansion of the Universe (see Mo et al. 2010).

Having observed nearby massive and luminous galaxies in the optical waveband, Edwin Hubble in 1936 classified them into three main categories, namely: ellipticals (E), spirals and irregulars (Irr), which became known as the Hubble sequence or Hubble "tuning fork" of galaxy classification (see Hubble 1936; and also Figure 1.1). The spirals were further sub-grouped into two classes: normal spirals (S) and barred spirals (SB). Again, based collectively on the eminent appearance of the central bulge and tightness of the windings of the spiral arms, each spiral class was further divided into subtypes a, b and c. An intermediate class of galaxies between the ellipticals and the spirals is referred to as the lenticulars. These were further separated into ordinary (S0) and barred (SBO) lenticulars.

The Hubble galaxy classification (see Figure 1.1) was based primarily on the morphological appearance of the galaxies, but not on any evolutionary significance. However, the appearance of a galaxy depends on the observing wavelength, the resolving power of the observing instrument (i.e., image resolution), the depth of exposure, the inclination and the redshift of the galaxy in question. Intriguingly, along the sequence (i.e., E $\rightarrow$ S0 $\rightarrow$ S $\rightarrow$ Irr), bulge-to-disk ratio, galaxy mass and luminosity, and stellar population age all decrease whilst ongoing star formation, fractions of dust and gas contents increase: a trend earlier thought to depict a progenitor-to-descendant relationship (Toomre & Toomre 1972, Toomre 1977). In furtherance, Kennicutt (1992) revealed a trend in galaxies' integrated optical spectra along the Hubble sequence showing flattening of the continuum spectrum, increase in emission line strengths, gradual change in the composition of the absorption spectrum and decrease in absorption line strength for elliptical, spirals and irregular galaxies (i.e., E $\rightarrow$ Sa $\rightarrow$ Sc $\rightarrow$ Irr) in that order as shown in Figure 1.2 and also in Kennicutt (1998). The Hubble galaxy classification system is thus more popular and famous in contemporary astronomy than the subsequent revised and more specialised classifications (see Binney & Merrifield 1998).

According to the Hubble classification system, elliptical and lenticular galaxies are referred to as early-type galaxies, whilst the spirals and irregulars are known as late-type galaxies. In this study, attention will be given to the early-type galaxies.

**Early-Type Galaxies:** Early-type galaxies are in general dominated by old stellar populations (such as G-and K-type giants) with a depleted interstellar medium, molecular clouds, dust and gas. They are round or elliptical in shape with supposedly weak or non-existent
star formation potentials. Elliptical galaxies are particularly triaxial in outline with no spiral arms or disks, and have few hot bright stars. They are grouped into eight types: in the range E0–E7 (see figure 1.1), where the E0’s are nearly round and the E7’s very stretched out. Statistically, about 60% of all known bright galaxies are ellipticals (see Steinicke & Jakiel 2007). In a broader sense, elliptical galaxies may be classified into normal, dwarfs (smallest and less luminous), cD (massive and most luminous), dwarf spheroids and blue compact dwarf ellipticals. Often referred to as "armless and gas-stripped spirals or normal ellipticals with disks", lenticular galaxies can also be round or 'sombrero' shaped. They have central bulge and disk components, but no spiral arms; they were in the past believed to be spiral galaxies which had been stripped of their arms, gas and dust during collisions in galaxy clusters (see Spitzer & Baade 1951, Dressler & Gunn 1990). Their pivotal location in the Hubble "tuning fork", higher bulge-to-disk ratios, central bars and their dominance in clusters make them uniquely interesting objects for detailed studies (e.g., Burstein 1979, Naim et al. 1997, Hinz et al. 2003, Christlein & Zabludoff 2004).
Figure 1.2: Evolution of optical spectra along the Hubble sequence from elliptical to spiral and irregular galaxies. The galaxies are absorption-line (top) and emission-line (bottom) objects. Flux measurements on the vertical axes are normalized to unity at 5500 Å (Figure taken from Kennicutt 1992).

Late-Type Galaxies: Late-type galaxies include all the classes of spiral and irregular galaxies. They host younger stellar populations, gas and a dust rich interstellar medium, and may have ongoing star formation and nuclear (AGN) activity (Steinicke & Jakiel 2007, Bureau et al. 2011).

The Hubble classification (see Figure 1.1) works well for massive and luminous galaxies in fields and nearby small clusters, but has its own shortcomings. It fails to provide a useful framework for the classification of low-luminosity and low surface brightness dwarf galaxies, giant and diffuse cD galaxies, active and powerful radio galaxies, interacting, merging and star-bursting galaxies among others (see Binney & Merrifield 1998, Mo et al. 2010). Although the sequence offers hints about galactic structure, formation and evolution, and also gives a vivid picture of how galaxies can change from one type to another (see Toomre & Toomre 1972, Elmegreen 2006), the historic origin was purely nomenclature based on visual appearance and not on any evolutionary significance.
Other Classifications: Galaxies may also be classified based on the densities of molecular clouds in their interstellar media, age and star formation capabilities. Labels such as Dwarf Galaxies, Active Galactic Nuclei (AGNs), "Peculiar" Galaxies and Starburst Galaxies are also commonly used. Furthermore, galaxies may be classified based on their excess luminosities in the electromagnetic window where their radiation is measured. Hence we have Radio Galaxies, Infrared Galaxies, and Submillimeter Galaxies etc. Depending on their luminosities, infrared galaxies may be sub-divided into Hyper-luminous Infra-red Galaxies (HLIRGs: $L_{IR} \geq 10^{13} \, L_\odot$), Ultraluminous Infrared Galaxies (ULIRGs: $L_{IR} > 10^{12} \, L_\odot$) and Luminous Infrared Galaxies (LIRGs: $10^{10} \, L_\odot < L_{IR} < 10^{12} \, L_\odot$). Submillimeter galaxies are the dust-obscured high-redshift galaxy population and are the source of the extragalactic cosmic infrared background. Most of the submillimeter galaxies detected so far are identified as ULIRGs or LIRGs (Sanders & Mirabel 1996, Efstathiou & Siebenmorgen 2009, Rex et al. 2010).

1.2 Galaxy Mergers

Galaxy mergers have been occurring throughout the history of the Universe. Even our own Milky Way galaxy is presently undergoing a merger with several dwarf galaxies, including the Sagittarius Dwarf, the Canis Major Dwarf and the two Magellanic Clouds (Gómez et al. 2012a). Andromeda, our Galaxy’s closest large galactic neighbour located at about 2.5 million light-years ($\sim 0.77$ Mpc) from Earth, is a product of a merger which took place some 700 million years ago (Gilbert et al. 2007). The Andromeda galaxy is approaching the Milky Way at a speed of about $120$ km s$^{-1}$ and there is a possibility that the two will collide in approximately 4.5 billion years from now. According to recent simulations (e.g., van der Marel et al. 2012), the remnant of the predicted merger (nicknamed Mikulina or Mikiłdromeda) may turn into a giant elliptical or large disk galaxy. It is further postulated that in the distant future, the rest of the galaxies in the Local Group will merge into the Mikulina remnant (Chilingarian et al. 2010, van der Marel et al. 2012).

1.2.1 Merger Remnant Galaxies

Merger remnants are coalesced galaxies that are either completely relaxed or at different levels of relaxation after the merger events. They have signatures such as tidal tails or shell structures and loops, which indicate past dynamical interactions. NGC 1316 is one of the closest examples of a merger remnant galaxy (see Figure 1.3 and Section 2.2.1). Many studies on merger remnants (e.g., James et al. 1999, Genzel et al. 2001, Rothberg & Joseph 2004, Dasyra et al. 2006) focused on their stellar properties, due to the purported evolutionary link between spirals and ellipticals. However, the exact effects on their morphology and physical states, which depend largely on parameters such as composition, collision orbit, gas-richness, collision speed and relative size of the merging galaxies, are relevant to determine their dynamical properties and nuclear activities’ potentials.
1.2.2 What Happens During the Merger Process?

Galaxy mergers are purportedly the principal driving forces of galaxy assembly, massive starbursts, gas accretion into the centers of supermassive black holes, formation of radio sources, AGNs and massive spheroid-dominated early-type galaxies in both the nearby Universe and at high redshifts (e.g., Schweizer 1982, Mihos & Hernquist 1996, Hopkins et al. 2008). A merger scenario is an example of violent and dramatic galaxy interactions in the Universe. Galaxy mergers and interactions are fundamentally significant in astronomy because they display the act of galaxy formation and evolution over cosmic time. The increasing galaxy merger rate at higher redshifts (see Lin et al. 2004, Bridge et al. 2010, Kartaltepe et al. 2010, Ueda et al. 2014) therefore assumes cosmological significance.
1.2 Galaxy Mergers

The stars or star systems in galaxies are vastly distant from each other. Therefore the stellar systems in merging galaxies would only collide extremely rarely. The orbits of the stars in merging galaxies are however greatly distorted, causing them to completely lose track of their previous orbits during the turbulent merger and relaxation processes (van Albada 1982). The stars in a post-merger galaxy are in rather erratic disordered orbits as are observed in many bright elliptical galaxies (see Schweizer 1982, Rothberg & Joseph 2006). The dust and gas therein are greatly affected by frictional force during the gravitational interactions. Dust and gas that falls into the centres of the rapidly spinning colliding systems contribute to nuclear starbursts and formation of the spheroidal components, whereas constituents that survive the collision are transformed into gaseous disks and eventually to stellar disks (Springel & Hernquist 2005).

Merger hierarchical hypotheses (e.g., Toomre 1977), observations (e.g., Ueda et al. 2014) and computer simulations (e.g., Hopkins et al. 2008, Xu et al. 2010), and gas accretion along cold streams (Dekel et al. 2009) are still relevant for explaining the links between the dynamics and structures of many giant early-type galaxies. Signatures such as tidal tails, filaments of dust lanes and patches, shells, ripples, identifiable cores, misaligned rotation axes, multiple-nuclei and extended gaseous disks and bulges are attributes of merger aftermaths (e.g., Schweizer 1982, Somerville et al. 2001, Rothberg & Joseph 2006). Galaxy mergers spark massive starbursts and AGNs, and are often regarded as nearby analogues of massive galaxies in the early Universe. They have long been tipped as the evolutionary link between disk systems and elliptical galaxies (Naab & Burkert 2003, Di Matteo et al. 2008).

1.2.3 A Variety of Galaxy Mergers

Galaxy mergers can be categorized into three distinct groups based on the number: the relative size and the gas abundance of the participating merging galaxies.

Based on Number: When the merging takes place between only two galaxies, we refer to the system as a binary merger. Once the merger entails more than two galaxies it is known as multiple merger.

Based on Relative Size: The relative sizes of the merging galaxies are very crucial in galaxy mergers. It is the major determinant of the extent of the gravitational interactions and the nature and type of the resulting remnants after the merger process.

Minor mergers (i.e., merger between unequal-mass galaxies with mass-ratio of less than or greater than one) transpire when one of the partaking galaxies is markedly larger than the other(s). The larger galaxy usually "swallows" the smaller one, absorbing and engulfing almost all of its gas and stars. The minor merger event is commonly known as galactic cannibalism. Due to its large relative size, the bigger galaxy only witnesses minor effects and changes in its galactic system. The 3:1 mass-ratio mergers N-body simulation studies by Barnes (1999), Naab & Burkert (2001) and González-García & Balcárs (2004) are examples of minor mergers. Cosmological-scale numerical simulations and semi-analytic merge
models proposed that minor mergers played salient roles in triggering starbursts in the early universe (e.g., Somerville et al. 2001), accumulated mass onto galaxies (e.g., Guo & White 2008, Genel et al. 2009), and accreting the stellar haloes of massive galaxies (e.g., Bell et al. 2008).

Mergers between two equal-mass galaxies or two precursors of comparable masses (i.e., 1:1 mass-ratio mergers or mass-ratio of one) are called major mergers. Promulgated first by Toomre in 1977, subsequent studies (e.g., Mihos & Hernquist 1996, Hopkins et al. 2008, Di Matteo et al. 2008) have hypothesized and established peculiar massive elliptical galaxies as the end products of major mergers between two spiral galaxies.

Findings from recent studies by Robotham et al. (2013), De Propris et al. (2014) and Davies et al. (2015) have revealed that tidal turbulence and shocks during the early stages of merger events could result in enhanced star formation in the merger remnants (both major and minor) formed by massive galaxies. Even at the later phases of the merger, star formation is most probably boosted, since both (massive) galaxies have sufficient mass (relative to the other) to conserve their gas. However, the gas in low mass mergers may be tidally stripped off, heated or merely stretched to a lower mean density, and may not be enough to trigger star formation; hence, star formation is quenched in low-mass mergers (i.e., both major and minor). The star formation potentials of merger remnants are in agreement with the merger simulation by Di Matteo et al. (2007).

**Based on Gas Abundance:** To a larger extent, the star formation histories, stellar mass growth and morphologies of the resulting merger remnants depend on the richness of gas contents in the participating merging galaxies (Lin et al. 2004, Bluck et al. 2009). On the basis of gas abundance in the resulting galaxies, galaxy mergers may be identified as wet, dry, mixed or damp.

A *Wet merger* is the merger between gas-rich galaxies. They mostly trigger intense formation of stars, powerful radio sources and active galactic nuclei (AGNs). It is believed that wet mergers transform disk galaxies into elliptical galaxies. The merger between gas-poor galaxies is called a *dry merger*. These mergers exhibit little ongoing star formation before, during and after the merger event. They however contribute immensely to the stellar mass build-up and are potential contributors of mass assembly of present-day massive elliptical galaxies (Jonsson et al. 2005, Lin et al. 2007).

A *Mixed merger* occurs when gas-rich and gas-poor galaxies merge. Depending on the gas-mass fractions of the colliding galaxies, mixed mergers may have star formation potentials and support stellar mass assembly of resulting merger remnants: their properties lie in-between wet and dry mergers. Also known as wet-dry mergers, *damp mergers* are the merger between wet and dry merger galaxies. In general, not much is known about their behaviour. There may be sufficient gas in damp mergers to fuel significant star formation, but not enough to form globular clusters (van Dokkum 2005, Lin et al. 2008).
1.2.4 Outcomes of Mergers

The galaxy merger sequence presented by Toomre (1977) is based on the idea that major mergers between disk galaxies form giant elliptical galaxies (e.g., Barnes & Hernquist 1992, Hernquist 2000) and minor mergers result in lenticular galaxies (e.g., Naab & Burkert 2003).

![Merger sequence simulation of two spirals to form an elliptical galaxy.](image)

Figure 1.4: Merger sequence simulation of two spirals to form an elliptical galaxy. It shows the pre-merger, merger and post-merger stages which occur over a timescale of about 2.4 Gyrs (Credit: Springel and White at the Max Planck Institute for Astrophysics, Garching, Germany).

This proposition is supported by merger signatures such as ripples, tidal features and
shell structures associated with peculiar elliptical galaxies (Schweizer 1996). Numerical simulations (e.g., Figure 1.4) and merger models indicate clearly that some giant ellipticals do form from major gas-rich (disk) mergers in accordance with Toomre’s early work (also see Barnes 1992).

Contrary to the classical merger evolution scenario (i.e., Toomre’s sequence), high-resolution numerical simulations of gas-rich disks that incorporate realistic gas-mass fractions of the progenitors have shown that not all major mergers result in the formation of early-type galaxies. Some turn into disk-dominated late-type galaxies (see Hopkins et al. 2006, Robertson & Bullock 2008, Xu et al. 2010). In the instances of sufficient gas-mass fractions, some gas will survive the collision without losing angular momentum through the stellar torques. The surviving gas portion first forms gaseous disk and subsequently a stellar disk or a disk galaxy (Springel & Hernquist 2005).

A more recent study (Ueda et al. 2014) using a combination of current observational data from ALMA (Atacama Large Millimeter/submillimeter Array) and a number of radio telescopes confirms that major mergers of spiral galaxies result in giant disk galaxies as well.

1.2.5 Relevance of Galaxy Mergers

New studies (e.g., Di Matteo et al. 2008, Robotham et al. 2013, De Propris et al. 2014, Davies et al. 2015) continue to show the complicated nature and impacts of sizes, masses and wetness differentials of the merging systems and the phases and feedbacks of interactions during the merger events. Notwithstanding, it remains that remnants of galaxy mergers are associated with rapid star formation, active galactic nuclei, radio sources, nuclear activity, and physical and morphological disturbances which are attributes of many observed galaxies. The merger sequence from simulations (e.g., Figure 1.4; also see Figure 13 of Di Matteo et al. 2008) further depicts a plausible galaxy evolution over cosmic time. Therefore, direct observations and in-depth studies of galaxy merger scenarios and rates will pertinently nourish our understanding of the very important yet poorly-understood processes in galaxy formation and evolution.

1.3 Galactic Interstellar Dust

Dust grains are ubiquitous in the interstellar medium of galaxies. They are a mixture of amorphous silicates, carbonaceous (e.g., graphites) and small amounts of polycyclic aromatic hydrocarbon (PAHs) molecules, which span over a wide range of sizes (Tielens 2001, Draine & Li 2007). From the thermodynamics and chemistry of interstellar gas to the dynamics of star formation, dust grains play significant roles in the interstellar medium of galaxies (Blain et al. 2002, Tielens 2012). They absorb the energetic short-wavelength ultraviolet and optical radiation from stars, ionized gases in the ambient interstellar medium and stellar birth clouds. They subsequently re-radiate about 90% of the absorbed starlight into the longer wavelength infrared and submillimeter bands of the electromagnetic spectrum (Tielens et al.
1.3 Galactic Interstellar Dust

The infrared emission from galaxies is therefore understood to come from three main constituents of interstellar dust: molecular PAHs, very small grains (with average sizes less than 0.01 \( \mu m \)) and the big grains (with sizes ranging between 0.01 and 0.25 \( \mu m \)). The submillimeter emission from galaxies is generally emitted by the cold component of interstellar dust grains in thermal equilibrium at low temperatures in the diffuse interstellar medium (Draine & Lee 1984. Leger & Puget 1984).

1.3.1 Formation and Redistribution of Dust Grains

The interstellar dust grains are believed to form when heavy elements (such as C, Al, Ca, O, Mg, Fe, Ni & Si) released by mass loss during stellar evolution and ejecta from supernova explosions condense in the interstellar medium (Stecher & Donn 1965, Meikle et al. 1996). Dust may be formed elsewhere in the interstellar medium, but commonly in the circumstellar envelopes of the evolved relatively low-mass stellar population. Such environments with a high concentration of heavy elements, within a critical temperature range and dense conditions, are suitable for the formation and growth of dust grains (Whittet 1992, Johnson & Li 2012). Dust grains are also formed during nova outbursts (Smith et al. 1994). Furthermore, accretion of heavy metals results in grain growth and hence dust formation in the interstellar medium (Draine 2009a). Interstellar dust is therefore not only formed in the atmosphere of low-to-intermediate-mass stars on the asymptotic giant branch (AGB), but also in the ejecta of high-mass stars. Thus one mechanism is associated with evolved stars, the other with star formation regions.

High-velocity shocks or waves from supernova blasts destroy the dust grains through shattering and sputtering processes (Jones et al. 1994, Bianchi & Schneider 2007). On average, the lifetime of interstellar dust in a galaxy (e.g., the Milky Way) is on a time-scale of about 500 million years and the mean dust injection timescale from low-to-intermediate-mass stars is approximately 2000 million years (Jones et al. 1996, Draine 2009b). This signifies a positive dust-balance. Although in some galaxies the rate at which dust is perceived to be formed appears to be less than it is destroyed, galaxies have positive dust growth. The positive dust-budget is restored by the net contribution of the initial supernova formation, the aftermath blast waves and/or the protective icy mantle layers formed on the surface of dust grains (Tielens & Allamandola 1987). The icy mantles on the surface of dust grains are sputtered during supernova blast shocks. They cover the dust grains but do not destroy them (Barlow et al. 2012, Gómez et al. 2012b). However, the mechanism of dust-budget is not well understood.

Gravitational interactions and mergers play significant roles in dust redistribution in galaxies. During merger and/or gas accretion activities (involving dusty galaxies), dust grains are injected into the galactic centres and the interstellar medium of the remnant galaxies formed (e.g., Sage & Galletta 1993, Lanz et al. 2010). This is commonly observed in early-type galaxies and more rarely also in disk galaxies. A typical example is NGC 1316 which will be looked at in this study. Dust-rich gas injection during galaxy interactions
is conducive to star formation, active galactic nuclei feedback and other nuclear activities as witnessed in some early-type galaxies (Werner et al. 2004a, Hopkins & Quataert 2010). Moreover, dust grains and PAH molecules are destroyed by powerful radiation fields, notably in AGN.

1.3.2 Heating Sources and Phases of Galactic Dust Grains

The overall emission from dust in galaxies has also been summarised by Charlot & Fall (2000) and da Cunha et al. (2008) as coming from four main dust components: (i) the emission from PAHs; (ii) the mid-infrared continuum from hot dust; (iii) the emission from warm dust in thermal equilibrium; and (iv) the emission from cold dust in thermal equilibrium, in the wavelength range 3–1000 μm.

With the advent of sensitive and high-resolution infrared and submillimeter observational instruments (such as Spitzer, WISE, Herschel, APEX-LABOCA and ALMA), dust in galaxies can be studied in detail. In the interstellar medium, galactic dust does not exist in isolation, but in mixed-up environments with the cold atomic gas, molecular gas and the hot neutral gas in the photo-dissociation regions. This suggests that there are different heating sources and phases of the dust grains (Tielens 2010).

Star formation is a key heating source of galactic dust, as attested to by the fact that starburst and interacting galaxies are strong sources of infrared emission. Radiation fields from older non-ionizing stellar populations also contribute significantly to dust heating in galaxies (Cox & Mezger 1989, Sauvage & Thuan 1994). Moreover, the intense radiation from active galactic nuclei due to mass accretion onto the central supermassive black holes may also be a heating source (Pety et al. 2005, Rogers et al. 2007).

Van der Hulst (1997), in his review on The Interstellar Medium in Galaxies describes in detail the three main dust phases, namely the hot, warm and cold dust phases. These multiple dust phases are associated with their respective types of galaxies, stars, gas content and star formation potentials in various components and regions of the interstellar medium. Thus, the distribution of dust temperature in a galaxy reflects the different nature and environment of the dust grain components therein.

The hot dust phase (with dust temperature $T_d > 55$ K) falls in the mid-infrared band ($\lambda = 10 - 40 \mu m$) of the electromagnetic spectrum. The total emission in this wavelength band is believed to come from a mixture of radiation from PAHs (i.e., polycyclic aromatic hydrocarbons: see Section 1.3.3), hot dust grains in thermal equilibrium with massive hot stars, HII regions and compact sources (i.e., powerful radiation sources such as radio sources and active galactic nuclei). The radiation from this range (i.e., $\lambda = 10 - 40 \mu m$) has also been associated with star formation (see Calzetti et al. 2005, Alonso-Herrero et al. 2006, Rieke et al. 2009, Rujopakarn et al. 2012, Jarrett et al. 2013, Cluver et al. 2014). However, the mid-infrared emission in galaxies with AGN (e.g., radio galaxies) is typically from hard non-thermal sources which may not be directly related to star formation (Jarrett et al. 2011).

The warm dust phase ($25 < T_d < 55$ K) has emissions peaking around 60 μm. This range is similar to the emission from the spatially resolved IRAS 60 μm band. Star formation
cannot be completely dissociated from this dust phase emission, but the main contributors here are the evolved stars in very strong interstellar radiation fields (Smith et al. 1994, Sauvage & Thuan 1994). The warm dust component is mostly located on the outskirts of molecular clouds, away from the intense ultraviolet and optical radiation from high mass stars. Emission from this component is very little in galaxies with insignificant star formation activity. The bolometric luminosity of nearby star-forming galaxies is mostly due to the thermal mid-infrared emissions from warm dust (Dale et al. 2007, Draine 2009a).

The cold dust phase (10 K < \(T_d\) < 25 K) is mainly observed in the far-infrared and submillimeter/millimeter wavelength regime (\(\lambda > 100\) \(\mu m\)). It is normally viewed in conjunction with the emission from the warm component towards the shorter wavelength ends. The cold dust grains which constitute a large fraction of the galaxies' total dust mass are associated with the molecular gas phase rather than the atomic gas phase, and are shielded from intense heating by molecular clouds (e.g., Weiss et al. 2008, Galametz et al. 2012).

### 1.3.3 Polycyclic Aromatic Hydrocarbons (PAHs)

The unusual broad infrared emission features (sometimes referred to as the unidentified infrared band) between 3 \(\mu m\) and 19 \(\mu m\) discovered in the spectra of galactic planetary nebulae in the early 1970's (Gillett et al. 1972; 1973) remained a mystery until a decade later when PAHs were proposed as the source of such emission features (Leger & Puget 1984, Allamandola et al. 1985, Clemett et al. 1993). PAHs are aromatic molecules of organic materials found in the interstellar medium of the Milky Way and in most extragalactic environments with recent or ongoing star formation (Rhee et al. 2007, Witt et al. 2008, Cordiner et al. 2008). They provide much of the photoelectrons which heat up the interstellar gas in many ionised stellar environments (Weingartner & Draine 2001, Draine & Li 2007).

PAH molecules have varying compositions and size distributions which inevitably affects their emission spectrum (Peeters et al. 2004, Sáramá 2008). The longer wavelength PAH emission emanates from the larger PAH grains and vice versa. Emission from PAH molecules peaks at the interface between molecular and ionized gas in the photo-dissociation regions, at the outskirts of the HII regions (Hony et al. 2001, van Diedenhoven et al. 2004). In these regions of efficient transient heating, the non-ionizing ultraviolet radiation from young stellar populations dominates. Molecules such as \(H_2\) and CO dissociate, but the PAH molecules could survive (Verstraete et al. 1996, Hollenbach & Tielens 1997, Jolbin et al. 2005). PAH molecules will be referred to interchangeably as small grains in this thesis.

### 1.3.4 Emission and Destruction of PAH Molecules

As an interstellar dust component, PAH molecules absorb ultraviolet and optical photons from starlight and ionized gas and re-emit vibrational thermal emission into the mid-infrared wavelength band. The thermal emission spectra of PAHs in the mid-infrared regime primarily peak at 3.3, 6.2, 7.7, 8.6, 11.3 & 12.7 \(\mu m\) wavelengths (see Sellgren 1984, Allamandola, Tielens & Barker 1985; also see Figure 1.5). The reprocessed emission from PAHs is a
PAHs are destroyed by strong interstellar radiation fields such as exist in HII regions, high-luminosity AGN hosting systems and nuclei of starburst galaxies (Peeters et al. 2002; Micelotta et al. 2010). The intense radiation in luminous active galactic nuclei destroys the small PAH grains or saturates their emission bands with the hot dust component. Also, low-luminous AGN produce unusual PAH emission spectra with reduced or missing band features and minimised PAH luminosity. Moreover, high metallicity favours emission in the long wavelength PAH bands. Therefore the presence of both high metallicity and luminous AGNs will destroy the small PAH grains and shift the dust emission features towards the longer wavelength region. Furthermore, silicate extinction or absorption troughs around the wavelengths 10 μm and 18 μm affect the PAH emission spectrum, and the NeII blends with the 11.3 μm PAH (see Smith & Newnham 2000, Smith ???). In such PAH molecules destroying and suppressing environments, PAH emission is a poor (under-estimate) tracer of star formation (see Martín-Hernández et al. 2003, Draine et al. 2007).
1.3.5 The Relevance of Dust Grains in the ISM

Interstellar dust grains are crucially important in understanding the evolution and the current states of galaxies in the Universe. As mentioned in Section 1.3, interstellar dust helps in the cooling of the interstellar medium by shielding regions of space from starlight with its extinction and re-radiative effects. Dust shielding causes suppression of molecular photodissociation in the dust-dominant regions of space and in effect provides the cooled environment for the formation of stars and molecular hydrogen. Dust extinction thus results in the removal of some of the elemental constituents (e.g., Fe, Si & Ni) of galactic gas, thereby depleting the gas and making some elements very rare in the gas phase. In regions dominated by starlight, the energetically fast moving electrons are generated by photoelectric effects. These electrons serve as the heating sources. Dust grains therefore act as both sources and sinks of molecules, and effectively couple the starlight energy to the gas phase (Krieger 2003, Draine 2004).

Moreover, the chemistry of the interstellar medium depends to some extent on the presence of molecular hydrogen (H$_2$), which forms predominantly on the surface of dust grains and acts as a chemical catalyst (Draine & Li 2001, Tielens 2012). Ice mantles and hydrides are also believed to form on dust grain surfaces in low density spatial regions (Barlow et al. 2012). Ice mantles for instance remove molecules other than H$_2$ from the gas phase and thereby contribute to the depletion of heavy molecules in the gas phase. This presents a good picture of the early Universe when dust grains were scanty in the era dominated by population III stars (Willner et al. 1982, Merrill 1988), and sparks the importance of dust grains in galaxy evolution studies. Population III stars are the very first generation of stars formed within a galaxy, which comprise of the primordial hydrogen and helium gas, and trace amounts of lithium and beryllium.

1.4 Interstellar Dust Emission Model

The emission from dust grains spans over the wavelength range 3 -1000 $\mu$m (i.e., from infrared to submillimeter regime) and comes from four main components: PAH molecules, mid-infrared hot dust, warm dust and cold submillimeter dust. The distribution of dust’s emission in the above wavelength range is in response to the absorption of starlight by the dust grains in the stellar birth clouds and the diffuse interstellar medium. Dust subsequently re-emits about 90% of the absorbed starlight. Continuum thermal emission from dust takes the form of a modified blackbody spectrum (known also as greybody), with peak temperatures ranging from 15 to 200 K. The dust temperature depends on the stellar activity, dust grain sizes and distributions, and the interstellar radiation field intensity in the region under consideration (Charlot & Fall 2000, Kennicutt et al. 2003, Draine 2009a).

The measured flux density $S_\nu$ at frequency $\nu$ of the continuum thermal dust emission in the optically thin case is given by:
\[ S_\nu = B_\nu(T_d)(1 - e^{-\tau_\nu}) \Omega_s \]  

(1.1)

where \(\tau_\nu\) is the dust optical depth, \(\Omega_s\) the source solid angle and \(B_\nu(T_d)\) is the Planck function at the dust temperature \(T_d\). However, unlike in the submillimeter and millimeter range, the optically thin approximation sometimes does not give better results in the far/mid-infrared wavelength band.

In situations where there is background radiation such as modelled by Weiss et al. (2008), which takes into accounts the background emission due to the cosmic microwave background (CMB) at average temperature 2.725 K, the above equation may be expressed as:

\[ S_\nu = (B_\nu(T_d) - B_\nu(T = 2.725\, K))(1 - e^{-\tau_\nu}) \Omega_s \]  

(1.2)

The dust optical depth may be defined as:

\[ \tau_\nu = \frac{\kappa_d(\nu) M_d}{D^2 \Omega_s} \]  

(1.3)

where \(\kappa_d\) is the dust absorption coefficient, \(M_d\) the dust mass and \(D\) is the distance to the galaxy. Krügel & Siebenmorgen (1994) defined a relationship between frequency \(\nu\) and dust absorption coefficient \(\kappa_d\) as:

\[ \kappa_d(\nu) = 0.04(\nu/250\, GHz)^\beta \]  

(1.4)

where emissivity index \(\beta = 2\) (see Priddey & McMahon 2001).

For data spanning over a wider wavelength range (such as from near-infrared to submillimeter), the spectral energy distribution can be fitted with more than two temperature components to estimate the parameters of interest.

Assuming the optically thin emission approximation over all wavelengths, such as in the submillimeter/millimeter wavelength range (Beuther et al. 2002), the emission from the dust may be modelled using the two-temperature modified blackbody (greybody) expression of the form:

\[ S_\nu = N_w \lambda^{-\beta_w} B_\nu(T_w) + N_c \lambda^{-\beta_c} B_\nu(T_c) \]  

(1.5)

where \(S_\nu\) is the observed flux density, \(\beta_w\) and \(\beta_c\) are the dust emissivity indices for the respective warm \((T_w)\) and cold \((T_c)\) temperature components. \(B_\nu(T)\) is the Planck function at the temperature of interest, \(N_w\) and \(N_c\) are normalized constants that relate to the approximate dust masses of the warm and cold dust components respectively (see Dunne & Eales 2001). All the parameters may be evaluated by fitting Equation 1.5 or through statistical evaluation.

With the best-fit parameters from the spectral energy distribution fit to Equation 1.5, the dust masses of the various components may be estimated (Hildebrand 1983, Draine 1990) using the equation
\[ M_d = \frac{S_\nu D^2}{k_\nu B_\nu(T_d)} \]  \hspace{1cm} (1.6)

where \( D \) is the distance to the galaxy, and \( k_\nu \) is the dust absorption coefficient (dust opacity). \( S_\nu \) is the observed flux density and \( B_\nu(T_d) \) is the Planck’s constant at dust temperature \( T_d \). The dust component mass \((M_d)\) and \( T_d \) have continuum of values. Considering two dust components (e.g., warm and cold), Equation 5.2 may be expressed as:

\[ M_{d \text{ total}} = \frac{S_\nu D^2}{k_\nu} \left[ \frac{1}{B_\nu(T_w)} + \frac{1}{B_\nu(T_c)} \right] \]  \hspace{1cm} (1.7)

### 1.5 Star Formation in Galaxies

Star formation is an important phenomenon in galaxy structure and its evolution. It mutates giant molecular clouds of cold gas and dust in galaxies into stars, thereby diversifying the stellar populations and enriching the metallicity of the interstellar and intergalactic medium. Star formation through observations (e.g., Barger et al. 2000, Wilson et al. 2002, Giavalisco et al. 2004, Norman et al. 2004, Chapman et al. 2005, Hopkins & Beacon 2006) and modeling (e.g., Springel et al. 2005, Kennicutt et al. 2007) are ways of visualising galaxy formation and evolution.

Molecular clouds in a galaxy can be impacted by supernova explosion shock waves to cause parts of them to collapse under gravity and form stars. Also, rotation of a galaxy, such as the Milky Way, can cause molecular clouds to pile up and precipitate collisions between such piled-up clouds, which may eventually collapse under gravity to form stars. Moreover, large-scale galactic bars in disk galaxies drive outer gas inflow into the regions around the nuclei (Hao et al. 2009, Ann & Thakur 2005). Gravitational interactions in these larger systems then transfer the dense gas angular momentum to trigger central star formation and AGN activity (Sharma & Steinmetz 2005, Oh & Kroupa 2012). With adequate amounts of dense gas in a galaxy, star formation could be triggered by either/both internal and external processes.

Gas (together with dust) is the essential constituent that fuels star formation in galaxies: a prerequisite to understand the structure and evolution of galaxies. Gas in galaxies is of external origin, accreted through mergers and/or interactions with neighbouring galaxies, or internal as a by-product of the cooling of the hot interstellar medium that originates from stellar mass loss (Kim & Fabbiano 2003). Galaxies need continuous and fresh gas accretion to sustain their current star formation. Does that happen through mergers or galaxy-galaxy interactions or accretion through the intergalactic medium, or through cold flows? This remains a major question of current research interest (Di Matteo et al. 2008, Genel et al. 2009, Prandoni et al. 2012).

Stars are massive luminous balls of hydrogen held together by gravity. They are formed when giant molecular clouds (i.e., dense concentrations of interstellar gas and dust) collapse under their own gravity in extremely cold temperature (of about 10 to 20 K) conditions.
During star formation, the gas (and dust) accreted into the galaxy first transforms into HI cloud complexes as it becomes cooler and denser. It then transitions into giant molecular clouds (also known as stellar nurseries). The cold and dense self-gravitating giant molecular clouds then fragment into cloud clumps of around 0.1 pc in size and 10 to 50 $M_\odot$ in mass, which in turn form protostars before ultimately ending up as stars. The entire process lasts for about 10 million years.

The star formation rate (SFR) is the rate at which dense and cold molecular clouds of gas and dust in galaxies are converted to stars. It is a measure of the current status and state of the galaxy and its evolution. It is therefore important to characterize and physically calibrate the laws of star formation to be able to measure with certainty the star formation rates of galaxies. Fundamentally, SFR tracers have been delineated at all wavelengths across the electromagnetic spectrum, from the X-ray to the radio (e.g., Kennicutt 1998, Kennicutt et al. 2002, Runallesi et al. 2003, Calzetti et al. 2005; 2007. Kennicutt et al. 2007). In this study, emphasis will be placed on the infrared band SFR indices.

The ultraviolet ($\lambda \sim 920 - 3000$ Å) continuum emission of galaxies traces young massive stars. It is therefore appropriate for use as a star formation rate (SFR) indicator (see Calzetti et al. 1994, Kennicutt 1998, Witt & Gordon 2000). The use of the ultraviolet continuum as a starburst measure is however hampered by either the presence of dust obscuration or strong AGN emission (e.g., Buat et al. 2005, Sargent & Weedman 2009). Dust extinction, short lifespan of ionized stellar photons and stellar absorption also hamper the use of the optical and near-infrared wavelength range ($\lambda \sim 3000 - 25000$ Å) as star formation indices (see Gallagher et al. 1989, Rosa-Gonzalez et al. 2002, Moustakas et al. 2006, Calzetti 2008). Moreover, emission from the evolved stellar population contributes to the continuum infrared band (i.e., $\lambda \sim 5 - 1000$ $\mu$m) making this band not very ideal for estimating the SFR.

The star formation rate estimations of weak AGN-hosting early-type galaxies such as NGC 1316 and NGC 612 in the mid-infrared band has been calibrated using the Spitzer MIPS 24 $\mu$m monochromatic wavelength band (see Calzetti et al. 2005, Alonso-Herrero et al. 2006, Calzetti et al. 2007, Rieke et al. 2009, Rujopakarn et al. 2012; also see Equation 1.8):

$$\text{SFR} (M_\odot \text{yr}^{-1}) = 1.27 \times 10^{-38} [L(24 \mu \text{m}) (\text{erg s}^{-1})]^{0.885} \quad (1.8)$$

where $L(24 \mu \text{m}) (\text{erg s}^{-1})$ is the spectral luminosity of the 24 $\mu$m emission band.

The WISE W4 (22 $\mu$m) and the Spitzer MIPS 24 $\mu$m bands are equally sensitive to warm dust continuum from young stars and AGN-activity. Moreover, the emission in the WISE W3 (12 $\mu$m) band, which is dominated by the 11.3 $\mu$m PAH emission feature, comes primarily from the ultraviolet radiation from both young massive and evolved older stellar populations.

Based on the star formation rates in the infrared (i.e., SFR$_{IR}$) relation derived by Rieke et al. (2009) using the MIPS-24 calibration, Jarrett et al. (2013) established global WISE SFR$_{IR}$ relations using the W3 (12 $\mu$m) and W4 (22 $\mu$m) bands’ luminosities. The authors thus
normalized the luminosity densities \((L)\) of the bands by the total solar luminosity \((L_\odot = 3.839 \times 10^{26} \text{ W})\) and obtained:

\[
\begin{align*}
\text{SFR}_{\text{IR}}(M_\odot \text{ yr}^{-1}) &= 4.91(\pm 0.39) \times 10^{-10} \nu L_{12}(L_\odot) \\
\text{SFR}_{\text{IR}}(M_\odot \text{ yr}^{-1}) &= 7.50(\pm 0.07) \times 10^{-10} \nu L_{22}(L_\odot)
\end{align*}
\]

(1.9) (1.10)

where \(\nu L_{12}(L_\odot)\) and \(\nu L_{22}(L_\odot)\) are the respective normalized bolometric luminosities of the \(W3\) and \(W4\) bands. These calibrations yielded root mean square scatters of barely 0.28 and 0.04 \(M_\odot \text{ yr}^{-1}\) for SFR (12 \(\mu\text{m}\)) and SFR (22 \(\mu\text{m}\)) respectively, a tight relation that reflects the close correspondence between \(WISE\) and \(Spitzer\) bands.

Furthermore, by taking dust attenuation corrections determined from the Balmer decrement (see Gunawardhana et al. 2013) into account in the calibrations from the previous works (e.g., Calzetti et al. 2007, Rieke et al. 2009, Jarrett et al. 2013), Czévér et al. (2013) have determined dust-corrected H\(\alpha\)-derived star formation rates calibrations using the \(WISE\) \(W3\) (12 \(\mu\text{m}\)) and \(W4\) (22 \(\mu\text{m}\)) bands respectively (see Equations 1.11 and 1.12). This was in an attempt to reduce the ambiguity and improve the efficiency of the calibrations in their earlier work (i.e., Jarrett et al. 2013):

\[
\begin{align*}
\log_{10} \text{SFR}_{\text{H\alpha}}(M_\odot \text{ yr}^{-1}) &= 1.08 \log_{10} \nu L_{12\mu m}(L_\odot) - 9.66 \\
\log_{10} \text{SFR}_{\text{H\alpha}}(M_\odot \text{ yr}^{-1}) &= 0.82 \log_{10} \nu L_{22\mu m}(L_\odot) - 7.30
\end{align*}
\]

(1.11) (1.12)

These solutions were derived by comparing the strengths of the H\(\alpha\) to the mid-infrared emission of nearby, resolved galaxies in the GAMA (Galaxy And Mass Assembly; Taylor et al. 2011) survey. For early-type galaxies, the SFR estimations from the (22 \(\mu\text{m}\)) emission bands look more credible.

### 1.6 Dust in Early-Type Galaxies

Early-type galaxies were long believed to be red, old (i.e., with average stellar ages \(\gtrsim 10\) Gyrs) and inactive with little interstellar medium. They were thought to consist predominantly of older stellar populations devoid of capabilities for star formation and nuclear activity (Faber & Gallagher 1976, Thomas et al. 2005). Recent studies however proclaim that most massive early-type galaxies are rich in molecular clouds (i.e., gas and dust), show recent star formation (i.e., evidence of younger stellar population with mean ages of \(\lesssim 5\) Gyrs) and sometimes display nuclear activity (see Schawinski et al. 2007a, Leeuw et al. 2008, Kunetschn et al. 2010, Dale et al. 2012). Howbeit, the star formation and nuclear activity in these galaxies are insufficient to affect their morphological classification, but contribute in no small measures to the overall stellar mass.
Figure 1.6: Color composite image of the dust-enshrouded galaxy NGC 5128 (Centaurus A) obtained with the Wide-Field Imager (WFI) camera at the ESO/MPG 2.2 m telescope on La Silla. It shows the dark dust lane of the galaxy in visible light. (Figure credit: ESO; http://www.eso.org/public/usa/images/eso0315a/).

The dust in these early-type galaxies (e.g., Figure 1.6; also see NGC 1316 dust map in the right panel of Figure 2.1) supposedly originates from gas accretion due to past galaxy gravitational interactions and/or mergers with neighbouring dust-rich companions which transpired many years ago (Sage & Galletta 1993; Lanz et al. 2010). Figure 1.6 is a color image of NGC 5128 (also known as Centaurus A), an example of a nearby dusty merger remnant elliptical galaxy with a dust lane along the semi-minor axis.

The galaxy-galaxy gravitational interactions may consequently result in the injection of dust-rich gas into the centers of the merging systems to trigger the formation of stars and radio sources or feed the active galactic nuclei in such systems with rapidly twirling central supermassive black holes (Kaviraj et al. 2007; Schawinski et al. 2007b). This ultimately boosts emission in the infrared and submillimeter regime of the electromagnetic spectrum of the systems involved. It also facilitates the ejection of radio jets which interact with the interstellar medium of the remnant galaxies (Rogers et al. 2007, Hopkins & Quataert 2010, Morganti et al. 2013). The dust emission in these galaxies dominates the mid- and far-infrared regime of their spectral energy distributions (e.g., Figure 1.7), and are thus good
indicators of current star formation.

In early-type radio galaxies associated with radio jets, the jet plasma orientations are related to the level of relaxation of the dust structures in the systems. Conspicuously for galaxies with "dust lanes", the jets are aligned at right angles to the dust structures, whilst in "dust-patches" galaxies there are no specific orientations of the jets relative to the dust structures (Verdoes Kleijn & de Zeeuw 2005).

It is worth repeating that the broad-band mid-infrared dust emission includes PAH molecules. In non-AGN hosting early-type galaxies, the PAH emission strength at 17 μm increases with increasing oxygen abundance. It is therefore a good test for the presence of oxygen in such systems. The unusual PAH emission features in low-luminosity AGNs can also be used to detect weak AGN systems in dust-rich local galaxies through spaceborne mid-infrared spectroscopy.

1.7 Spectral Energy Distributions (SEDs)

Emission from galaxies span over the entire electromagnetic spectrum (i.e., from radio waves to gamma radiation). This study focuses on the thermal dust re-emission from the infrared and submillimeter wavelength bands, the dust reprocessed radiation absorbed from stars in the ultraviolet and optical bands, and ionized gas in the diffuse interstellar medium.

The spectral energy distributions (SEDs) of galaxies are plots of observed flux (i.e., integrated flux density or luminosity) against wavelength or frequency (see Figure 1.7). They reveal pertinent information such as stellar, gaseous and dust contents in galaxies. Stellar radiation observed in the ultraviolet, optical and the near- and mid-infrared wavelength bands provides hints of the past star formation history, chemical enrichment of the interstellar medium and attenuation by dust in the galaxy. Dust, in contrast, re-emits chiefly in the mid-infrared-submillimeter wavelength range.

Science instruments providing data for probing galaxy samples at ultraviolet, optical and infrared wavelengths include: the Galaxy Evolution Explorer (GALEX; Martin et al. 2005) in the ultraviolet, the Two-degree Field Galaxy Redshift Survey (2dFGRS; Colless et al. 2001) and the Sloan Digital Sky Survey (SDSS; Stoughton et al. 2002) in the optical, the Two Micron All Sky Survey (2MASS; Skrutskie et al. 1997) in the near-infrared, the Infrared Astronomical Satellite (IRAS; Beichman et al. 1988), the Infrared Space Observatory (ISO; Kessler et al. 1996), the Spitzer Space Telescope (SST; Werner et al. 2004b), the Japanese AKARI Space Telescope (Murakami & Matsuhara 2008) and the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) in the mid- and far-infrared. The Submillimeter Common User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT; Holland et al. 1999) and the Large APEX BOlometer CAmera (LABOCA; Siringo et al. 2009) on the Atacama Pathfinder EXperiment 12 m telescope (APEX; Güsten et al. 2006b) also serve in the submillimeter regime.

Radio data, obtained with instruments such as the Very Large Array (VLA) in Mexico, the Molonglo Observatory Synthesis Telescope (MOST) and the Australian Telescope
Compact Array (ATCA) in Australia are very useful for investigating the interaction of the radio jet plasma with dust-rich molecular clouds. The higher angular resolution and better sensitivity of new and upcoming instruments such as the Square Kilometer Array (SKA; which will operate in the range 3 cm (10 GHz) - 4.3 m (70 MHz)) and its prototypes (KAT 7, MeerKAT, ASKAP) in South Africa and Australia and their partner countries, will add crucial data in the millimeter and meter wavelength bands. The Atacama Large Millimeter/Submillimeter Array (ALMA), is already operating in the range 0.3 mm (1 THz) - 9.6 mm (32 GHz) in Chile. Emission in the radio regime comes mainly from the non-thermal synchrotron emission generated by the accelerating particles in the nuclear magnetic fields.

Dust emission in the infrared and submillimeter bands is known to come from two main regions in the ISM of galaxies: the star forming region and the ambient interstellar medium. The dust re-emission from the stellar birth clouds also comes from three segments: the polycyclic aromatic hydrocarbons, the mid-infrared continuum characterizing the emission...
from hot dust grains in the temperature range 130 - 250 K and the warm dust grains in thermal equilibrium with temperature ranging from 30 to 60 K. In the ambient interstellar medium, the cold dust grains in thermal equilibrium with adjustable temperature in the range 15 - 25 K emit in the far-infrared and submillimeter wavelengths range (e.g., da Cunha et al. 2008). The physical conditions of the star-forming gas in the birth clouds and the current star formation activity in galaxies are revealed by the nebular emission lines from gas heated by the young stars.

1.8 In this dissertation

Mid-infrared and submillimeter dust properties of five nearby and bright merger-remnant radio galaxies in the southern hemisphere were characterized and studied. The galaxies are categorized into two main groups: the primary galaxies comprising the radio-loud NGC 1316 and NGC 612, and the other galaxies also consisting of compact-cored radio galaxies NGC 5078, NGC 7172 and IC 5063. The focus was on both the mid-infrared and submillimeter studies of the primary galaxies, whilst the study of the other galaxies was based on the mid-infrared data only.

The rest of the dissertation is organized as follows. A short review the galaxy sample, and the underlying reasons that informed their selection for the study are presented in Chapter 2. In Chapter 3, the major science instruments (i.e., WISE, Spitzer and APEX-LABOCA), an outline of the observations of the primary galaxies with APEX-LABOCA and the data processing are described. Major findings and discussions of the results are in Chapters 4 and 5. The main conclusions drawn from the study, and the anticipated direction of the study in future are treated in Chapters 6.
Chapter 2

Galaxy Sample

This chapter is devoted to the introduction of the galaxies chosen for the study. It highlights what is known about them in the wavelength regimes of interest, and why they were selected.

2.1 Sample Selection

Radio galaxies are living evidence of relatively recent activity in the nuclei of their host galaxies. Most radio galaxies are hosted by giant gas-poor early-type galaxies, but some contain significant amounts of dust in their central regions. Such dust is likely of external origin, injected during recent infall of low-mass gas-rich galaxies onto the giant elliptical and lenticular galaxies. Whereas mergers might be a necessary condition for the triggering of AGNs, ejection of radio lobes and formation of supermassive black holes in radio galaxies, it is clearly not sufficient, because only a small fraction of elliptical galaxies with signs of merging activity and recent star formation are radio-loud (Ramos Almeida et al. 2012). However, the dust properties of such sources may be relevant to understand the connectivity between the various scenarios.

NGC 1316, NGC 612, NGC 5078, NGC 7172 and IC 5063 are dusty early-type galaxies in the southern hemisphere (see Sections 2.2 and 2.3). The dust in them is believed to be of external origin, from merger activities with nearby gas-rich companions. They exhibit signatures which attest to their past merger events, gravitational interactions and/or gas accretion. They host radio sources and low-luminosity AGNs. They have been studied quite extensively in most wavelength regimes due to their interesting characteristics, and are also listed in major catalogues and surveys such as the Catalog of Dusty Elliptical Galaxies (Elmiger & Balick 1985), the IRAS Bright Catalog of Galaxies and Quasars (Sanders et al. 1995), the Sample of Early-Type Ellipticals (Winkin, Combes & Henkel 1995), Spitzer Infrared Nearby Galaxies Survey (SINGS; Kennicutt et al. 2003) and the Key Insights on Nearby Galaxies: A Far-Infrared Survey with Herschel (KINGFISH; Kennicutt et al. 2011). Above all, they are all nearby galaxies and can be studied with much fidelity (see Tables 2.1 and 2.2).
Clearly, the central regions of the hosts of these radio galaxies contain relevant information about the history of activity in the interstellar medium. Mid-infrared images are valuable tracers of the relatively recent (< 1 Gyr) history of the galaxies, both in terms of star formation and AGN activity, and also the distribution of dust. Submillimeter images likewise reveal the content and the dust distribution in the interstellar medium. It is therefore of interest to image those regions in the mid-infrared and submillimeter bands, compare with other tracers of the AGN, the stars, and the surrounding interstellar medium and investigate their inter-relationships. Observations with the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) and the Large Apex BOlometer CAmera (LABOCA; Siringo et al. 2009) are well-suited for that purpose. These galaxies are also good candidates for future investigations of interactions between radio jets and interstellar dust with sensitive and high-resolution instruments such as ALMA (Atacama Large Millimeter/submillimeter Array) and the future SKA (Square Kilometre Array).

2.2 NGC 1316 and NGC 612

NGC 1316 and NGC 612 constitute the main galaxies investigated in the study. They are clear and close examples of dust-rich AGN-hosting merger remnant galaxies in the southern sky. The two galaxies are rather similar in their radio properties, with bright radio lobes extending out to large distances from the nuclear regions (the distance between the lobes is about 150 kpc for NGC 1316 and 250 kpc for NGC 612). They are however very different in the optical. NGC 612 possesses a dusty stellar disk, which is uncommon for a radio galaxy (Ekers et al. 1978, Véron-Cetty & Véron 2001), and an enormous (∼ 140 kpc in extent) rotating HI disk (Emonts et al. 2008). Both galaxies contain large amounts of molecular gas (see Horellou et al. 2001, Prandoni et al. 2012; also see Table 2.1). In contrast, NGC 1316 is bulge-dominated with ripples, dust patches and lanes (Schweizer 1981, Grillmair et al. 1999, Carlqvist 2010; see also right panel of Figure 2.1).

NGC 1316 is a giant elliptical galaxy which has been abundantly studied, but the luminous NGC 612, which is about six times more distant than NGC 1316 (see Tables 2.1), has received comparatively less attention. NGC 1316 is less abundant in atomic gas (Horellou et al. 2001) than NGC 612 (Prandoni et al. 2012).

2.2.1 NGC 1316 (Fornax A, PKS 0320-37)

NGC 1316 is a well-known peculiar early-type elliptical galaxy located at the outskirt of the Fornax Cluster at a projected angular distance of about 3° (∼1 Mpc) from the center of the cluster (Schweizer 1981). It is one of the two most luminous galaxies in the cluster (the other is the spiral galaxy NGC 1365) and the fourth most powerful nearby radio source in the sky after Centaurus A, Virgo A and Cygnus A. Its optical surface brightness distribution profile follows the de Vaucouleurs law (Schweizer 1980). It has also been classified by Schweizer (1981) as a D-type (giant) elliptical galaxy. NGC 1316 is a merger remnant (Schweizer 1980,
Figure 2.1: Merger features of NGC 1316. Left: Composite image of the two large radio lobes (in orange) overlaid on an optical image. Radio jets are visible in the very center. Right: HST image of the core showing extinction by dust in the central region (Credit: The Hubble Heritage Team (STScI/AURA), NASA, ESA, P. Goudfrooij 2005).

Figure 2.2: The colour image is the Spitzer 8 μm non-stellar map of NGC 1316 (taken from Lanz et al. 2010). Left: Isocontours (in red) of the inner radio jets at 0.04 to 6.0 mJy/beam (Geldzahler & Fomalont 1985). There appears to be a collision between the northern central radio jet and dense dust-rich gas cloud resulting in a slight change in the jet’s direction (Geldzahler & Fomalont 1984). Right: SEST CO(2-1) isocontours (in green) (Horellou et al. 2001). The northwest dust lane coincides with a large concentration of molecular gas.

Figure 2.3: Magnified high-resolution smoothed Chandra X-ray image of the central region of NGC 1316. The black circular dot in the center denotes the location of the optical nucleus, and the other dots are point sources. The southeast and northwest red lines at position angles of approximately 120° and 315° respectively, show the directions of propagation of the radio jets. The green contours with magenta background in the central region illustrate the interactions between the X-rays and the jets flow directions (figure taken from Kim & Fabbiano 2003).

<table>
<thead>
<tr>
<th></th>
<th>NGC 1316 (Fornax A)</th>
<th>NGC 612 (PKS 0131-36)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA [J2000]</td>
<td>03h 22m 41.70s</td>
<td>01h 33m 57.74s</td>
</tr>
<tr>
<td>Dec [J2000]</td>
<td>−37° 12′ 30″.0 ′′</td>
<td>−36° 29′ 35″.7 ′′</td>
</tr>
<tr>
<td>Distance [Mpc]</td>
<td>20.0 ′′</td>
<td>125.0 ′′</td>
</tr>
<tr>
<td>Redshift</td>
<td>0.0059 ′′</td>
<td>0.0298 ′′</td>
</tr>
<tr>
<td>Size</td>
<td>12 ′.0 × 8 ′.5 ′′</td>
<td>1′.6 × 1′.2 ′′</td>
</tr>
<tr>
<td>M_{H_2} [10^8 M_☉]</td>
<td>5.0  ′′</td>
<td>79.0  ′′</td>
</tr>
<tr>
<td>M_{H_1} [10^8 M_☉]</td>
<td>0.20  ′′</td>
<td>18.0  ′′</td>
</tr>
<tr>
<td>Flux_{max} [Jy]</td>
<td>259.0  ′′</td>
<td>160.0  ′′</td>
</tr>
</tbody>
</table>

Table 2.1: Some characteristics of NGC 1316 and NGC 612

References: aNASA NED average measurement; bHorellou et al. (2001); cPrandoni et al. (2012); dEmonts et al. (2008); eLarge et al. (1981); fParkes Catalogue 1990 (PKSCAT90).

and Lanz et al. (2010) also point towards a second minor merger event 0.5 Gyr ago.

NGC 1316 harbours prominent disturbed dust patches, clumps and a lane in the central 2′.5 × 2′.5 (see Grillmair et al. 1999, Lanz et al. 2010; and also the right panel of Figure 2.1).
Color-index and extinction maps (e.g., Carlqvist 2010, Deshmukh et al. 2012) and the HST image reveals a T-shaped dust pattern inclined at a position angle of about \(-45^\circ\) to the north aligned north-west-to-south-east of the nucleus (see Figure 2.1, right panel). Evidence from Spitzer observations by Temi et al. (2005) suggests that a massive dust-heating stellar population is being formed in the galaxy, which is uncommon in ellipticals.

Precursor CO observations with the Swedish - ESO (European Southern Observatory) 15 m Submillimeter Telescope (SEST) revealed a non-uniform CO emission distribution in the galaxy; very little in the centre and concentrated in two regions, about 30'' south-east and 45'' north-west of the nucleus (see Sage & Galletta 1993, Horellou et al. 2001; also see Figure 2.2, right panel). The equivalent molecular hydrogen mass derived from the CO emission measurements within the central 2' is \(5.0 \times 10^8 \, M_\odot\) (\(2.2 \times 10^8 \, M_\odot\) in the north-west, \(1.0 \times 10^8 \, M_\odot\) in the centre and \(1.8 \times 10^8 \, M_\odot\) in the south-east). The CO distribution appears to coincide with the dust emission, suggesting that the dust and the CO emissions co-habitate. The HI to H$_2$ mass ratio is about 0.04. The large amount of molecular hydrogen gas (e.g., Horellou et al. 2001; also see Table 2.1) and a misalignment between the gas and the central stellar kinematics (Bosma et al. 1985, Horellou et al. 2001) provide further evidence of a recent merger with a gas-rich companion galaxy.

NGC 1316 has a pair of radio lobes (extending about 300 kpc across) lying outside the optical galaxy (see Ekers et al. 1983; Figure 2.1, left panel) and a two-sided radio jet in the central 30'' (~2.9 kpc) of the galaxy (see Geldzahler & Fomalont 1984). The origin of these twin-jets is associated with the outbursts of the AGN that was supposedly triggered by the recent merger events (Lim et al. 2000, Lanz et al. 2010). The northern central radio jet appears to collide with a cloud of dense gas and dust on the north-west of the nuclear region (Geldzahler & Fomalont 1984, Lanz et al. 2010; Figure 2.2, left panel); a jet-cloud collision is the most direct and observable kind of AGN activity. However, AGN activity is widely considered to hinder star formation through turbulent quenching and utilizing the gas cloud for feeding AGN (see Hopkins & Quataert 2010).

X-ray observations have revealed the presence of a low-luminosity AGN (with \(L_X \sim 5.0 \times 10^{39}\) erg s$^{-1}$) in the energy range 0.3–8.0 keV (Kim & Fabbiano 2003). The magnified smoothed high-resolution Chandra X-ray image of NGC 1316 in Figure 2.3, reveals the surface brightness distribution of the diffuse X-ray emission of the galaxy. It shows the interactions between the hot interstellar medium (X-rays) and the propagating radio jets (see Figure 2 in Geldzahler & Fomalont 1984; and also the left panel of Figure 2.2).

All in all, NGC 1316 is a good candidate to research the processes in galaxy mergers, gas relaxation toward equilibrium after the merger, and the impacts from AGN on the star-forming interstellar medium.

### 2.2.2 NGC 612 (PKS 0131-36)

NGC 612 is an early-type disk galaxy (Slee et al. 1994, Emonts et al. 2008) with an optical luminosity profile that also obeys the de Vaucouleurs law (de Vaucouleurs 1948, Fasano et al. 1996). It is often described as an S0 (lenticular) galaxy (Véron-Cetty & Véron 2001).
NGC 612 is a powerful radio galaxy (Morganti et al. 1993, Gopal-Krishna & Wiita 2000). It hosts one of the most powerful and extended nearby two-sided structure radio sources, PKS 0131–36, (see Ekers et al. 1978, Morganti et al. 1993, Emonts et al. 2008; and also Figure 2.5) and showcases both of the Fanaroff-Riley radio classification morphologies (FR-I & FR-II) (see Fanaroff & Riley 1974, Gopal-Krishna & Wiita 2000), which is very rare in normal early-type galaxies. Most double radio sources are hosted by giant ellipticals. Figure 2.5 is a radio continuum VLA (4.8 GHz) image of the galaxy observed by Morganti et al. (1993). The image agrees well with that constructed by Emonts et al. (2008) from the 750C array data of the Australian Telescope Compact Array (ATCA) 8.6 GHz band.

The galaxy has a pronounced dust lane confined to a few central arc-minutes along the apparent major axis, perpendicular to the radio axis (see Goss et al. 1980, Fasano et al. 1996, Bettoni et al. 2001; Figure 2.4, left image).

A large amount of cool neutral hydrogen gas rotates regularly at a total velocity of 850 km s$^{-1}$ in a disc-like structure spanning about 3.9 (~140 kpc wide) around the galaxy (see Goss et al. 1980, Emonts et al. 2008; also see Table 2.2). APEX CO(2-1) emission line measurements by Prandoni et al. (2012) also revealed an unusually large amount of molecular gas (see Table 2.2) in the central 28" (~17 kpc). The $M_{\text{HI}}$ to $M_{\text{H}_2}$ ratio is about 0.23, compared to the 0.04 for NGC 1316. NGC 612 has a faint HI shell structures at the outer envelope in the central 4.4 (~160 kpc) which extends as a bridge joining the nearby gas-rich companion NGC 619 (located at ~ 400 kpc away, with HI mass of $8.9 \times 10^9$ $M_\odot$ extending over the disk length of ~400 kpc). This suggests past gravitational interactions...
Figure 2.5: Radio continuum (VLA: 4.9 GHz) image of NGC 612 (in contours). It shows the FR II and FR I radio classification morphologies (separated by a distance of about 500 kpc) on the left and right sides of the galaxy respectively. Contour levels range from ~0.45 to 45 mJy/beam (Morganti et al. 1993). For NGC 612 at a distance of 125 Mpc, $10^{-16}$ is equivalent to 6.1 kpc.

between the two systems about 1 Gyr ago (Holt et al. 2007b). Moreover, Kileen et al. (1986), Golombek et al. (1988) and Tadhunter et al. (1998) also found from independent optical studies that NGC 612 is a major merger remnant.

NGC 612 is a weak-line radio galaxy with a low-ionisation nuclear emission region (LINER) (Véron-Cetty & Véron 2006). A young stellar population in the age range of approximately 0.04 – 0.1 Gyrs has also been identified in the entire stellar disc of the galaxy (Raimann et al. 2005, Holt et al. 2007a). It is thus interesting to investigate how the powerful radio source, the low-luminosity AGN and the recent star formation activity are related to the mid-infrared and submillimeter dust emission in the galaxy.

The infrared spectrum of the nuclear region of the galaxy is dominated by emission lines (see Figure 2.6). Figure 2.6 is a Spitzer IRS spectrum of the nuclear region of the galaxy. It shows the emission lines, indicating the high excitation in the nuclear region. PAH emission features are predominant around the 8 µm and 12 µm wavelengths, with forbidden transitions of FeII and OIV around 26 µm.
Figure 2.6: Spitzer IRS spectrum of NGC 612 showing the emission lines in the nuclear region of the galaxy. The ticks on the top axis indicate the commonly detectable mid-infrared emission lines. The strong lines are PAHs and the forbidden transitions of FeII and OIV. The light grey horizontal bars mark wavelength ranges centered at 10 $\mu$m and 18 $\mu$m. (Figure from Asmus et al. 2014; http://dc.zah.uni-heidelberg.de/samirala/q/prod/qp/NGC612).

<table>
<thead>
<tr>
<th></th>
<th>NGC 5078 (PKS 1323-271)</th>
<th>NGC 7172</th>
<th>IC 5063 (PKS 2048-572)</th>
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<tr>
<td>RA [J2000]</td>
<td>13h 19m 50.0s $^a$</td>
<td>22h 02m 01.9s $^a$</td>
<td>20h 52m 02.3s $^a$</td>
</tr>
<tr>
<td>Dec [J2000]</td>
<td>$-27^\circ 24' 37''.0$ $^a$</td>
<td>$-31^\circ 52' 11''.0$ $^a$</td>
<td>$-57^\circ 04' 05''.0$ $^a$</td>
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<tr>
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<td>33.5 $^{a,b}$</td>
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<td>Redshift</td>
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<td>0.0078 $^{a,b}$</td>
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<tr>
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<td>$M_{H_2}$ [$10^8 M_\odot$]</td>
<td>7.9 $^c$</td>
<td>21.0 $^d$</td>
<td>3.0 $^c$</td>
</tr>
<tr>
<td>$M_{H_2}$ [$10^8 M_\odot$]</td>
<td>--</td>
<td>2.6 $^d$</td>
<td>39.4 $^e$</td>
</tr>
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</table>

Table 2.2: Some characteristics of NGC 5078, NGC 7172 and IC 5063.

References: $^a$NASA NED; $^b$Corrected to the Reference Frame defined by the 3K CMB; $^c$Wilkind & Henkel (1989); $^d$Anupama et al. (1995); $^e$Wilkind, Combes & Henkel (1995).

2.3 The Radio-quiet Galaxies

The CO-bright lenticular galaxies NGC 5078, NGC 7172 and IC 5063 are three prominent nearby examples of compact core radio galaxies in the southern hemisphere (see Figure 2.8).
2.3 The Radio-quiet Galaxies

Figure 2.7: Carnegie-Irvine Galaxy Survey (CGS) colour images. **Top Left:** NGC 5078 showing the visibly broad dust lane along the major axis (Mollenhoff, Hummel & Bender 1992). The S-shaped galaxy to the south-west is the companion radio-quiet spiral IC 879 (Lamberts 1982). **Top Right:** NGC 7172 depicting the prominent dust lane running east-west along the major axis (Sharples et al. 1984). **Bottom:** IC 5063 showing the dust lane lying northwards of the nucleus (Colina, Sparks & Macchetto 1991).

They have distinct (equatorial) dust lanes located a few kiloparsec away in projection from their nuclei (see Figure 2.7), directly comparable with NGC 612 (see Figure 2.4, left panel).

### 2.3.1 NGC 5078 (PKS 1323-271)

NGC 5078 features in the Ekers et al. (1989) sample of southern radio galaxies. It is a merger remnant with a boldly visible dust lane along the major axis (see Mollenhoff, Hummel & Bender 1992; Figure 2.7, top left panel) with unresolved radio jets in the core (see Condon et al. 1996; Figure 2.8, left image). The radio jets emanate mainly from the nucleus to
the disk plane with a flux density $S_v$ of 188 mJy at 1.49 GHz in the compact radio core. The difference in flux measurements of the extended component emission between the low resolution source of about 20" diameter and high resolution one of about 0.4 diameter is $\sim$ 60 mJy (Condon et al. 1996, Eskridge et al. 2002).

Interestingly, this galaxy seems to be interacting with the nearby Sa spiral radio-quiet galaxy IC 879 (Lauberts 1982), which has resulted in that galaxy (i.e., IC 879) being distorted into an S-shaped structure (see south-west of Figure 2.7, left image). Wiklind & Henkel (1989) detected huge amounts of molecular hydrogen gas (see Table 2.2) in the centre of the galaxy from CO(1-0) measurements at a CO integrated intensity of 13.0 K km s$^{-1}$. They calculated a star formation rate of approximately 6.0 $M_\odot$ yr$^{-1}$ and a corresponding star formation efficiency (SFE: ratio of the star formation rate to the amount of local molecular hydrogen gas) of about $15.5 \times 10^{-3}$ yr$^{-1}$. This is an indication of the presence of both younger and older stellar populations in the galaxy.

2.3.2 NGC 7172

NGC 7172 is a peculiar early-type S0 galaxy (see Aumapana et al. 1995). It is the brightest member of the Hickson Compact Group 90 (HCG90) (Guainazzi et al. 1998). This dust-obscured edge-on Seyfert 2 (i.e., AGN-hosting) galaxy is a merger remnant with a prominent east-west equatorial dust lane (see MacKenty 1990; Figure 2.7, top right panel). Smaili et al. (2012) detected AGN tracer lines (i.e., molecular hydrogen and hydrogen recombination lines, and FeII excitation lines) and confirmed that the nucleus of the galaxy is behind the dust lane. They found an accreting supermassive black hole of mass $M_{BH} = 4.5 \times 10^8 M_\odot$ in the centre of the galaxy, traced by the SiVI line, and the narrow Paα and Brγ excitation bands.

CO (1-0) measurements at integrated intensity of 8 K km s$^{-1}$ by Wiklind & Henkel (1989) provided the corresponding large amount of molecular hydrogen (see Table 2.2) in the centre of the galaxy. The authors further reported a star formation rate and efficiency of 3.0 $M_\odot$ yr$^{-1}$ and 8.8 $\times$ 10$^{-3}$ yr$^{-1}$ respectively from the emission line measurements. The galaxy has moderate HI mass estimated from optical extinctions (see Table 2.2), and a far-infrared dust mass at temperature $T_d \sim 36$ K of $M_{dust} = 3.0 \times 10^6 M_\odot$ (Knapp et al. 1989. Aumapana et al. 1995).

The VLA 1.49 GHz and 4.86 GHz maps of the compact core of this radio source reveal an unresolved segment about 3" (~0.49 kpc) south of the optical nucleus (see Unger et al. 1987). Moreover, the VLA 1.49 GHz and ATCA 8.6 GHz core maps show the radio core embedded in diffuse radio emission stretching linearly along the galaxy’s major axis (e.g., Unger et al. 1987, Morganti et al. 1999; also see Figure 2.8, middle panel). NGC 7172 hosts a hard X-ray source. H1258-321 (see Polletta et al. 1996).

Molecular hydrogen gas, which is closely associated with far-infrared emission, is crucial for fuelling star formation and other nuclear activities in normal and starburst galaxies (Heckman 1989). Seyfert 2 galaxies are strong emitters of CO and far-infrared (and submillimeter) emission. The amount and properties of dust (mid-infrared and submillimeter) in
the central region of the galaxy will therefore give much insight into the star formation and AGN-activity in the galaxy.

### 2.3.3 IC 5063 (PKS 2048-572)

IC 5063 is a massive ($M^* \sim 10^{11} M_\odot$) peculiar early-type S0 (sometimes referred to as an elliptical) galaxy with a de Vaucouleurs optical surface brightness distribution profile (see Tadhunter et al. 2014). It is associated with a strong compact double-lobed radio source, PKS 2048–572 (Mills et al. 1961, Ekers 1970, Morganti et al. 1999) and has a slightly warped gaseous (III) disc of radius $\sim 30$ kpc (Morganti et al. 1998). The gas disc has a flat rotation curve over a distance of about 6.8 kpc and rotates rapidly at a total velocity of about 180 km s$^{-1}$ within the inner 1 kpc range from the nucleus (Danziger, Goss & Wellington 1981), similar to NGC 612 (Goss et al. 1980) and NGC 5128 (Graham 1979). There is an intense heating source at the centre of the galaxy which could be responsible for illuminating and warping the HI disc.

Again, IC 5063 hosts a very bright radio-loud Seyfert 2 nucleus (AGN) and one of the strongest radio sources found in Seyfert galaxies (Danziger et al. 1981). It is thus a Seyfert and a radio galaxy (Colina et al. 1991, Kewley et al. 2001). It has X-ray luminosity of $5.0 \times 10^{44}$ erg s$^{-1}$ in 0.5 - 200 keV energy band (Kewley et al. 2001), with a black-hole mass of $2.8 \times 10^8 M_\odot$, and Eddington luminosity of $3.8 \times 10^{46}$ erg s$^{-1}$ (see Tazaki et al. 2011). Its AGN power is comparable to that of NGC 612 (i.e., with $L_X \sim 5.0 \times 10^{43}$ erg s$^{-1}$ and $M_{BH} = 1.0 \times 10^8 M_\odot$) in the energy range 2-10 keV (Kewley et al. 2001).

The galaxy has radio jets similar to those of NGC 7172 and NGC 5078 (see Figure 2.8). High-resolution 8 GHz and 17.8 GHz ATCA radio continuum images display a linear triple layout (i.e., continuum 3-component radio structure) of 5".7 (about 1.3 kpc in extent) along the galactic major axis (e.g., Morganti et al. 1998, 2007; Figure 2.8, right panel). The
central segment of the triple radio continuum structure corresponds to the inner core, whilst the remaining two lie on either side of the core along with the radio jets (see Morganti et al. 1998; 2007).

IC 5063 is a dust-enshrouded merger remnant with a prominent dust lane along the major axis northwards of the nucleus. The dust lane is in alignment with the radio structure (Colina, Sparks & Macchetto 1991, Martini et al. 2003; Figure 2.7, bottom panel). CO(1-0) line emission measurements by Wiklind, Combes & Henkel (1995) revealed a corresponding large amount of neutral molecular hydrogen (i.e., H₂) gas and a huge amount of H I in the galaxy (see Table 2.2). The authors further measured a far-infrared dust of mass of 2.5 × 10⁸ M☉ at a dust temperature of 67 K. Morganti et al. (2013) investigated the interplay between the radio plasma jets in the compact core and the gas-rich interstellar medium of this galaxy using APEX CO(2–1) observations and confirmed that the fast outflow of molecular, ionized and atomic neutral gas co-exists at about 0.5 kpc from the nucleus and coincides with the radio lobe (Oosterloo et al. 2000).

IC 5063 is the first nearby galaxy where a fast (i.e., ∼ 700 km s⁻¹) outflow of neutral hydrogen and ionized gas was detected (Morganti et al. 1998; 2007). The galaxy thus appears to be in a special evolutionary state (Colina et al. 1991). If this gas outflow continues at the current high rate for a longer time, the galaxy will experience a scenario similar to that predicted by the semi-analytical models (e.g., Cole et al. 1994), which are inverses of the hierarchical galaxy formation models (Toomre 1977, Dressler 1980, Barnes 1990) where the present-time galaxies are envisaged to form across the Hubble diagram (i.e., a bulge dominated galaxy accreted from a disc galaxy). IC 5063 is therefore a good source to investigate dust properties and its interactions with the galactic medium.
Chapter 3

Observations and Data Reduction

In this chapter, a brief introduction is given of the main telescopes and cameras supplying data for this study. The observations and reduction of the LABOCA data are discussed here. An outline of how the WISE and Spitzer data sets were treated is also given in this chapter.

3.1 Observing Instruments

The Wide-field Infrared Survey Explorer (WISE), the Spitzer Space Telescope (Spitzer) and the Large APEX BOlometer CAmera (LABOCA) are the main science instruments used in this study. The WISE single frames were used to construct new images and to do a full source characterization. Spitzer data was analysed to perform source characterization and photometry, and LABOCA data to create submillimeter dust maps of the primary galaxies.

3.1.1 The Wide-field Infrared Survey Explorer (WISE)

WISE is a National Aeronautics and Space Administration (NASA)-funded Medium-Class Explorer (MIDEX) mission space infrared telescope (Wright et al. 2010; also see Figure 3.1). Figure 3.1 is the artist’s illustration of the telescope flight system in survey configuration mode around the Earth. It was built mainly by Ball Aerospace & Technologies Corporation (Ball Aerospace) and Space Dynamics Laboratory (SDL) at an estimated cost of 320 million US$. The main science instruments of this 40 cm primary-mirror space-based telescope include the HAWAII 1-RG 1024×1024 HgCdTe arrays (near-IR channels; 3.4 and 4.6 μm) and the DRS Si:As 1024×1024 Blocked Impurity Band detectors (mid-IR channels; 12 and 22 μm). The telescope and the detectors were cooled to their optimum operating temperatures with a two-stage solid hydrogen cryostat. WISE has a dichroic beam-splitter which facilitates simultaneous continuum imaging in the four mid-infrared bands at 8.8 seconds exposure time (see Table 3.1). Each band covered a field of view of 47′ × 47′ (∼0.6 deg²) (Mainzer et al. 2005, Wright et al. 2010, Jarrett et al. 2011).
Figure 3.1: An illustration of the WISE telescope flight system in survey configuration mode around the Earth with cover off. The visible blue panel is the solar array, which provided the usable 301 W of its possible 500 W power output (Wright et al. 2010).

The wider sky-coverage of WISE differentiates it from the preceding Spitzer Space Telescope and the Herschel Space Observatory infrared missions. The WISE system was designed with the potential to scope wider sky areas to be able to capture and scan a greater variety of unobserved cosmic objects, such as rarely detected oddities. It was about 1000 times more sensitive than earlier surveys such as the Infrared Astronomical Satellite, AKARI and the Cosmic Background Explorer’s Diffuse Infrared Background Experiment (Schwalm et al. 2005, Mainzer et al. 2010b).

The weighted mean relative spectral response of the WISE bands are shown in Figures 3.2 and Figures 3.3. They were constructed using the weighted mean of the measured, design and component prediction values (see Wright et al. 2010).

WISE was launched into a Sun-synchronous polar orbit on December 14, 2009 at an altitude of 525 km and started its two-fold survey mission on January 14, 2010. It achieved a full coverage of the sidereal sky on July 17, 2010. The primary mission (known as WISE and led by Edward L. Wright) was to map the entire sky of the coolest stars and the Universe’s most luminous galaxies. This phase ended when the frozen hydrogen cooling
Figure 3.2: The weighted mean WISE relative spectral response functions in electrons per photon units (figure taken from Wright et al. 2010).

Figure 3.3: Normalised WISE weighted mean relative spectral response functions (figure taken from Wright et al. 2010).

the telescope from its primary cryogenic tank was exhausted on September 30, 2010, after mapping the entire sky in the four mid-infrared wavelength bands (see Table 3.1). The
Table 3.1: Some characteristics of the WISE maps:
(a) WISE bands. (b) Central wavelengths (taken from Brown, Jarrett & Cluver 2014).
(c) Nominal spatial resolutions (see Wright et al. 2010). (d) HiRes angular resolutions (see Jarrett et al. 2012). (e) Approximate 1σ Vega magnitude surface brightnesses as measured for the NGC 1316 mosaic images and (f) the corresponding 1σ surface brightness values.

<table>
<thead>
<tr>
<th>Band b</th>
<th>Wavelength b (µm)</th>
<th>Resolution c (arcsec)</th>
<th>Resolution d (arcsec)</th>
<th>Sensitivity e (mag arcsec^{-2})</th>
<th>Sensitivity f (µJy arcsec^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>3.4</td>
<td>6.1</td>
<td>2.6</td>
<td>23.4</td>
<td>0.14</td>
</tr>
<tr>
<td>W2</td>
<td>4.6</td>
<td>6.4</td>
<td>3.0</td>
<td>22.4</td>
<td>0.19</td>
</tr>
<tr>
<td>W3</td>
<td>12.0</td>
<td>6.5</td>
<td>5.0</td>
<td>18.6</td>
<td>1.10</td>
</tr>
<tr>
<td>W4</td>
<td>22.8</td>
<td>12.0</td>
<td>5.5</td>
<td>16.1</td>
<td>2.90</td>
</tr>
</tbody>
</table>

Two shortest wavelength detectors (i.e., W1 and W2 bands) continued to operate with the same survey strategy in the post-cryogenic regime till February 01, 2011. This is the second phase of the WISE mission (also known as NEOWISE with Amy Mainzer as the Principal Investigator). The NEOWISE (near-Earth-objects + WISE) survey uncovered hundreds of thousands of the darkest and hazardous near-Earth asteroids and comets (see Mainzer et al. 2010a; 2011). The WISE telescope was finally put into hibernation on February 17, 2011 when its main transmitter was switched off to signify the completion of its major mandates. NEOWISE was brought out of hibernation and reactivated in December 2013 for a planned three-year survey in the 3.4 and 4.6 µm infrared bands, during which NEOWISE plans to discover and characterize the near-Earth (or solar system) objects (NEOs) and archive accurate measurements of their diameters and albedos (see Mainzer et al. 2014).

Science operations, data processing and archiving of the main WISE and NEOWISE missions take place at the Infrared Processing and Analysis Center (IPAC) at the California Institute of Technology in Pasadena. The main accrued products, the WISE All-sky Data Products and Atlas Images, are archived by the NASA IPAC in the Infra-Red Science Archive (IRSA). For the present study, the focus is on the main WISE mission and its data in the four mid-infrared bands (see Wright et al. 2010, Jarrett et al. 2011, Cutri et al. 2012).

During the main survey period, WISE mapped the entire sky at the four mid-IR bands with minimum 5σ sensitivities of 0.08, 0.11, 0.8 and 6 mJy respectively in the ecliptic regions at eight individual exposures per band detection (see Wright et al. 2010). The sensitivity gets better away from the ecliptic regions due to lower background zodiacal light and denser coverage there (see Jarrett et al. 2011). The public-release co-added WISE Atlas images at a pixel scale of 1.375 arcsec/pixel are optimized for point source detection and therefore have a degraded resolution (see Table 3.1) of about 30% to 40% compared to the native single frames (see Cutri et al. 2012, Jarrett et al. 2013). That sparked the need for the creation of the resolution-enhanced image mosaics at 1″.00 and 0″.687 pixel scales via the "drizzle" and Maximum Correlation Method (MCM; Masci & Fowler 2009) High-Resolution (MCM-HiRes) methods used in this study (see Jarrett et al. 2012, 2013, Masci 2013; also see Table 3.1). Moreover, the source characterization pipeline (Jarrett et al. 2013) was used to characterize and extract photometric, shape and surface brightness information.
3.1 Observing Instruments

![Figure 3.4: WISE color-color diagram depicting the distribution of a variety of classes of celestial objects. Stars and early type galaxies have colors near zero in both W1-W2 and W2-W3, brown dwarfs are very red in W1-W2, while spiral galaxies are red in W2-W3 and lie in between elliptical and starburst galaxies. ULIRGS, LINERs and obscured AGNs are red in both colors (Wright et al. 2010, Jarrett et al. 2011).](image)

The *WISE* bands (*W1 to W4*) were chosen to reveal special spectral information. The *W1* and *W2* bands are virtually dust extinction-free bands that are primarily sensitive to the evolved luminous stellar population; the Rayleigh-Jeans part of the black-body emission of cool stars (*T* > 2000 K). The emission in the *W3* band is dominated by polycyclic aromatic hydrocarbons (PAHs) that peak at 11.3 μm and warm continuum dust emission from small dust grains. The *W4* band is largely sensitive to the warm continuum dust emission which comes from photon-dominated regions or ultraviolet radiation fields in the diffuse interstellar medium (Jarrett et al. 2011, Cutri et al. 2012).

The *WISE* color-color diagram (see Figure 3.4) defines regions occupied by various types of celestial objects. It is therefore relevant for distinguishing between galaxies and field stars and also for separating the different extragalactic sources (Wright et al. 2010).

### 3.1.2 The Spitzer Space Telescope (Spitzer)

The Spitzer Space Telescope (*Spitzer*) was formerly known as the Space Infrared Telescope Facility (SIRTF). It was renamed on December 18, 2003 in honour of an American astrophysicist, Lyman Spitzer Jr., who in a seminal paper in 1946 highlighted the relevance of
operating large astronomical telescopes from space as enshrined in his previous paper (see Spitzer 1990). *Spitzer* is the fourth and final mission in the NASA’s Great Observatories Program: a fleet of four space-based observatories, each orbiting and mapping the Universe in a different wavelength band (Ferguson et al. 2000, Giavalisco et al. 2004). The Hubble Space Telescope (Hubble), the Chandra X-Ray Observatory (Chandra) and the Compton Gamma-Ray Observatory (Compton) are the other missions in the program.

*Spitzer* was designed to detect infrared heat or radiation by objects in space. It has highly sensitive science instruments (Werner et al. 2004b; also see Table 3.2) which pave ways for astronomers and astrophysicists to probe the cosmic regions of dust-rich stellar nurseries, giant molecular clouds, organic molecules (which can help detect the presence of life on other planets), newly forming planetary systems, brown dwarfs and extrasolar planets among others. *Spitzer* is also a member of NASA’s Cosmic Origins Program, which aims to investigate our cosmic roots and how galaxies, stars and planets are formed and evolve.

The Spitzer Space Telescope was launched into an Earth-trailing heliocentric solar orbit on August 25, 2003 for an estimated 2.5-year minimum observational mission. Like any other satellite, the 800 million US$. *Spitzer* consisted of two main components: the Cryogenic Telescope Assembly and the Spacecraft. The Cryogenic Telescope Assembly comprised of a 0.85 m diameter telescope and three science instruments (i.e., IRAC, IRS and MIPS; see Table 3.2) on-board, whilst the spacecraft navigates the telescope through space, pow-
3.1 Observing Instruments

<table>
<thead>
<tr>
<th>Instruments&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Wavelength&lt;sup&gt;b&lt;/sup&gt; (μm)</th>
<th>Array&lt;sup&gt;c&lt;/sup&gt; (pixels)</th>
<th>Material&lt;sup&gt;d&lt;/sup&gt;</th>
<th>FOV&lt;sup&gt;e&lt;/sup&gt;</th>
<th>Resolution&lt;sup&gt;f&lt;/sup&gt;</th>
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<td>InSb</td>
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<td>2″</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>256×256</td>
<td>InSb</td>
<td>5′.2×5′.2</td>
<td>2″</td>
</tr>
<tr>
<td></td>
<td>5.8</td>
<td>256×256</td>
<td>Si:As</td>
<td>5′.2×5′.2</td>
<td>2″</td>
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<td></td>
<td>8.0</td>
<td>256×256</td>
<td>Si:As</td>
<td>5′.2×5′.2</td>
<td>2″</td>
</tr>
<tr>
<td>IRS</td>
<td>18.7 - 37.2</td>
<td>128×128</td>
<td>Si:As</td>
<td>11′.1×22′.3</td>
<td>~ 600</td>
</tr>
<tr>
<td></td>
<td>5.12-14.29</td>
<td>128×128</td>
<td>Si:As</td>
<td>3′.7×57′.0</td>
<td>60 – 127</td>
</tr>
<tr>
<td></td>
<td>9.89-19.51</td>
<td>128×128</td>
<td>Si:Si</td>
<td>4′.7×11′.3</td>
<td>~ 600</td>
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<td>24</td>
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<td>Si:As</td>
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<td>6″</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>32×32</td>
<td>Ge:Ga</td>
<td>2′.5×2′.5</td>
<td>18″</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>2×20</td>
<td>Ge:Ga</td>
<td>0′.5×0′.5</td>
<td>40″</td>
</tr>
</tbody>
</table>

Table 3.2: Some characteristics of the Spitzer Space Telescope:

<sup>a</sup> The three main instruments on the Spitzer Space Telescope (Werner et al. 2004); Infrared Array Camera (IRAC; Fazio et al. 2004), Infrared Spectrograph (IRS; Houck et al. 2004) and Multiband Imaging Photometer (MIPS; Rieke et al. 2004).  
<sup>b</sup> Central wavelengths of IRAC and MIPS cameras, and IRS wavelength range.  
<sup>c</sup> Array size of the detector.  
<sup>d</sup> Material made-up of the detector.  
<sup>e</sup> Field of view of the respective cameras and detectors.  
<sup>f</sup> The angular resolutions (IRAC and MIPS) and the resolving powers (IRS) of the detectors (Spitzer Telescope Handbook, 2013).

The science instruments, manages the accrued scientific data and communicates with Earth. The primary instrument package (telescope and cryogenic chamber) was built by Ball Aerospace & Technologies Corporation and the Spacecraft by Lockheed Martin. The individual detector instruments were developed collaboratively by many industrial, academic and governmental institutional players.

The compartmentalization of Spitzer was important to keep the different components at their respective appropriate working temperatures (see Werner et al. 2004b). This is because, the telescope needed to be both warm and cold at the same time to function satisfactorily. The units in the Cryogenic Telescope Assembly must be cooled to only a few degrees above absolute zero (~ -278°C) by the on-board tank of liquid helium or cryogen (also known as coolant), while the electronic equipment in the spacecraft compartment requires a room temperature environment to operate. Spitzer lasted in the "cold or cryogenic mission" (when all the three science instruments listed in Table 3.2 were operational) for about 5 years and 9 months till May 15, 2009, when the coolant completely depleted. It immediately went into the "warm mission" (when only the two IRAC 3.6 μm and 4.5 μm channels are operational) as soon as the coolant was exhausted. It will continue in this mode until late in this decade to pick up heat radiation from dusty stars, planet-forming disks, gas-rich giant planets and asteroids in our solar system and faraway galaxies.

During the cryogenic mission era Spitzer did over 36,000 hours of science observations with the three key science instruments. It obtained images and spectra by detecting the infrared energy radiated by celestial objects in space in the wavelength range 3 - 180 μm. This (and the warm mission) resulted in large amounts of data in the NASA/IPAC Infrared
Science Archive (IRSA) for the scientific community to explore.

The Infrared Array Camera (IRAC), one of the three science instruments on-board Spitzer, observed simultaneously in four infrared wavelength bands (Fazio et al. 2004; also see Table 3.2). It is the only instrument that survives and still functions in the two shortest channels (3.6 μm and 4.5 μm channels) during the "Spitzer warm mission", where the equilibrium temperature of the telescope has risen to around 30–34 K. The Infrared Spectrograph (IRS; Houck et al. 2004), another one of the three instruments onboard Spitzer, is an infrared spectrometer which has four distinct sub-modules with different inlets of the infrared radiation into the spectrograph. The modules include a low-resolution short-wavelength (SL; 5.12–14.29 μm), a low-resolution long-wavelength (LL; 13.90–39.90 μm), a high-resolution short-wavelength (SH; 9.89–19.51 μm) and a high-resolution long-wavelength (LH; 18.70–37.20 μm) detector (see Table 3.2). The Multi-band Imaging Photometer (MIPS; Rieke et al. 2004); the other Spitzer instrument, is an imaging detector-array or camera just like the IRAC, but maps the far-infrared radiation in three wavelength bands which peak at 24.70 and 160 μm (see Table 3.2). Like IRS, MIPS is capable of performing simple spectroscopy in addition to the imaging.

3.1.3 The Large APEX BOlometer CAmera (LABOCA)

The Large APEX BOlometer CAmera (LABOCA; Siringo et al. 2009; also see Figure 3.6) is a facility instrument operating on the Atacama Pathfinder EXperiment (APEX; Güsten et al. 2006a) 12 m submillimeter telescope. APEX is located at 5105 m above sea level on the Llano de Chajnantor in the Atacama desert in northern Chile, one of the driest places on Earth. Figure 3.6 shows the APEX telescope with the arrow pointing towards LABOCA. LABOCA is a high sensitivity AC-biased and DC-coupled bolometer camera with a composite 295-element receiver made from neutron-transmutation-doped (NTD; Haller et al. 1982) germanium thermistors. It was primarily designed for fast mapping of larger sky areas. The 295 semiconducting composite bolometers are arranged in a hexagonal layout, consisting of a central channel and 9 concentric hexagons, which designate the heart of the camera (see Figures 1 and 6 of Siringo et al. 2009). LABOCA is an evolutionary receiver system exclusively designed with optimum capability for fast scanning and mapping of large areas of the sky at an unrivalled angular resolution and sensitivity.

LABOCA was developed by the Max-Planck-Institut für Radioastronomie (MPIfR) Bolometer Group in Bonn, Germany. The complex LABOCA system (see Figure 2 of Siringo et al. 2009) comprises of parts originating from technological advancements in different fields ranging from optics, high vacuum, low temperature cryogenics, digital electronics to computer hardware and software.

LABOCA was commissioned in May 2007 and observes in the submillimeter continuum at a central wavelength of 870 μm (345 GHz) in total-power scanning observing mode (see Figures 3.8 and 3.9). Figure 3.8 denotes a set of Archimedian spirals centered on a 2×2
raster in azimuth and elevation traced by the instrument during observations. The adopted standard scanning pattern for LABOCA is often referred to as a \textit{raster-spiral} scanning pattern. Figure 3.9 also represents the footprint left on the sky by the instrument during observations.

LABOCA operates at a moderate angular resolution of 19\arcmin.5 with a field of view of 11\arcmin.4. Its passband or spectral response has a full width half maximum (FWHM) of about 60 GHz ($\sim$150 $\mu$m) to match the corresponding atmospheric transmission window between 313 and 372 GHz (see Figure 3.7). The high efficiency of APEX in combination with the excellent dry atmospheric transmission at the telescope site provide unprecedented opportunity for LABOCA to map\textsuperscript{*} submillimeter continuum emission.

\begin{flushright}
\footnotesize
\textsuperscript{*}Allocation times to observe with APEX are based on the financial and other commitments during its construction; German scientists own 45\% of the observing time, 21\% for Sweden, 10\% for Chile and the remaining 24\% for the European Southern Observatory (ESO) member countries.
\end{flushright}
3.2 WISE and Spitzer Data Reduction and Analysis

The main WISE science data products are the Atlas Images, the Source Catalog and ancillary data and metadata (Cutri et al. 2011). These are already photometrically and astrometrically calibrated by adopting the standard WISE Science Data System (WSDS) pipelines developed and operated by the WISE Science Data Center (WSDC). Similar pipelines are used by the Spitzer Science Center (SSC) in processing the Spitzer data obtained from the Spitzer Heritage Archive. Photometric calibration is detailed in Jarrett et al. (2011).

The Spitzer IRS spectra used for the study were retrieved from the Infrared Science Archive (IRSA), the SINGS legacy database\(^a\) for NGC 1316 and also the Spitzer Heritage Archive\(^b\) for NGC 612. In the next subsection, an outline is given of the treatment and manipulations of the WISE data to obtain the desired results presented in Chapter 4 and 5.

3.2.1 WISE Enhanced Resolution Imaging

The mid-infrared nominal WISE Atlas Image mosaics of the investigated galaxies downloaded from the WISE (Wright et al. 2010) archive (i.e. WISE All-sky Data Products and

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\(^a\)http://irsa.ipac.caltech.edu/data/SPITZER/SINGS/galaxies/ngc1316.html

3.2 WISE and Spitzer Data Reduction and Analysis

![Diagram](image)

Figure 3.8: Azimuth-Elevation single raster-spiral scanning pattern of the central bolometer of an array in horizontal coordinates. It is optimized to image the entire field of view of LABOCA (Siringo et al. 2009).

Atlas Images were those put together via the WSDS pipelines (see Section 3.2), created from co-added single-exposure image frames (Cutri et al. 2011). The recovery processes resulted in sky intensity nominal WISE Atlas 4095×4095 pixels image mosaics at 1.375 arcsec pixel⁻¹ scale, translating to a 1°.56×1°.56 field of view. These publicly released co-added images have degraded angular resolutions (see Table 3.1) and reduced full width half maximum values (see Table 3.3) in the respective WISE bands.

The co-addition interpolation method used in creating the nominal publicly released Atlas images employs a re-sampling technique based on a matched filter extracted from the WISE point-spread function (PSF). This technique was primarily designed for optimum point sources detections. It therefore ends up smearing the images during the co-addition process, thereby rendering them less efficient for detection and resolved sources characterization. The publicly released co-added images (i.e. WISE All-sky Data Products and Atlas Images) therefore have a degraded resolution of about 30% to 40% compared to the nominal single-exposure image frames (see Cutri et al. 2011, Jarrett et al. 2011).

To avert the poor resolutions and do the photometric measurements described in Sec-
Figure 3.9: LABOCA footprint on the sky. The circles denote measured positions and FWHM sizes on sky of all the functional LABOCA detectors with appreciable signal-to-noise ratios. The coloured rings represent the possible scanning pattern of a single-channel bolometer map for a four-point raster of spirals (Sirinto et al. 2007).

In section 3.2.2, the enhanced resolution imaging and custom pipeline source characterization methods, Variable-Pixel Linear Reconstruction (known as drizzle) and the Maximum Correlation Method (MCM-HiRes; Masci & Fowler 2009) developed by the WSDC, were run on the downloaded WISE single-exposure image frames to reconstruct enhanced-resolution mosaic images of the galaxies for the study (Jarrett et al. 2012). Specifically, super-resolution images of NGC 1316 and NGC 612 were generated via the MCM-HiRes method, and native angular resolution images of NGC 5078, NGC 7172 and IC 5063 were also created using the drizzle technique. The resolution enhancement methods do not only improve the spatial resolution of the images, but also preserve the integrated flux and retain the photometric robustness of especially the low surface brightness galaxies’ extended emission.

The Image Co-addition with Optional Resolution Enhancement software package (ICORE; Masci 2013) was used to construct the high-resolution image mosaics of the galaxies at a 0’.687 pixel scale via the maximum correlation method (MCM-HiRes; Masci & Fowler 2009). The MCM-HiRes algorithm used here is an extension of the model Richardson–Lucy decon-
3.2 WISE and Spitzer Data Reduction and Analysis

<table>
<thead>
<tr>
<th>Technique</th>
<th>W1 (3.4 µm) FWHM (arcsec)</th>
<th>W2 (4.6 µm) FWHM (arcsec)</th>
<th>W3 (12 µm) FWHM (arcsec)</th>
<th>W4 (22 µm) FWHM (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlas(^a)</td>
<td>8.4</td>
<td>9.2</td>
<td>11.4</td>
<td>18.6</td>
</tr>
<tr>
<td>drizzle(^b)</td>
<td>5.9</td>
<td>6.5</td>
<td>7.0</td>
<td>12.4</td>
</tr>
<tr>
<td>MCM - HiRes(^c)</td>
<td>2.6</td>
<td>3.0</td>
<td>3.5</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Table 3.3: Techniques and Full Width Half Maximum (FWHM) of WISE Imaging:  
\(^a\) WISE nominal public release co-added images.  \(^b\) Variable-Pixel Linear Reconstruction or “drizzle” for creating the enhanced-resolution WISE native images \(^c\) MCM-HiRes technique for producing super-resolution WISE images.  [see Jarrett et al. 2012]

volution algorithm devised for bettering IRAS resolutions some years back (see Aumann et al. 1990, Fowler & Aumann 1994). This comprehensive image co-addition and resolution enhancement MCM-HiRes technique allows recovery of the WISE super-resolution image versions, ranging in FWHM from 2\(^\prime\).6 to 5\(^\prime\).5 (see Table 3.3). The images created via this technique have a beam width of \(\sim3\) arcsec, which is comparable to the Spitzer IRAC resolution of \(\sim2\) arcsec (Werner et al. 2004b), and are about 3-4 times better than the nominal WISE Atlas imaging resolution.

The standard drizzle co-addition technique employed to create the resolution-enhanced WISE native images of NGC 5078, NGC 7172 and IC 5063 at a 1\(^a\).00 pixel scale yields about a 2-3 times improvement in spatial resolution in comparison with the nominal WISE Atlas images. This was necessary to improve the native angular resolution (FWHM) of the images to the range 5\(^\prime\).9 - 12\(^\prime\).4 in the bands (see Table 3.3).

According to Jarrett et al. (2012), the deconvolution MCM-HiRes resolution enhancement approach introduces noise fluctuations and “ringing” artifacts in galaxies with smaller near-infrared diameters (\(\leq\sim2\)) and low surface brightnesses. For such sources, the moderate CPU-intensive generic drizzle co-addition method works better. This therefore informed the choices of the adopted techniques for the respective galaxies.

The pixel values of the constructed enhanced resolution WISE images are in data number (DN), and are converted into mJy/pixel by using the following conventional conversion factors: 1.9350 \times 10^{-3} (W1), 2.7048 \times 10^{-3} (W2), 1.8326 \times 10^{-3} (W3), and 5.2269 \times 10^{-2} (W4) (Wright et al. 2010, Cutri et al. 2012). For sources with steeply rising mid-infrared spectra such as the dust-enshrouded galaxy sample, the flux–magnitude conversion relation used is given by: \(F_{\text{mJy}} = [F_0 \times 10^{(-0.4 \times m_{\text{mag}}})] \times 10^3\), where \(F_0\) (the zero magnitude flux density) is 306.681 (W1), 170.663 (W2), 29.0448 (W3) and 7.870 (W4) (Wright et al. 2010; Brown, Jarrett & Cluver 2014a).

3.2.2 WISE and Spitzer Iso Photoc-Aperture Photometry

Source characterization of the WISE and Spitzer data was carried out using a software package specifically developed for WISE and Spitzer imaging, encompassed in the enhanced resolution imaging and custom pipeline source characterization (described in Jarrett et al. 2013). This interactive analysis package was developed vigorously from the Two Micron All
Sky Survey (2MASS) Extended Source Catalog (XSC) pipeline (Jarrett et al. 2000) and the WISE Photometry System (Cutri et al. 2011).

The most important steps in the characterization process included foreground star removal (PSF-subtraction), local background estimation using an elliptical-shaped annulus, ellipticity and position angle estimation from the 3σ isophote (thereafter fixed for all radii), and the radial size scaled by the 1σ isophote so that the annulus is located well outside of the target galaxy. Using a double Sérsic model to fit the galaxies’ inner and outer regions, the total integrated flux was then computed from the integrated isophotal flux and the extrapolated light extending beyond the 1σ isophote. The flux density uncertainties are computed from the background and Poisson error estimations. Finally, these global measurements were complemented with curve of growth and azimuthally-averaged surface brightness measurements that provide internal structural changes with radius (see Wright et al. 2010, Jarrett et al. 2011; 2013).

3.2.3 Radial Surface Brightness Profiles

Azimuthally averaged elliptical–radial profiles of the WISE bands images were created for the galaxies using the enhanced resolution imaging and custom pipeline source characterization techniques delineated in Sections 3.2.1 and 3.2.2.

The shapes of the WISE images profiles are simply characterized using a double modified Sérsic function fit (Sérsic 1963).

\[
SB(R) = SB_{\text{central}} \exp \left\{ -\left(\frac{R}{\alpha}\right)^{1/\beta} \right\}
\]

where \(SB(R)\) is the surface brightness at radius \(R\) (i.e. radial surface brightness), \(SB_{\text{central}}\) is the central surface brightness, \(\alpha = \text{scale length}\) (radius at which the surface brightness drops by e\(^{-1}\)), and \(\beta = \text{Sérsic index (shape parameter)}\).

3.3 LABOCA 870 μm Observations and Data Reduction

An overview of the observations, reduction and analysis of the LABOCA data is presented below. The Crush (Kovács 2008) software package was used to reduce and analyse the data.

3.3.1 LABOCA 870 μm Observations of NGC 1316 and NGC 612

The proposal to observe NGC 1316 was submitted by the APEX-LABOCA October 15, 2011 deadline (PI: Cathy Horellou), and that of NGC 612 by the October 15, 2012 deadline (PI: Bernard Duah Asabere). At the times the observing proposals were submitted, nothing was known about the submillimeter continuum emission between 160 μm (Spitzer MIPS) and 3 mm (94 GHz, WMAP) of NGC 1316, and between 170 μm (ISO) and 13.6 mm (22 GHz, ATCA) of NGC 612. The LABOCA observations were needed to add points to these empty
regions of their global spectral energy distributions. Figures 5.1 and 5.2 are spectral energy
distribution models from the near-infrared to the radio wavelength to estimate the LABOCA
(870 μm) flux densities and quantify the contributions of the various physical processes on
the overall energy distributions of the systems. The dust in NGC 1316 is located in the
inner 2' × 2' of the galaxy.

NGC 1316 was observed\(^a\) in June 2012 for 8 hours and 10 minutes. The NGC 612
observations\(^b\) were carried out in May 2013 for 3 hours and 51 minutes.

The observations were performed in satisfactory weather conditions with a typical precipit-
able water vapour (PWV) value of 0.5 mm, which corresponds to a zenith opacity of 0.2 at
the observing wavelength (i.e. 870 μm). The mapping of the cold dust was done using a set
of Archimedian spiral scanning patterns centered on a 2×2 raster in azimuth and elevation,
known as the raster-spiral scanning pattern (see Figure 3.8; and also Figure 1 of Johansson
et al. (2010); leaving footprints similar to that seen in Figure 3.9). This observational mode
is one of the standard observing set-up patterns for LABOCA. It is optimized to map the
entire field of view of the instrument.

The telescope traced a set of spirals with radii between 18′′ and 97′′ at nine raster
positions at intervals of 60′ in azimuth and elevation on each scan. This pattern resulted in
a fully sampled map of the LABOCA field of view in every single scan. The telescope
overheads were kept at a minimum with the radii and spacings of the spirals being optimized
to ensure uniform noise coverage across the entire field of view. The scanning speed was
set to between 0.5 s\(^{-1}\) and 2.5 s\(^{-1}\) and angular speed at 90° s\(^{-1}\) to modulate the source
signals into the useful post-detection bandwidth (0.1–12.5 Hz) of LABOCA. The pointings
were regularly checked on nearby sources, and were then focussed on Uranus and Neptune to
ensure better source calibrations (see Siringo et al. 2009). The atmospheric attenuation was
determined from continuous scans in elevation at a fixed azimuth (referred to as "skydips")
and radiometric measurements. For more details on the instrument’s pointings, description,
optimum observing mode settings and source calibration see Siringo et al. (2009) and Weiss
et al. (2008).

### 3.3.2 LABOCA Data Reduction: NGC 1316 and NGC 612

The streaming data from LABOCA observations is stored in Multi-Beam FITS format (MB-
FITS) by an in-built data writer in the APEX Control Software (APECS; Muders et al.
2006). The MB-FITS raw data storage format provides a suitable way of storing data which
are meant for further processing.

Bolometer array data Analysis software (BoA) is a special package developed for LABOCA
data reduction (both on-line and off-line). As part of APECS routines, the on-line data pro-
cessing pipeline does an instantaneous data reduction of each scan of the observations carried
out at APEX to give the observer a swift preliminary view of the maps or spectra being
observed. This is very important for the observer to get information about the pointing off-

\(^a\) Swedish program ID 089.F-9301(A)
\(^b\) Swedish program ID 091.F-9302(A)
sets or focus corrections to be implemented. However, only quick estimates of the correlated noise are evaluated and subtracted from the data in both the focus and pointing scans in the preview maps formed. Hence, off-line reduction is needed to produce the full and detailed dust maps of the observed sources.

In this study, the actual off-line data reduction was performed with version 2.12-2 of the Crush program, referred to here as Crush-2. Crush-2\(^a\) is a comprehensive bolometer reduction utility and imaging software package developed by Kovács (2008). It is a pipeline reduction software with many functional tools for bolometric data reduction, image manipulation and analysis. The different options (i.e., default, deep, faint and extended) were tested.

Iteratively, Crush-2 removed correlated noise from the raw data in the digitized time-streams, identified and flagged problematic or vexed data pixels, and provided clean and independent bolometer signals in the individual scans (\(~70\) for NGC 1316 and \(~90\) for NGC 612), which were then co-added to produce the final dust maps of the sources.

The flux density measurements, signal-to-noise ratio and the root-mean-square analyses and estimations were all done with the Crush-2 program.

\(^a\)http://www.suhm.caltech.edu/~sharc/crush/
Chapter 4

Global Measurements

This chapter is devoted to a presentation and analysis of the WISE and Spitzer data and the LABOCA observations. Attention is given to the analysis and manipulation of the data and image products to obtain the global measurements of the galaxies needed for estimating the stellar and dust properties. It highlights on the analysis of the LABOCA data to retrieve the dust distribution of NGC 1316 and NGC 612 in the submillimeter band, and compare the dust maps with existing images.

4.1 WISE and Spitzer Photometry

The different spectral bands of the mid-infrared emission have special information (see Section 5.2) relevant for tracing the stellar mass, recent star formation, AGN activity, and the distribution of dust. To show the emission distributions in the WISE and Spitzer bands of the galaxies and retrieve the needed measurements for stellar and dust properties investigation, aperture photometry was performed on the images/data retrieved from their respective archives, after enhancing their resolutions.

In the case of WISE, WISE single-exposure (Level 1B) image frames were taken to reconstruct enhanced-resolution mosaic images to create new mosaics; followed by source characterization and related measurements of the galaxies. This has been discussed in Section 3.2.1 (also see Jarrett et al. 2013).

A double Sersic model was used to fit the galaxies’ inner and outer regions in these reconstructed images. The total integrated flux was then computed from the integrated isophotal flux and the extrapolated light that extends beyond the 1σ isophote. These global measurements were complemented with curve of growth and azimuthally-averaged surface brightness measurements that highlighted internal structural changes with radius. The flux density uncertainties were computed from the background and Poisson error estimations (see Wright et al. 2010, Jarrett et al. 2011; 2013).

Tables 4.1 and 4.2 present the WISE aperture photometric measurements of NGC 1316 and NGC 612 in all the four bands. The measurements in the WISE bands and the Spitzer
Figure 4.1: Mid-infrared spectral energy distribution of the galaxies using the WISE integrated flux density measurements. For NGC 5078, NGC 7172 and IC 5063, both the WISE and Spitzer points are plotted. At short wavelengths, the decrease of the stellar continuum at the Rayleigh–Jeans part of the spectrum is clearly seen in NGC 1316, NGC 612 and NGC 5078.

IRAC and MIPS bands of NGC 5078, NGC 7172 and IC 5063 are also recorded in Table 4.3 - 4.8. Those Spitzer flux measurements have not been done before and are being reported for the first time.

Figure 4.1 shows the mid-infrared emission distribution in the galaxies. The intention was to reveal the distribution of the galaxies global flux measurements. The galaxies show varying levels of fall in emission in the Rayleigh–Jeans part at lower wavelength. The emission in NGC 1316 decreases rather steeply with wavelength, which is almost opposite to the case of IC 5063. This is related to their morphologies (as E and S0 galaxies; see Figure 4.4) and star formation potentials (see Table 4.11). The shapes of the emission distribution in NGC 612 and NGC 5078 are similar. Longward of the 8 μm point, emission increases steadily in NGC 612, NGC 5078 and NGC 7172, but steeply in IC 5063. This is due to the star formation in the ISM traced by warm dust grains.

The WISE flux density measurements in the four bands of NGC 1316 (see Table 4.1)
<table>
<thead>
<tr>
<th>NGC 1316</th>
<th>W1 (3.4 μm)</th>
<th>W2 (4.6 μm)</th>
<th>W3 (12 μm)</th>
<th>W4 (22 μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA&lt;sup&gt;a&lt;/sup&gt; (deg)</td>
<td>34.7</td>
<td>34.7</td>
<td>34.7</td>
<td>34.7</td>
</tr>
<tr>
<td>AR&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>R&lt;sub&gt;pos&lt;/sub&gt; (arcsec)</td>
<td>761.1</td>
<td>588.7</td>
<td>188.0</td>
<td>101.6</td>
</tr>
<tr>
<td>R&lt;sub&gt;eff&lt;/sub&gt; (arcsec)</td>
<td>101.3</td>
<td>93.4</td>
<td>62.2</td>
<td>39.5</td>
</tr>
<tr>
<td>Int. Flux&lt;sup&gt;c&lt;/sup&gt; (mJy)</td>
<td>2843.10 ± 29.82</td>
<td>1488.78 ± 15.62</td>
<td>449.90 ± 4.78</td>
<td>325.11 ± 4.06</td>
</tr>
<tr>
<td>Int. Magnitude&lt;sup&gt;d&lt;/sup&gt; (mag)</td>
<td>5.08 ± 0.01</td>
<td>5.15 ± 0.01</td>
<td>4.53 ± 0.01</td>
<td>3.46 ± 0.01</td>
</tr>
<tr>
<td>S&lt;sub&gt;B&lt;/sub&gt;&lt;sup&gt;e&lt;/sup&gt; (mag/arcsec&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>16.61</td>
<td>16.50</td>
<td>14.82</td>
<td>12.73</td>
</tr>
<tr>
<td>S&lt;sub&gt;B&lt;/sub&gt;&lt;sup&gt;f&lt;/sup&gt; (mag/arcsec&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>13.58</td>
<td>13.61</td>
<td>12.67</td>
<td>11.98</td>
</tr>
<tr>
<td>Total Flux&lt;sup&gt;g&lt;/sup&gt; (mJy)</td>
<td>2895.63</td>
<td>1520.94</td>
<td>537.80</td>
<td>401.82</td>
</tr>
<tr>
<td>Total Magnitude&lt;sup&gt;h&lt;/sup&gt; (mag)</td>
<td>5.06</td>
<td>5.13</td>
<td>4.33</td>
<td>3.23</td>
</tr>
<tr>
<td>Total Radius&lt;sup&gt;i&lt;/sup&gt; (arcsec)</td>
<td>1141.7</td>
<td>1141.7</td>
<td>282.0</td>
<td>207.0</td>
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<td>Reduced chi-squared&lt;sup&gt;j&lt;/sup&gt;</td>
<td>57.33</td>
<td>53.57</td>
<td>22.11</td>
<td>4.67</td>
</tr>
</tbody>
</table>

Table 4.1: WISE isophotal-aperture photometry of NGC 1316 of nuclear Right Ascension (J2000) 50.67380<sup>°</sup> and Declination (J2000) -37.20796<sup>°</sup>:<br><sup>a</sup> and <sup>b</sup> are the position angle and axis ratio of the W1 3σ isophote respectively. <sup>c</sup> 1σ isophotal radius or semi-major axis for the aperture photometry. <sup>d</sup> Effective (half-light) radius. <sup>e</sup> and <sup>f</sup> are the respective integrated flux density and integrated magnitude within <sup>c</sup> and <sup>b</sup>. <sup>g</sup> Effective (half-light) surface brightness. <sup>h</sup> Concentration index (75% to 25% light ratio). <sup>i</sup> Central surface brightness. <sup>j</sup> Total flux density and <sup>b</sup> total magnitude are the respective measurements within an aperture of <sup>i</sup> total radius. <sup>k</sup> The reduce chi-squared for the profile-fit photometry

<table>
<thead>
<tr>
<th>NGC 612</th>
<th>W1 (3.4 μm)</th>
<th>W2 (4.6 μm)</th>
<th>W3 (12 μm)</th>
<th>W4 (22 μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA&lt;sup&gt;a&lt;/sup&gt; (deg)</td>
<td>170.9</td>
<td>170.9</td>
<td>170.9</td>
<td>170.9</td>
</tr>
<tr>
<td>AR&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.60</td>
<td>0.60</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>R&lt;sub&gt;pos&lt;/sub&gt; (arcsec)</td>
<td>141.3</td>
<td>92.6</td>
<td>48.6</td>
<td>44.3</td>
</tr>
<tr>
<td>R&lt;sub&gt;eff&lt;/sub&gt; (arcsec)</td>
<td>16.7</td>
<td>13.8</td>
<td>14.0</td>
<td>17.6</td>
</tr>
<tr>
<td>Int. Flux (mJy)</td>
<td>67.93 ± 0.73</td>
<td>39.64 ± 0.43</td>
<td>113.90 ± 1.23</td>
<td>136.78 ± 2.07</td>
</tr>
<tr>
<td>Int. Magnitude (mag)</td>
<td>9.14 ± 0.01</td>
<td>9.09 ± 0.01</td>
<td>6.02 ± 0.01</td>
<td>4.40 ± 0.02</td>
</tr>
<tr>
<td>S&lt;sub&gt;B&lt;/sub&gt;&lt;sup&gt;e&lt;/sup&gt; (mag/arcsec&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>16.65</td>
<td>16.19</td>
<td>13.04</td>
<td>11.97</td>
</tr>
<tr>
<td>S&lt;sub&gt;B&lt;/sub&gt;&lt;sup&gt;f&lt;/sup&gt; (mag/arcsec&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>5.29</td>
<td>4.20</td>
<td>3.24</td>
<td>3.06</td>
</tr>
<tr>
<td>Total Flux (mJy)</td>
<td>20.57</td>
<td>19.60</td>
<td>15.13</td>
<td>13.51</td>
</tr>
<tr>
<td>Total Magnitude (mag)</td>
<td>70.25</td>
<td>40.80</td>
<td>130.17</td>
<td>148.60</td>
</tr>
<tr>
<td>Total Radius (arcsec)</td>
<td>9.10</td>
<td>9.05</td>
<td>5.87</td>
<td>4.31</td>
</tr>
<tr>
<td>Reduced chi-squared</td>
<td>211.9</td>
<td>213.1</td>
<td>145.7</td>
<td>84.9</td>
</tr>
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</table>

Table 4.2: WISE isophotal-aperture photometry of NGC 612 of nuclear Right Ascension (J2000) 23.49028<sup>°</sup> and Declination (J2000) -36.49324<sup>°</sup>. Quantities in column 1 are the same as in Table 4.1.

are in good agreement with the corresponding Spitzer IRAC and MIPS values reported in Table 1 of Dale et al. (2005). For NGC 612, the measurement in W4 compares very well with the IRAS value at 25 μm (130 ± 33 mJy; NED). The W3 flux is significantly lower than the 12 μm IRAS flux (200 ± 35 mJy; NED) and the 9 μm AKARI flux of 135 mJy (Ichikawa
Table 4.3: WISE isophotal-aperture photometry of NGC 5078 of nuclear Right Ascension (J2000) 199.95856°, and Declination (J2000) -27.41013°. For a description of the quantities in column 1, see Table 4.1.

<table>
<thead>
<tr>
<th>NGC 5078</th>
<th>W1 (3.4 μm)</th>
<th>W2 (4.6 μm)</th>
<th>W3 (12 μm)</th>
<th>W4 (22 μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA (deg)</td>
<td>145.7</td>
<td>145.7</td>
<td>145.7</td>
<td>145.7</td>
</tr>
<tr>
<td>AR</td>
<td>0.39</td>
<td>0.39</td>
<td>0.39</td>
<td>0.39</td>
</tr>
<tr>
<td>R_{iso} (arcsec)</td>
<td>379.3</td>
<td>276.1</td>
<td>164.0</td>
<td>117.5</td>
</tr>
<tr>
<td>R_{eff} (arcsec)</td>
<td>38.8</td>
<td>34.0</td>
<td>32.3</td>
<td>34.8</td>
</tr>
<tr>
<td>Int. Flux (mJy)</td>
<td>636.94 ± 6.68</td>
<td>361.74 ± 3.80</td>
<td>683.30 ± 7.21</td>
<td>816.64 ± 9.36</td>
</tr>
<tr>
<td>Int. Magnitude (mag)</td>
<td>6.71 ± 0.01</td>
<td>6.68 ± 0.01</td>
<td>4.07 ± 0.01</td>
<td>2.46 ± 0.01</td>
</tr>
<tr>
<td>S_{B,iso} (mag/arcsec²)</td>
<td>15.60</td>
<td>15.31</td>
<td>12.52</td>
<td>11.11</td>
</tr>
<tr>
<td>S_{B,central} (mag/arcsec²)</td>
<td>5.90</td>
<td>4.91</td>
<td>3.41</td>
<td>2.86</td>
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<tr>
<td>Total Flux (mJy)</td>
<td>653.04</td>
<td>364.49</td>
<td>727.67</td>
<td>847.29</td>
</tr>
<tr>
<td>Total Magnitude (mag)</td>
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<td>6.68</td>
<td>4.00</td>
<td>2.42</td>
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<tr>
<td>Total Radius (arcsec)</td>
<td>568.9</td>
<td>568.9</td>
<td>246.0</td>
<td>246.0</td>
</tr>
<tr>
<td>Reduced chi-squared</td>
<td>110.00</td>
<td>68.38</td>
<td>70.59</td>
<td>66.09</td>
</tr>
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</table>

Table 4.4: Spitzer isophotal-aperture photometry of NGC 5078 of nuclear Right Ascension (J2000) 199.95857°, and Declination (J2000) -27.41033°:

<table>
<thead>
<tr>
<th>NGC 5078</th>
<th>IRAC 1 (3.6 μm)</th>
<th>IRAC 2 (4.5 μm)</th>
<th>IRAC 3 (5.8 μm)</th>
<th>IRAC 4 (8 μm)</th>
<th>MIPS 24 (24 μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA² (deg)</td>
<td>144.8</td>
<td>144.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ARb (arcsec)</td>
<td>0.42</td>
<td>0.42</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>R_{iso} (arcsec)</td>
<td>188.0</td>
<td>188.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Int. Flux (mJy)</td>
<td>525.32 ± 9.69</td>
<td>346.85 ± 6.41</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Int. Magnitude (mag)</td>
<td>6.82 ± 0.02</td>
<td>6.79 ± 0.02</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

(a) and (b) are the position angle and axis ratio of the W1 3σ isophote respectively. (c) 1σ isophotal radius or semi-major axis for the aperture photometry. (d) and (e) are the respective integrated flux density and integrated magnitude within an aperture of (c) and (b).

et al. 2012). Similarly, the respective WISE flux density measurements of NGC 5078, NGC 7172 and IC 5063 (listed in Tables 4.2, 4.5 and 4.7) and Spitzer (also in Tables 4.4, 4.6 and 4.8) are consistent with each other.

In the bulge-dominated NGC 1316, the light is dominated by the Rayleigh-Jeans stellar component which is much stronger in W3 compared to W4 (i.e., W3/W4 > 1), whereas for the disk-dominated or S0 galaxies (NGC 612, NGC 5078, NGC 7172 and IC 5063) the interstellar medium continuum (i.e., W3) emission is rather much less strong compared to the dust (i.e., W4) emission. There is however, a sudden drop in the WISE fluxes from W1 to W2 in NGC 1316. NGC 612 and NGC 5078 that is not observed in the other objects.

Interestingly, the increasing flux density with wavelength in IC 5063 is the reverse of the scenario of the flux distribution in the NGC 1316. The same trends are seen when the WISE fluxes are measured in the same aperture for each galaxy (Table 5.7). This could be due to the AGN activity and/or star formation in the central region of the galaxy (Morganti...
### Table 4.5: WISE isophotal-aperture photometry of NGC 7172 of nuclear Right Ascension (J2000) 330.50787°, and Declination (J2000) -31.86960°. See Table 4.1 for the description of the quantities in column 1.

<table>
<thead>
<tr>
<th>NGC 7172</th>
<th>W1 (3.4 μm)</th>
<th>W2 (4.6 μm)</th>
<th>W3 (12 μm)</th>
<th>W4 (22 μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA (deg)</td>
<td>101.7</td>
<td>101.7</td>
<td>101.7</td>
<td>101.7</td>
</tr>
<tr>
<td>AR</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
</tr>
<tr>
<td>R_{iso} (arcsec)</td>
<td>125.8</td>
<td>101.4</td>
<td>67.9</td>
<td>59.9</td>
</tr>
<tr>
<td>R_{eff} (arcsec)</td>
<td>12.8</td>
<td>8.3</td>
<td>12.6</td>
<td>17.7</td>
</tr>
<tr>
<td>Int. Flux (mJy)</td>
<td>235.10 ± 2.48</td>
<td>212.32 ± 2.23</td>
<td>296.20 ± 3.16</td>
<td>529.70 ± 6.11</td>
</tr>
<tr>
<td>Int. Magnitude (mag)</td>
<td>7.79 ± 0.01</td>
<td>7.26 ± 0.01</td>
<td>4.98 ± 0.01</td>
<td>2.93 ± 0.01</td>
</tr>
<tr>
<td>SB_{eff} (mag/arcsec²)</td>
<td>14.77</td>
<td>13.31</td>
<td>11.88</td>
<td>10.51</td>
</tr>
<tr>
<td>SB_{central} (mag/arcsec²)</td>
<td>14.52</td>
<td>13.68</td>
<td>11.64</td>
<td>10.86</td>
</tr>
<tr>
<td>Total Flux (mJy)</td>
<td>239.01</td>
<td>214.67</td>
<td>313.53</td>
<td>591.60</td>
</tr>
<tr>
<td>Total Magnitude (mag)</td>
<td>7.77</td>
<td>7.25</td>
<td>4.92</td>
<td>2.81</td>
</tr>
<tr>
<td>Total Radius (arcsec)</td>
<td>188.7</td>
<td>188.7</td>
<td>134.7</td>
<td>179.8</td>
</tr>
<tr>
<td>Reduced chi-squared</td>
<td>14.96</td>
<td>4.81</td>
<td>14.94</td>
<td>3.38</td>
</tr>
</tbody>
</table>

### Table 4.6: Spitzer isophotal-aperture photometry of NGC 7172 of nuclear Right Ascension (J2000) 330.50801°, and Declination (J2000) -31.86950°. Quantities column 1 are the same as in Table 4.4.

<table>
<thead>
<tr>
<th>NGC 7172</th>
<th>IRAC 1 (3.6 μm)</th>
<th>IRAC 2 (4.5 μm)</th>
<th>IRAC 3 (5.8 μm)</th>
<th>IRAC 4 (8 μm)</th>
<th>MIPS 24 (24 μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA (deg)</td>
<td>93.9</td>
<td>93.9</td>
<td>93.9</td>
<td>93.9</td>
<td>93.9</td>
</tr>
<tr>
<td>AR</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
</tr>
<tr>
<td>R_{iso} (arcsec)</td>
<td>119.24</td>
<td>110.01</td>
<td>68.82</td>
<td>75.52</td>
<td>78.25</td>
</tr>
<tr>
<td>Int. Flux (mJy)</td>
<td>216.73 ± 4.00</td>
<td>175.99 ± 3.25</td>
<td>306.19 ± 5.73</td>
<td>480.47 ± 8.90</td>
<td>542.02 ± 10.28</td>
</tr>
<tr>
<td>Int. Magnitude (mag)</td>
<td>7.78 ± 0.02</td>
<td>7.52 ± 0.02</td>
<td>6.44 ± 0.02</td>
<td>5.31 ± 0.02</td>
<td>2.81 ± 0.02</td>
</tr>
</tbody>
</table>

### IC 5063

<table>
<thead>
<tr>
<th></th>
<th>W1 (3.4 μm)</th>
<th>W2 (4.6 μm)</th>
<th>W3 (12 μm)</th>
<th>W4 (22 μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$PA$ (deg)</td>
<td>131.2</td>
<td>131.2</td>
<td>131.2</td>
<td>131.2</td>
</tr>
<tr>
<td>$AR$</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
</tr>
<tr>
<td>$R_{iso}$ (arcsec)</td>
<td>113.5</td>
<td>95.1</td>
<td>96.6</td>
<td>99.0</td>
</tr>
<tr>
<td>$R_{eff}$ (arcsec)</td>
<td>15.5</td>
<td>6.6</td>
<td>8.5</td>
<td>12.1</td>
</tr>
<tr>
<td>Int. Flux (mJy)</td>
<td>154.59 ± 1.63</td>
<td>165.59 ± 1.74</td>
<td>867.06 ± 9.13</td>
<td>3133.50 ± 33.25</td>
</tr>
<tr>
<td>Int. Magnitude (mag)</td>
<td>8.24 ± 0.01</td>
<td>7.53 ± 0.01</td>
<td>3.81 ± 0.01</td>
<td>1.00 ± 0.01</td>
</tr>
<tr>
<td>$SB_{eff}$ (mag/arcsec$^2$)</td>
<td>16.04</td>
<td>13.49</td>
<td>10.30</td>
<td>8.25</td>
</tr>
<tr>
<td>$Con_{index}$</td>
<td>6.49</td>
<td>5.37</td>
<td>3.70</td>
<td>3.70</td>
</tr>
<tr>
<td>$SB_{central}$ (mag/arcsec$^2$)</td>
<td>15.66</td>
<td>14.49</td>
<td>10.76</td>
<td>9.67</td>
</tr>
<tr>
<td>Total Flux (mJy)</td>
<td>157.87</td>
<td>167.44</td>
<td>893.45</td>
<td>3221.29</td>
</tr>
<tr>
<td>Total Magnitude (mag)</td>
<td>8.22</td>
<td>7.52</td>
<td>3.78</td>
<td>0.97</td>
</tr>
<tr>
<td>Total Radius (arcsec)</td>
<td>170.2</td>
<td>170.2</td>
<td>144.8</td>
<td>148.4</td>
</tr>
<tr>
<td>Reduced chi-squared</td>
<td>21.61</td>
<td>3.40</td>
<td>2.91</td>
<td>1.35</td>
</tr>
</tbody>
</table>

Table 4.7: WISE isophotal-aperture photometry of IC 5063 of nuclear Right Ascension (J2000) 313.00974°, and Declination (J2000) -57.06875°. Quantities column 1 are the same as in Table 4.1.

<table>
<thead>
<tr>
<th></th>
<th>IRAC 1 (3.6 μm)</th>
<th>IRAC 2 (4.5 μm)</th>
<th>IRAC 3 (5.8 μm)</th>
<th>IRAC 4 (8 μm)</th>
<th>MIPS 24 (24 μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$PA$ (deg)</td>
<td>40.7</td>
<td>40.7</td>
<td>40.7</td>
<td>40.7</td>
<td>40.7</td>
</tr>
<tr>
<td>$AR$</td>
<td>0.82</td>
<td>0.82</td>
<td>0.82</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td>$R_{iso}$ (arcsec)</td>
<td>69.40</td>
<td>51.78</td>
<td>36.63</td>
<td>46.46</td>
<td>69.22</td>
</tr>
<tr>
<td>Int. Flux (mJy)</td>
<td>156.67 ± 2.90</td>
<td>153.38 ± 2.86</td>
<td>314.68 ± 6.15</td>
<td>466.93 ± 8.85</td>
<td>2940.71 ± 54.32</td>
</tr>
<tr>
<td>Int. Magnitude (mag)</td>
<td>8.13 ± 0.02</td>
<td>7.67 ± 0.02</td>
<td>6.41 ± 0.02</td>
<td>5.35 ± 0.02</td>
<td>0.97 ± 0.02</td>
</tr>
</tbody>
</table>

Table 4.8: Spitzer isophotal-aperture photometry of IC 5063 of nuclear Right Ascension (J2000) 313.00987°, and Declination (J2000) -57.06877°. Quantities column 1 are the same as in Table 4.4.
4.2 Elliptical-Radial Surface Brightness Profiles

Figure 4.2: Azimuthal elliptical–radial surface brightness profiles of NGC 1316 WISE images. The plots show the mean radial surface brightness distribution profiles of the respective bands. In each plot, the dashed vertical purple line marks the 1σ isophote radius and the red triangle is the 1σ isophote surface brightness. A double Sersic function, shown by the dotted black line, is fitted to the radial profile. The green dashed curve is the 1st Sersic fit (bulge component), and the orange dotted line is the 2nd Sersic fit (disk component). The dashed blue line is the sum of the two components.
Figure 4.3: Azimuthal elliptical–radial surface brightness profiles of NGC 612 WISE images. Caption is the same as in Figure 4.2.
Table 4.9: Parameters from the mean radial surface brightness distribution of the double Sérsic fit to the WISE images of NGC 1316 (see radial surface brightness distribution in Figure 4.2). $\alpha$ is the scalelength (radius at which the surface brightness drops by a factor of $e^{-1}$), and $\beta$ is the Sérsic index for the respective fits.

<table>
<thead>
<tr>
<th>Band</th>
<th>First Sérsic $\alpha$ (kpc)</th>
<th>First Sérsic $\beta$</th>
<th>Second Sérsic $\alpha$ (kpc)</th>
<th>Second Sérsic $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1 (3.4 $\mu$m)</td>
<td>0.46</td>
<td>1.55</td>
<td>5.83</td>
<td>1.36</td>
</tr>
<tr>
<td>W2 (4.6 $\mu$m)</td>
<td>0.28</td>
<td>2.00</td>
<td>3.98</td>
<td>1.62</td>
</tr>
<tr>
<td>W3 (12 $\mu$m)</td>
<td>0.28</td>
<td>1.95</td>
<td>3.43</td>
<td>1.62</td>
</tr>
<tr>
<td>W4 (22 $\mu$m)</td>
<td>0.28</td>
<td>0.95</td>
<td>1.52</td>
<td>1.30</td>
</tr>
</tbody>
</table>

Table 4.10: Parameters from the mean radial surface brightness distribution of the double Sérsic fit to the WISE images of NGC 612 (see radial surface brightness distribution in Figure 4.3). As in Table 4.9, $\alpha$ is the scalelength, and $\beta$ is the Sérsic index for the respective fits.

<table>
<thead>
<tr>
<th>Band</th>
<th>First Sérsic $\alpha$ (kpc)</th>
<th>First Sérsic $\beta$</th>
<th>Second Sérsic $\alpha$ (kpc)</th>
<th>Second Sérsic $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1 (3.4 $\mu$m)</td>
<td>2.95</td>
<td>1.25</td>
<td>58.36</td>
<td>0.50</td>
</tr>
<tr>
<td>W2 (4.6 $\mu$m)</td>
<td>2.95</td>
<td>1.15</td>
<td>13.03</td>
<td>1.40</td>
</tr>
<tr>
<td>W3 (12 $\mu$m)</td>
<td>4.13</td>
<td>0.90</td>
<td>25.70</td>
<td>0.68</td>
</tr>
<tr>
<td>W4 (22 $\mu$m)</td>
<td>2.95</td>
<td>1.40</td>
<td>8.84</td>
<td>0.66</td>
</tr>
</tbody>
</table>

The radial surface brightness distribution of a galaxy provides vital information about the shape and recent history of activity (starburst or AGN) in the galaxy. Azimuthally averaged elliptical-radial distribution profiles of the WISE band images were created for the galaxies using the enhanced resolution imaging and custom pipeline source characterization techniques delineated in Sections 3.2.1 and 3.2.3 to further reveal their starlight (shape) and dust (star formation) properties.

The shapes of the WISE images profiles were characterized using double modified Sérsic function fit defined by the Equation 3.1 discussed in Section 3.2.3. The main difference between this approach of surface brightness distribution analysis and GALFIT 5.2 technique is that whereas GALFIT uses the complete Sérsic function, the enhanced resolution imaging and custom pipeline source characterization technique employs modified (modified) Sérsic function.

The elliptical-radial surface brightness distribution profiles and the best-fit parameters of NGC 1316 and NGC 612 are presented in Figures 4.2 and 4.3, and Tables 4.9 and 4.10. The best-fit parameters presented denote the two classes of the sample in the study: elliptical and S0 galaxies. The Sérsic index of NGC 1316 ranges between 1 and 2, which is an example of a pseudo-bulge elliptical galaxy (Gadotti 2008) with potentials for current star formation activity (as confirmed in Table 4.11). However, NGC 612 has a Sérsic index of 1, which is typical of a disk-like galaxy.

Compared to NGC 612, there are deviations between the data (dotted blue lines) and the surface brightness distribution profiles (dotted black lines) in NGC 1316, especially in
the W1 to W3 bands. This means that NGC 1316 has significant deviations from symmetry.

Also shown in Figures A.1, A.2 and A.3 in Appendix A are the radial surface brightness distribution profiles of NGC 5078, NGC 7172 and IC 5063. For these galaxies the profiles look largely symmetric with slight deviations. But in all the galaxies studied, the surface brightness distributions look asymmetric away from the center beyond the 1σ isophote surface brightness in the longer wavelength bands due to the interstellar medium contribution. The relatively intense star formation and/or AGN activity in IC 5063 is responsible for the highly asymmetric profiles in the W3 and W4 bands.

### 4.3 Stellar Mass and Star Formation Rate Estimations

Total stellar masses and histories of star formation rates are two essential parameters for the study of galaxy mass assembly and evolution. The stellar masses of the galaxy sample were estimated using the mid-infrared WISE short-wavelength (W1 and W2) bands, and current star formation rates using the long-wavelength (W3 and W4) bands in Sections 4.3.1 and 4.3.2, respectively.

#### 4.3.1 Stellar Mass Estimations

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$D^a$ (Mpc)</th>
<th>$(W1 - W2)_{rest}^b$ (mag)</th>
<th>$SFR_{W3}^c$ ($M_\odot$ yr$^{-1}$)</th>
<th>$SFR_{W4}^c$ ($M_\odot$ yr$^{-1}$)</th>
<th>$\log M_{stellar}^*$ ($M_\odot$)</th>
<th>$SFE_{W4}^d$ $\times 10^{-3}$ yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1316</td>
<td>20.0</td>
<td>-0.023</td>
<td>1.7 ± 0.03</td>
<td>0.7 ± 0.01</td>
<td>11.75</td>
<td>1.4</td>
</tr>
<tr>
<td>NGC 612</td>
<td>125.0</td>
<td>0.096</td>
<td>19.6 ± 0.4</td>
<td>7.3 ± 0.1</td>
<td>11.41</td>
<td>0.9</td>
</tr>
<tr>
<td>NGC 5078</td>
<td>35.5</td>
<td>0.056</td>
<td>9.0 ± 0.2</td>
<td>4.0 ± 0.2</td>
<td>11.40</td>
<td>5.1</td>
</tr>
<tr>
<td>NGC 7172</td>
<td>33.5</td>
<td>0.534</td>
<td>3.2 ± 0.1</td>
<td>2.6 ± 0.04</td>
<td>9.70</td>
<td>1.2</td>
</tr>
<tr>
<td>IC 5063</td>
<td>47.2</td>
<td>0.724</td>
<td>21.5 ± 0.4</td>
<td>19.4 ± 0.3</td>
<td>9.34</td>
<td>64.7</td>
</tr>
</tbody>
</table>

Table 4.11: Mid-infrared quantities based on WISE measurements:

$^a$ Average distance to the galaxy (taken from NASA NED). $^b$ Rest-frame redshift color-corrected W1–W2 WISE color. $^c$ and $^d$ are star formation rates based on W3 (12 μm) and W3 (22 μm), respectively. $^e$ Stellar mass of the galaxy, after rest-frame redshift color corrections. $^f$ Stellar formation efficiency of the galaxy at the SFR$_{W4}$ given the amounts of molecular mass in Tables 2.1 and 2.2.

The WISE W1 (3.4 μm) band is sensitive to evolved luminous stars that dominate the bolometric luminosity of the early-type galaxy. It is a major stellar emission component of the host galaxy. Based on stellar masses estimations from the Galaxy And Mass Assembly project (GAMA; see Taylor et al. 2011), Cluver et al. (2014) derived an expression (see Equation 4.1) based on the W1 for determining the stellar masses of resolved low redshift ($z < 0.15$) early-type galaxies as:

$$
\log_{10}[M_{stellar}/L_{W1}] = -2.54(W1 - W2) - 0.17
$$

(4.1)

where $L_{W1} (L_\odot) = 10^{0.4(M - M_{sun})}$, $M_{sun} = 3.24$ (Jarrett et al. 2013). $M$ is the absolute
magnitude of the galaxy in $W1$ and $(W1 - W2)$ is the WISE rest-frame color of the galaxy.

Using Equation 4.1, the stellar masses of the galaxy sample were estimated, after rest-frame redshift color corrections. The measurements of stellar masses in logarithmic units are presented in column 6 of Table 4.11. NGC 1316, the most massive source of the sample, has the largest stellar mass. It also has the largest stellar mass of the Skibba et al. (2011) sample of 62 galaxies and the Galametz et al. (2012) sample of 11 galaxies from the KINGFISH survey, who recorded 11.4 and 11.5 respectively compared to the 11.8 obtained in this study. NGC 1316 is also in the top 1% of all galaxies in terms of host mass in the GAMA project (see Cluver et al. 2014). NGC 612 is quite a massive source: its stellar mass is more than a half of that of NGC 1316.

The average stellar mass (in logarithmic unit) of the galaxies studied here is 10.72 $(31.2 \times 10^{10} \, M_\odot)$, which is also in the top 20% of Skibba et al’s sample. The variance and standard deviation of the stellar mass distribution are 0.989 and 0.994 respectively. The least massive, IC 5063, compares well with NGC 3077 (Walter et al. 2011) in stellar mass estimates, and NGC 7172 also with NGC 4631 (see Skibba et al. 2011).

### 4.3.2 Star Formation Rate (SFR) Estimations

Further, the dust-corrected Hα-derived mid-infrared star formation rate (SFR) calibrations based on the WISE $W3$ (12 μm) and $W4$ (22 μm) bands by Cluver et al. (2014) were used to evaluate the SFRs of the galaxies.

\[
\log_{10} \text{SFR}_{H\alpha}(M_\odot \, yr^{-1}) = 1.08 \log_{10} \nu L_{12\mu m}(L_\odot) - 9.66 \tag{4.2}
\]

\[
\log_{10} \text{SFR}_{H\alpha}(M_\odot \, yr^{-1}) = 0.82 \log_{10} \nu L_{22\mu m}(L_\odot) - 7.3 \tag{4.3}
\]

where $\nu L_{12}(L_\odot)$ and $\nu L_{22}(L_\odot)$ are the respective normalized spectral luminosities of the $W3$ (12 μm) and $W4$ (22 μm) bands.

The evaluated star formation rates of the galaxies are presented together with the stellar mass estimations in Table 4.11. However, for such evolved early-type galaxies, there are varying contributions towards the emission in the W3 (12 μm) image (see Smith et al. 2007; Jarrett et al 2013). Hence, the SFR estimations using the $W4$ (22 μm) band look more reasonable and credible, and will therefore be regarded as the star formation rates of the galaxies. However, contribution from the AGN in the $W4$ will cause over-estimation of the SFR.

The mean SFR and standard deviation of the galaxies are and $7 \, M_\odot \, yr^{-1}$ respectively. Molecular clouds (of gas and dust) which collapses gravitationally under their own weight to result in star formation, do so when the density of the cloud is high enough to be unstable under the local shear conditions. NGC 1316. with massive evolved stars (with stellar mass about 95 times that of the least massive IC 5063: see last column of Table 4.11) has the smallest star formation rate of $0.7 \, M_\odot \, yr^{-1}$. However, the specific star formation rates of the galaxies range from $9.8 \times 10^{-13} \, yr^{-1}$ in NGC 1316 to $2.5 \times 10^{-9} \, yr^{-1}$ in IC 5063.
For the S0 galaxies (i.e., NGC 612, NGC 5078, NGC 7172 and IC 5063), the SFR is proportional to the amount of atomic gas measured therein (see Tables 2.1 and 2.2). Of these galaxies, IC 5063, with the highest detected gas context, has the highest star formation rate (19.4 M$_\odot$ yr$^{-1}$) compared to the $\sim$10 M$_\odot$ yr$^{-1}$ of the nearby M 82; Förster Schreiber et al. (2003), whilst NGC 7172 has the least atomic gas amount and the lowest star formation rate. IC 5063 is similar to the starburst galaxy NGC 337 in terms of SFR (19.9 M$_\odot$ yr$^{-1}$; see Calzetti et al. 2010) and stellar mass (9.32 M$_\odot$; see Skibba et al. 2011). The high SFR in the galaxy is due the emission contribution in the W4 from the central AGN.

The mid-infrared traces obscured star formation that is hidden from the ultraviolet, but the measurements listed in Table 4.11 compare well with those listed in Table 1 of Skibba et al. (2011), which used a combination of far-ultraviolet and total infrared luminosities (Hao et al. 2011), and are also in good agreements with the morphological classifications revealed by the band colors (see Figure 4.4) of the respective galaxies.

Star formation efficiencies (SFE; the star formation rate per unit molecular hydrogen mass) estimated from the star formation rates (SFR$_W$; column 5 of Table 4.11) and the amount of molecular hydrogen gas (MH$_2$; Tables 2.1 and 2.2) in the respective galaxies range from $9 \times 10^{-9}$ yr$^{-1}$ to $65 \times 10^{-9}$ yr$^{-1}$ in IC 5063. This compares with the average value of $1.5 \times 10^{-8}$ yr$^{-1}$ for a sample of spiral galaxies (Bigiel et al. 2011).

At the current star formation rates, it will take about 0.7 and 1.1 Gyrs for all the local gas in NGC 1316 and NGC 612 respectively to be converted to stars. Likewise, NGC 5078 and NGC 7172 will take approximately 0.2 and 0.8 Gyrs to transform all their molecular gas into stars. IC 5063 with the highest star formation rate and nuclear activity, will take the shortest period of 15.5 Myrs to convert all its local gas into stars. Although, the star formation rates listed in Table 4.11 were over-estimated due to the AGN emission in the W4 band, the most important scenario here is that star formation in these early-type galaxies will continues for a while unless they host supermassive black holes to accrete gas therein or undergo further gas-stripping interactions. This explains why many perceived old galaxies of merger origins still have traces of current star formation.

### 4.4 WISE Colors

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>[W1 − W2] (mag)</th>
<th>[W2 − W3] (mag)</th>
<th>[W1 − W3] (mag)</th>
<th>[W3 − W4] (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1316</td>
<td>$-0.022 \pm 0.016$</td>
<td>$0.623 \pm 0.016$</td>
<td>$0.601 \pm 0.016$</td>
<td>$1.261 \pm 0.020$</td>
</tr>
<tr>
<td>NGC 612</td>
<td>$0.132 \pm 0.016$</td>
<td>$3.069 \pm 0.017$</td>
<td>$3.200 \pm 0.016$</td>
<td>$1.621 \pm 0.020$</td>
</tr>
<tr>
<td>NGC 5078</td>
<td>$0.064 \pm 0.016$</td>
<td>$2.613 \pm 0.016$</td>
<td>$2.677 \pm 0.016$</td>
<td>$1.615 \pm 0.017$</td>
</tr>
<tr>
<td>NGC 7172</td>
<td>$0.542 \pm 0.016$</td>
<td>$2.284 \pm 0.016$</td>
<td>$2.826 \pm 0.016$</td>
<td>$2.062 \pm 0.017$</td>
</tr>
<tr>
<td>IC 5063</td>
<td>$0.735 \pm 0.016$</td>
<td>$3.720 \pm 0.016$</td>
<td>$4.455 \pm 0.016$</td>
<td>$2.814 \pm 0.016$</td>
</tr>
</tbody>
</table>

The mid-infrared WISE filters are instrumental in source classifications. The WISE color-color diagram constructed by Wright et al. 2010 (also shown in Figure 3.4) is a
Figure 4.4: Shows the locations of the galaxies on the WISE color-color diagram. It depicts the distribution of galaxies spanning from Ellipticals to ULIRGs. The red squares at the tips of the arrows denote the positions of the galaxies of the sample.

useful tool designed to characterise individual celestial objects. On the diagram, field stars reside in the near-zero color magnitude region, extending slightly into the evolving luminous populations regime. Early-type field galaxies are located in the "green" region, stretching into the redder colors in the star forming spiral galaxies' end, whilst white dwarfs extend redward from $W1 - W2 = 1.7$ mag. Ultra-Luminous Infra-Red Galaxies (ULIRGs) and obscured AGNs are red both in $W1 - W2$ and $W2 - W3$ colors.

In an attempt to investigate the link between the morphological classes and the current star formation potentials of the galaxy sample, the WISE colors of the galaxies (see Table 4.12) were plotted on the color-color diagram. The results are shown in Figure 4.4.

The position of IC 5063 as a Seyfert galaxy and NGC 1316 as an elliptical galaxy, are in line with expectations. However, the locations of NGC 612, NGC 5078 and NGC 7172 do not match their known morphological classes determined in the optical. This is not surprising since these galaxies were selected for being specially dusty and gas-rich for their morphological type.

Moreover, the location of the galaxies along the horizontal axis (i.e., $[4.6]-[12]$ in mag) is correlated with star formation potentials. The object with the lowest star formation rate, NGC 1316, is located at the far left, whilst the galaxy with the highest star formation rate, IC 5063, is situated at the far right. For the sample of early-type galaxies, the WISE color-
color diagram is an indicator of star formation rates. Stellar mass and AGN activity also increase along the vertical (i.e. [4.6]-[12] in mag). In other words, dust content increases along the horizontal, and heating activity (such as AGN) increases along the vertical on the diagram. Furthermore, AGN can inflate the $WISE$ magnitudes, even the $W1$, and causes over-estimation of the stellar mass.

4.5 Dust in Resolution-Enhanced WISE Images

![Image of NGC 1316 and NGC 612](image)

Figure 4.5: Super-resolution three-color $WISE$ images ($W1$ in blue, $W2$ in green, $W3$ in red) of NGC 1316 (left panel) and NGC 612 (right panel). The dust lanes are clearly seen.

![Image of NGC 5078, NGC 7172, and IC 5063](image)

Figure 4.6: Enhanced-resolution three-color ($W1$ in blue, $W2$ in green, $W3$ in red) $WISE$ images of NGC 5078 (left panel), NGC 7172 (middle panel) and IC 5063 (right panel). The dust lanes lie along the disk-structures.

In an attempt to reveal the mid-infrared dust morphologies of the galaxies, the $WISE$ resolution-enhanced images generated and discussed in Section 3.2.1 were used to create
three-color images (W1 in blue, W2 in green, W3 in red) of the galaxies (see Figures 4.5 and 4.6).

The resulting super-resolution images (images created using the MCM-HiRes technique) of the galaxies in Figure 4.5 have a beam width of \(\sim 3\) arcsec, which is comparable to the Spitzer IRAC resolution of \(\sim 2\) arcsec (Werner et al. 2004). In NGC 1316 (see Figure 4.5; left image), the inner dust lanes and the outer dust concentrations are apparent in this big elliptical galaxy. This shows that a lot of interesting activities such as star formation and AGN feedback are ongoing in the galaxy. These however need high resolution instruments (e.g., ALMA) to reveal details. The northern and southern dust concentrations seen in extinction in the HST image are also replicated in the WISE image.

Likewise, for NGC 612 (Figure 4.5; right image), the dust lane seen in the DSS image is reproduced in the WISE image as well. It is however not fully resolved due its distance (about 125 Mpc); the reddish dust is not revealing clearly here.

Figure 4.6 also shows the three-color WISE dust maps of NGC 5078 (left image), NGC 7172 (middle image) and IC 5063 (right image). They are not properly resolved; NGC 5078 looks less resolved, NGC 7172 slightly resolved and the dwarfish IC 5063 unresolved by WISE. They reveal only the "red" ISM activity, but not much detail. Notwithstanding, they portray much of the dust morphology seen in their respective Carnegie-Irvine Galaxy Survey CGS images in Figure 2.7.

4.6 LABOCA 870 \(\mu\)m Maps of NGC 1316 and NGC 612

The results of the LABOCA observations and data analysis are presented here. A search for excess emission in the LABOCA field of view led to the detection of a number of point sources which are reported in Appendix B. They are possible high-redshift submillimeter galaxies.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Flux Density (\mu)Jy</th>
<th>Signal-to-Noise Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1316</td>
<td>113.0 \pm 17.0</td>
<td>6</td>
</tr>
<tr>
<td>NGC 1317</td>
<td>34.0 \pm 13.0</td>
<td>3</td>
</tr>
<tr>
<td>NGC 612</td>
<td>35.2 \pm 4.9</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 4.13: LABOCA flux density measurements

The galaxies were detected in the maps (see Figure 4.7) obtained by reducing and analysing the LABOCA data with the Crush program. The LABOCA observations data were processed by the onboard APECS data manipulations facility (Muders et al. 2006) into Multi-Beam FITS image scans (see Lucas & Glendening 2001; and also Section 3.3.2). The individual scans were then reduced using the faint and extended option components in the Crush package for NGC 1316, and faint and deep options for NGC 612. The reduced individual scans were then coadded and smoothed to increase the signal-to-noise ratio.

The noise in the NGC 1316 map increases significantly in the outskirts. The map has a resolution (FWHM) of \(28''\), and a root-mean-square of \(\sim 2.5\) \(\mu\)Jy/beam. The nearly
Figure 4.7: Detection of NGC 1316 and its nearby companion NGC 1317 to the north (left) and NGC 612 (right) with LABOCA. The smoothed maps show the detected galaxies in red at the central regions of the respective panels. The map area is 167 arcmins$^2$ for NGC 1316 and 136 arcmins$^2$ for NGC 612.

Figure 4.8: Shows the HST image in grey-scale and LABOCA image in green contours. The contours range from 3 to 6 times the noise level, which is equal to 2.5 mJy/beam. The resolution of the LABOCA image (FWHM) is 28". The magenta circle is the LABOCA beam size.

Companion galaxy NGC 1317, located north of NGC 1316 was also detected in the LABOCA field (see Figure 4.7; left panel). The NGC 1316 map reported in this study is more resolved compared to that presented by Galametz et al. (2014) in their Figure 1.
The measured flux within the central 2′.0 of NGC 1316 (see Table 4.13) is slightly lower than the 170.0±50.0 mJy reported by Galametz et al. (2014) using the same instrument, but consistent within the error bars. There were possible emission contributions from free-free (≈ 2%) and synchrotron (≈ 8%) radiation in the former (since NGC 1316 hosts a weak AGN and therefore emits synchrotron radiation), but the observation in this study was scheduled to exclude emission from the synchrotron jets. A steep spectral index of −1.3 between 1.5 and 4.9 GHz (using fluxes from Fomalont & Geldzahler 1984) was used to estimate a flux of 0.13 mJy from the inner radio jets at the 870 μm wavelength well below the LABOCA sensitivity (see Figure 5.1). This assured that the LABOCA flux measurement in this study is without contamination from the synchrotron emission.

NGC 612 was also detected as a point source (see right panel of Figure 4.7; also see Table 4.13) at a signal root-mean-square of ≈ 1.7 mJy/beam. A smoothing of 13″.0 was applied to realize an overall image resolution of 23″.4, but the galaxy still remains unresolved, unlike NGC 1316. This is because NGC 612 is more than six times further away (125 Mpc) compared to NGC 1316 (20 Mpc).

At the time of the observations, no flux measurements had been made in the submillimeter continuum between 160 μm (Spitzer MIPS) and 3 mm (94 GHz, WMAP) of NGC 1316, and between 170 μm (ISO) and 13.6 mm (22 GHz ATCA) of NGC 612. The flux density measurements from this study have added a point each (in red) in the global spectral energy distribution of the galaxies (see Figure 5.1 for NGC 1316; and Figure 5.2 for NGC 612) in the submillimeter regime. This will be discussed further in the next chapter.

An attempt was made to compare the morphology of the LABOCA and HST maps of NGC 1316. To do that, overlay of the two maps were made (see Figure 4.8). The northern and the southern dust concentrations seen in the optical HST image are detected in the submillimeter LABOCA map. The dust lanes seen in extinction in the HST image correspond well to the dust revealed by the LABOCA map (see Figure 4.8). However, there is a slight misalignment of the southern concentration. This could be due to either the great difference in angular resolution of the two instruments, or the fact that the HST image shows foreground dust in extinction whereas the LABOCA image shows dust in emission. Observations at higher angular resolution (for example with ALMA in Chile or the Submillimeter Array in Hawaii) would be required for a detailed comparison with the HST image. We submitted an ALMA Cycle 3 proposal (with Jeffrey Kenney of Yale University, United States as the PI) to observe this Source. Unfortunately, the proposal was ranked in the 40 - 70% band of all proposals submitted, but the source was not observed. Future successful attempt for data from such high resolution instrument will be used for this course.
Chapter 5

Detailed Measurements and Modeling of Infrared and Submillimeter Emission

Dust is a vital component in galaxy evolution. This chapter focuses on the determination of dust component masses and the separation models used to retrieve the various infrared emission contributions in the galaxies. The global flux measurements were modeled to estimate the dust component masses and assess the intensity of activity in the nuclear regions. Two-dimensional modeling of the WISE images was performed to separate and characterize the various emission components, and to reveal the structural morphology of the dust in the respective images.

5.1 Spectral Energy Distribution Modeling

Assuming optically thin emission (Beuther et al. 2002), the spectral energy distribution of galaxies may be modeled by fitting flux density measurements from the mid-infrared to the submillimeter bands of the electromagnetic spectrum. This may be done by superimposing two modified black-body radiation curves defined by Equation 5.1 (see Galametz et al. 2012):

\[ S_\nu = A_w \lambda^{-\beta_w} B_\nu(T_w) + A_c \lambda^{-\beta_c} B_\nu(T_c) \]

where \( T_w \) and \( T_c \) are the temperature of the warm and cold dust components respectively, \( \beta_w \) and \( \beta_c \) are the dust emissivity indices for the respective warm and cold components, \( B_\nu(T_w) \) and \( B_\nu(T_c) \) are the Planck function at \( T_w \) and \( T_c \), and \( A_w \) and \( A_c \) are the overall amplitudes of the dust components. Emissivities (the surface effectiveness in emitting thermal radiation) are in the range 1.0-2.0, but the values 1.5 and 2.0 are commonly used (see Krugel & Siebenmorgen 1994, Priddle & McMahon 2001).
A single modified black-body model will be dominated by either the transiently heated
dust component or the cold diffuse ISM component, and cannot therefore fully describe
both the Rayleigh–Jeans part of the near/mid-infrared and the Wien part of the far-
infrared/submillimeter SED of the galaxy.

Essentially, a single-temperature fit to the entire galaxy yields an average dust tempera-
ture component and a subsequent single dust component mass (see Section 5.1.1). But most
dusty galaxies have multiple dust components distributed within the disk and/or the mole-
cular clouds in their star forming regions; star forming regions are associated with molecular
clouds. The motivation for using a two-temperature components model is to restrain and dis-
tangle the mid-infrared and far-infrared/submillimeter band emission components, which
are simplistically referred to as warm and cold respectively (e.g., Hildebrand 1983, Draine
1990, Dunne & Eales 2001, Weiss et al. 2008). The warm dust component is mostly associ-
ated with the evolved stars in the photo-dissociation region and the warm grains in thermal
equilibrium on the outskirts of dense molecular clouds. The cold dust component comes
from the star formation regions in the diffuse ISM, shielded by the dense molecular clouds.

In Section 5.1.1, the SED models of NGC 1316 and NGC 612 were used to evaluate the
respectively constrained dust component temperatures and masses. The WISE flux density
measurements from the study; homogenized photometric measurements from literature and
SED models were matched to Spitzer IRS spectra of the respective nuclei of NGC 1316 and
NGC 612 in Section 5.1.2.

5.1.1 Dust Temperature and Mass Estimations

Figures 5.1 and 5.2 are modeled spectral energy distributions of NGC 1316 and NGC 612
using homogenized published photometric measurements spanning from the near-infrared to
the radio wavelength parts of the electromagnetic spectrum. The data points include the
WISE and LABOCA measurements from this study. The LABOCA measurements (in red)
add the points in the submillimeter parts of the galaxies.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Dust Temperature</th>
<th>Dust Mass</th>
<th>Gas-to-Dust Mass Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_{\text{warm}}$ ($K$)</td>
<td>$T_{\text{cold}}$ ($K$)</td>
<td>$M_{\text{warm}}$ ($10^6 M_\odot$)</td>
</tr>
<tr>
<td>NGC 1316</td>
<td>55.0 ± 4.3</td>
<td>21.9 ± 1.3</td>
<td>8.3 ± 0.9</td>
</tr>
<tr>
<td>NGC 612</td>
<td>59.6 ± 4.9</td>
<td>25.4 ± 1.6</td>
<td>52.9 ± 5.3</td>
</tr>
</tbody>
</table>

Table 5.1: Temperature and mass of dust components (warm and cold) of NGC 1316 and
NGC 612 at dust emissivity value of 2 for both ($\beta_w$ and $\beta_c$) components. The $M_{\text{dust}}$
is the sum of cold and warm components ($M_{\text{dust}} = M_{\text{warm}} + M_{\text{warm}} \sim M_{\text{dust}}$) and the gas mass
is the sum of of the molecular and neutral hydrogen gas mass ($M_{H_2} = M_{H_2} + M_{H_1} \sim M_{H_2}$; see Table 2.1).

The homogenized photometric infrared measurement points from the Extragalactic Database
(NED) in Figures 5.1 and 5.2, include the MIPS 24, 70 and 160 $\mu$m, IRAS 25, 60 and 100 $\mu$m,
PACS 70, 100 and 160 $\mu$m and the recently added SPIRE 250, 350 and 500 $\mu$m by Galametz
Figure 5.1: Spectral energy distributions of NGC 1316 from the near-infrared to the radio wavelength band of the electromagnetic spectrum. The plotted homogenized photometric data points, labeled adjacent to the respective science instruments used (also shown in the same colors as the points), were extracted from the literature (NED) with the WISE and LABOCA measurements from this study. The dotted-dashed magenta line shows a diluted black-body spectrum at a temperature of 5600 K describing the stellar continuum. The dotted red (warm component) and blue (cold component) curves are the two-modified black-body model fits. The thick black curve is the resultant spectral energy distribution (same as in Figure 5.2). The figure also shows the estimated warm ($T_{\text{warm}}$) and cold ($T_{\text{cold}}$) dust temperature components.

e et al. 2012 for NGC 1316; and the AKARI 18, 90 $\mu$m (Ichikawa et al. 2012), IRAS 12, 25, 60, 100 $\mu$m and ISO 170 $\mu$m for NGC 612.

The peak of the spectral energy distribution varies between normal star forming galaxies (100 - 200 $\mu$m; Bendo et al. 2003) and starbursts (60 - 100 $\mu$m; Clements et al. 2010). The peak is around 150 $\mu$m for the low star forming NGC 1316 (Figure 5.1) and shifted to around 120 $\mu$m for NGC 612 (Figure 5.2) with a moderately high star formation rate. This indicates that both galaxies are normal star forming galaxies. It is consistent with the star formation rate estimates in Table 4.11.

The radio synchrotron emission from the outer radio lobes (Wilkinson Microwave Anisotropy Probe data points for NGC 1316, and Culgoora Circular Array and Parkes data points for
Figure 5.2: Spectral energy distributions of NGC 612 from the mid-infrared to the radio wavelength band of the electromagnetic spectrum. The AKARI points were picked from Ichikawa et al. 2014, WISE and LABOCA measurements from this study. The rest are homogenized photometric data points from the NED. The plotted data points, the respective instruments used, and the estimated warm ($T_{\text{warm}}$) and cold ($T_{\text{cold}}$) dust components temperatures are also shown (as in Figure 5.1).

NGC 612) plotted at the top right corner of Figures 5.1 and 5.2, come from much larger regions than the host galaxies. Unlike the other measurement points, the emission produced by the lobes extend beyond the galaxy’s region influenced by stars and dust re-emission.

Equations 5.1 and 5.2 were used to estimate the respective temperatures and masses of the dust components (Krügel & Siebenmorgen 1994, Weiss et al. 2008). With the best-fit parameters (including temperature components) determined from the spectral energy distribution fit to Equation 5.1. The dust masses of the various components may be estimated using Equation 5.2 (see Section 1.4 for details):

$$M_{\text{dust}} = \frac{S_{\nu} D^2}{k_{\nu} B_{\nu}(T_{\text{dust}})}$$

where $k_{\nu}$ is the dust absorption coefficient and $D$ is the distance to the galaxy. $S_{\nu}$ is the observed flux density and $B_{\nu}(T_{\text{dust}})$ is the Planck’s function at dust temperature $T_{\text{dust}}$. The dust component temperature and mass shown in Equation 5.2 have a range of values (see Hildebrand 1983, Draine 1990). This means for each $M_{\text{dust}}$ there is a corresponding...
$T_{\text{dust}}$. Restricting the model to only two components, the cold and warm dust temperature and their respective masses may be evaluated.

The dust temperature estimates depend slightly on the emissivity value used. Assuming $\beta = 1.5$ for early-type galaxies raises the dust component temperature by a few degrees (e.g., Bendo et al. 2003, Gordon et al. 2010, Skibba et al. 2011), hence the choice of $\beta = 2$ in the study. Fixing the emissivity index of both dust components at the adopted value of 2 for appropriate measurements (see Priddey & McMahon 2001, Li & Draine 2001, Xilouris et al. 2012, Galametz et al. 2014), the temperature and mass of the dust components of the galaxies were estimated (see Table 5.1).

The dust temperatures are relatively higher in NGC 612 compared to NGC 1316. Dust heating arises mainly from the stellar populations (i.e., evolved and young) and the radiation from the star forming regions in the ISM (Popescu et al. 2011). The stellar population is responsible for heating the warm dust component, and the cold component by the radiation from the star forming region. Dust temperatures relate directly to star formation in the galaxy. NGC 612 has a higher star formation rate and a larger fraction of young stars compared to NGC 1316, and therefore has higher dust temperatures which translate to their respective dust masses (see Equation 5.2). The relatively high radiation field in NGC 612 is thus created by the current star formation (see Table 4.11) and the AGN activity.

The temperature measurements obtained for NGC 1316 are consistent with those obtained by Galametz et al. (2012) who used submillimeter data from the Herschel Space Observatory. The warm component is slightly higher (58.9 K instead of 55.0 K in this study). The wavelength range is wider in this study (3.4-870 $\mu$m) compared to the former (24-500 $\mu$m); the wider the wavelength span, the more credible the results. The values obtained for NGC 612 also compare well with those of the star forming spiral galaxy NGC 4826 (see Table 3 of Galametz et al. 2012). NGC 612 has properties similar to those of spiral galaxies; it behaves like a starburst spiral (also see Table 4.11 and Figure 4.4).

The heating from the interstellar radiation field and the star forming region inside the molecular clouds is responsible for the cold dust emission component. The molecular gas in the cloud get heated by the photo-electric effect. The cold dust is thus associated more with the molecular gas phase than the atomic phase. NGC 1316 with the lower molecular gas content (see Table 2.1) and lower star formation rate (see Table 4.11) has a smaller cold dust fraction compared to NGC 612. Cold dust amount and molecular gas content are therefore measures of star formation rates. Moreover, cold dust is believed to fuel and sustain the AGN activity (Prandoni et al. 2012).

Tadhunter et al. (2014) used a single-component modified black body model to derive the dust masses of 32 intermediate ($z < 0.7$) radio galaxies (see Dicken et al. 2009) which range from quiescent elliptical galaxies ($7.2 \times 10^5 M_\odot$) to ultraluminous infrared galaxies ($2.6 \times 10^8 M_\odot$). Using the Herschel PACS and SPIRE fluxes, Parkin et al. (2012) estimated the dust mass of the nearby NGC 5128 (Centaurus A) as $1.6 \times 10^7 M_\odot$ at dust temperature of $\sim 30$ K, and Baes et al. (2014) measured a dust mass of $1.6 \times 10^7 M_\odot$ in the minor axis dust-lane lenticular galaxy NGC 5485. The dust masses of 352 dusty early-type galaxies
have been estimated using their IRAS fluxes \((10^5 - 10^7 \, M_\odot)\); Kaviraj et al. 2012). The dust masses of NGC 1316 \((5.3 \times 10^6 \, M_\odot)\) and NGC 612 \((5.3 \times 10^7 \, M_\odot)\) estimated from the two modified black body models over a wider wavelength range, are consistent with the aforementioned studies as an active elliptical and luminous infrared or AGN-loud galaxy respectively.

The gas-to-dust mass ratio is a measure of recent star formation and merger activity in the galaxy. Attention will be given to molecular gas because it is the gas phase that is closely linked to star formation (e.g., Young et al. 1989, Bigiel et al. 2008). Davis et al. (2012) estimated a diverse gas-to-dust mass ratio (ranging from 50 to 750) in a sample of dust lane early-type galaxies associated with minor mergers. The average ratio is between 100 and 150 for massive spiral galaxies (excluding atomic gas which dominates the molecular gas in spiral galaxies), which may rise to thousands in gas-rich sources (see Devereux & Young 1990). NGC 1316 has a gas-to-dust mass ratio of 94, which is close to the average value of 100 for the Milky Way Galaxy (Sodroski et al. 1997) but less than that of NGC 5128 (169; Parkin et al. 2012). The value for NGC 612 \((M_{H_2}/M_{dust} = 149)\) is consistent with the measurements from Davis et al. (2012).

NGC 1316 has witnessed two significant merger events; a major merger that occurred about 3 Gyrs ago (Goudsmit et al. 2004) to result in the disturbed optical morphology (Schweizer 1980), and the minor merger that happened barely 0.5 Gyrs ago to inject the dust in the central region of the galaxy (see Mackie & Fabbiano, Lanz et al. 2010). The moderate gas-to-dust mass ratio and low recent star formation rate (listed in Table 4.11) suggest that the former merger contributed insignificant gas amounts into the gas-poor host galaxy. The bulk of the gas was brought in during the latter merger with a dusty gas-rich companion. On the other hand, NGC 612 had substantial amounts of gas in situ (e.g., by stellar mass loss) before the minor merger added more dusty gas in the central region. This explains why the galaxy has a comparatively high recent star formation rate (see Table 4.11) and gas-to-dust mass ratio (see Table 5.1). These two galaxies are therefore good candidates for researching the link between recent star formation and merger activity. There is a high probability that appreciable amounts of the cold dust may be used to fuel and sustain the AGN in the systems.
5.1 Spectral Energy Distribution Modeling

Figure 5.3: Optical images of the central region of NGC 1316 (left panel) and NGC 612 (right panel) in inverted gray scale and overlaid contours of the radio emission in yellow. The size of the images is $2' \times 2'$ and the bright extended radio lobes are located outside the pictures. The rectangles show the regions from which the *Spitzer* IRS spectra displayed in Figure 5.4 were extracted. For NGC 1316, the size of the rectangle is $27.8'' \times 51.8''$ with a position angle (PA) of $149^\circ$. For NGC 612, it is $10.7'' \times 51.6''$ with a PA of 67.5$. Left panel: HST image of NGC 1316 with 4.9 GHz radio contours of the inner jet overlaid (Geldzahler & Fomalont 1984). The radio contours increase by a factor of 2 from 0.2 to 3.2 mJy/beam, where the beam is $1.38'' \times 1.02''$, with a PA of 20.3$. Right panel: Digitized Sky Survey image of NGC 612. The 6 cm radio contours are 5, 10 and 20 mJy/beam and the beam is $7.8'' \times 4.6''$ with a PA of $-1.3^\circ$ (Emonts et al. 2008). Note that NGC 612 is about six times more distant than NGC 1316.

5.1.2 Mid-Infrared Spectroscopy of the Nuclear Region

*Spitzer* IRS SL and LL module (low-resolution short-wavelength, SL; 5.12 – 14.29 µm and low-resolution long-wavelength, LL; 13.90 – 39.90 µm) spectra of the nucleus of NGC 1316 were created by the SINGS team (Kennicutt et al. 2003) and downloaded from the SINGS archivea. The IRS LL module spectrum of the NGC 612 nucleus was downloaded from the *Spitzer* archive as an Enhanced Imaging Product (project ID 30745, ‘*Spitzer* Observations of the First Unbiased AGN Sample of the Local Universe’, PI K.I. Weaver; Asmus et al. 2014). The spectra are shown in Figure 5.4. The regions from which they were extracted are shown in Figure 5.3 as rectangles overlaid on an *HST* image of NGC 1316 and on a Digitized Sky Survey image of NGC 612. The main objective is to reveal the molecular and dust-emitting components in the mid-infrared, including the *WISE* and *Spitzer* broad-bands, to emphasize the continuum from both the interstellar dust and AGN contributions.

The near-infrared to mid-infrared spectrum of NGC 1316 has been discussed before (the *Spitzer* IRS spectrum by Smith et al. (2007) and the 2.5–13 µm *AKARI* spectrum by Ichikawa et al. (2012)). It is shown here as a comparison to the NGC 612 spectrum and to help interpret the *WISE* broad-band observations. The response functions of the *WISE* W3 and W4 bands are displayed as shaded areas in Fig 5.4, and the corresponding fluxes

---

a irsa.ipac.caltech.edu/data/SPITZER/SINGS/galaxies
Figure 5.4: Spitzer IRS spectra of NGC 1316 (in blue) and NGC 612 (in magenta). The WISE W3 and W4 bands response functions are shown in grey, in arbitrary units. The WISE flux densities measured in the rectangular regions used to extract the spectra are shown in squares for NGC 1316 and dots for NGC 612. The spectra differ strongly at short wavelengths, where the Rayleigh-Jeans part of the stellar light is clearly seen for NGC 1316, whereas NGC 612 shows strong PAH emission. The dashed-dotted and the dashed lines are power-law curves with an index of +3 for NGC 1316 and +2.4 for NGC 612, highlighting the underlying continuum from both dust and AGN contributions.

In NGC 1316, the low-wavelength part of the spectrum is dominated by the Rayleigh-Jeans radiation of the old stellar population, whereas NGC 612 displays strong emission lines, in particular the 7.7 μm PAH line that enters the W3 filter. Smith et al. (2007) had pointed out the peculiar spectrum of NGC 1316, with an unusually low ratio of the 7.7 to 11.3 μm line strength. The 7.7 μm PAH feature is produced by smaller, ionized PAHs whereas the 11.3 μm feature is due to larger and neutral PAHs (e.g.,?). Such low ratios were found in the other low-luminosity AGNs of the SINGS sample (Smith et al. 2007) and in a sample of dusty elliptical galaxies (Kaneda et al. 2008). It is likely that the PAHs in NGC 1316 come from the recent infall of a small gas-rich galaxy. The 7.7 μm feature may be weakened by the X-ray radiation field in NGC 1316 that destroys the smaller PAHs.

The 11.3 μm PAH emission line from NGC 612 is as strong as that from NGC 1316.
Figure 5.5: Mid-infrared SED for NGC 1316. The figure shows Spitzer IRS (SL and LL modules) spectrum, 2MASS XSC, IRAC, MIPS, and the WISE measurement points plotted on an E-galaxy SED model for NGC 1316 adapted from the GRASIL code (Polletta et al. 2006, 2007; Silva et al. 1998), and normalized to the near-infrared.

despite the six-times greater distance, NGC 612 can be classified as a luminous infrared galaxy (LIRG) with a luminosity of $L_{8-1000 \mu m} = 1.2 \times 10^{11} L_\odot$, whereas NGC 1316 is about 25 times less luminous, $4.9 \times 10^{9} L_\odot$ (from the relation between the IRAS fluxes given by Sanders & Mirabel (1996) and using the corrected IRAS values provided by Knapp (1994)). The steeper slope of NGC 1316 in the IRS spectrum may indicate a higher dust temperature than in NGC 612, likely associated with AGN heating.

The centers of both galaxies were observed at subarcsecond resolution in the mid-infrared (the Sasmirala project°, Asmus et al. 2014). The nucleus of NGC 612 was undetected, and an upper limit of 33 mJy at 12 \( \mu m \) was set, well below the measurement in the Spitzer IRS spectrum. In NGC 1316, a flux density of 17 \( \pm 6 \) mJy was measured at 12 \( \mu m \), and a limit on the size of the emission of 38.1 pc was obtained (after correcting for our adopted distance). Those values show that in both galaxies the AGN is weak and the MIR emission is dominated by dust/star formation. Although very bright in the radio (at 6 cm, the total flux density of NGC 1316 (Fornax A) is 72 Jy and that of NGC 612 about 4 Jy. Morganti

°http://dc.zah.uni-heidelberg.de/sasmirala
Figure 5.6: Mid-infrared SED of NGC 612. It shows Spitzer IRS (LL module), 2MASS XSC, IRAC, MIPS, and the WISE measurement points plotted on a S0-galaxy model for NGC 612. The Spitzer IRS (LL module) spectrum of the nucleus of NGC 612 nucleus (from Asmus et al. 2014). There is no Spitzer IRS (SL module) spectrum for the galaxy.

et al. (1993)), most of the emission comes from the extended outer radio lobes. At 6 cm, the core of Fornax A has a flux density of 26 mJy and the value for NGC 612 is 38 mJy (Morganti et al. 1993). For comparison, the core of Virgo A at the center of M 87 (at 0.5” resolution) has a flux density of 2875 mJy at 6 cm (Nagar et al. 2001) and is detected across the entire EM spectrum, with a 24 µm MIPS flux of about 51 mJy (Shi et al. 2007). The non-thermal core and jet of M 87 were also detected in WISE images (Jarrett et al. 2013).

For a similar spectral index, the flux density of Fornax A and NGC 612 would be about 60 times weaker than at 6 cm, and therefore fainter than 1 mJy at 24 µm. This is much lower than what is measured in both galaxies’ IRS spectra, which indicates that most of the emission in the long-wavelength part of the IRS spectra and in the WISE W3 and W4 images is not due to synchrotron emission from the nucleus. The jet of NGC 1316 was not detected in the Spitzer images either, and upper limits were set (Lanz et al. 2010).

Also, using an E-galaxy SED model for NGC 1316 and S0-galaxy model for NGC 612 adapted from the GRASIL code (Polletta et al. 1996; 2006; 2007, Silva et al. 1998) and normalized to the near-infrared. Figures 5.5 and 5.6 were created by matching the mid-
infrared global measurements (from the study and literature) and the IRS spectra on the respective galaxy models. The \textit{WISE} points plotted here are the integrated flux densities in Tables 4.1 and 4.2, and those of IRAC. IRS and MIPS 24 are synthetic photometric measurements. The E-galaxy model was scaled by a factor of 6 and the spectrum module by 0.2 for NGC 1316. For NGC 612, the S0-galaxy model was scaled by 0.14 and the spectrum model also by a factor of 1.5. As shown in Figures 5.5 and 5.6, there is infrared excess relative to the galaxy templates, and the spectra are redder compared to the template spectral energy distributions. The infra-red excesses affirm that there is ongoing activity in the nuclear regions of the galaxies.

For NGC 1316, the photometric measurements match well with the E-galaxy spectral energy distribution model. The flux density peaks at the \textit{2MASS} $H$-band (1.6 \text{$\mu$m}) and drops steeply thereafter towards the longer wavelength. The MIPS-24 and the W4 points, which trace the warm dust from the current star formation, however deviate slightly upward from the model. The \textit{Spitzer} IRS (SL and LL modules) spectrum from the nuclear emission spectroscopy also departs from the old galaxy model to depict the excess emission coming from the warm dust grains tracing the emission from younger stars.

Similarly for NGC 612, the photometric data points align well with the S0-galaxy model at the lower wavelengths, but there is a departure long-ward of the IRAC 8 \text{$\mu$m} band. Thus, the \textit{WISE} longer wavelengths (W3 and W4) measurement points and the IRS nuclear emission spectrum do not agree with the S0 galaxy template, but they match nicely with each other. The departures are due to the presence of the warm dust in the ISM (tracing the current star formation) and/or the asymptotic giant branch stars.

\section{5.2 Resolved Maps and Components Separation}

The major components that contribute to the mid-infrared emission of early-type galaxies such as NGC 1316 and NGC 612, are the stellar, the AGN, ISM and the dust components. Each of these components has a specific spatial and spectral shape. The stellar component is extended and smooth and can be modeled using simple geometrical models (such as Sersic, Exponential disk and Gaussian). The spectrum is that of the Rayleigh-Jeans side of a black-body curve, and the flux is anticipated to follow as such. The AGN, on the other hand, is a point-like source which is unresolved at all wavelengths in all bands. It can however be modeled by a point spread function (PSF). The PSF is thus a convolution of the AGN and the emission in the nuclear region of the galaxy. The flux is expected to increase with wavelength. The dust component (the infrared excesses), which is sometimes associated with star formation in early-type galaxies, may include thermal dust continuum, emission lines and contribution from the asymptotic giant branch in the case of S0 galaxies. The morphology may vary from one galaxy to the other. For instance, the dust in NGC 1316 appears very irregular, whereas in NGC 612 the dust lanes seen in extinction seem to be associated with an almost edge-on warped disk. These could be resolution-dependent effects. The distribution and orientation of the diffuse ISM may also indicate the recent activity that
has taken place in the galaxy. The dust flux decreases with wavelength in NGC 1316, but increases with wavelength in the case of NGC 612.

Of the many techniques, the GALFIT approach and the scaling method will be used in this thesis for the emission components separation. This will give the opportunity to explore and compare the two techniques.

In order to characterize the various contributions to the mid-infrared emission of the galaxies, GALFIT (see Peng et al. 2002 for comprehensive documentation) was used, a two-dimensional image decomposition program that fits parametric functions to digitized images using standard chi-squared minimization. As inputs for each band’s fit, GALFIT utilizes the image of the particular band, the corresponding uncertainty map and point-spread function (PSF) image of the band. An optional PSF-modeled mask or image may be included to exclude regions of conspicuous emission and/or regions intended to be concealed from the fit.

The analyses were performed on the inner 6′ × 6′ (35×35 kpc²) region of the images of NGC 1316, and on 4′ × 4′ (145×145 kpc²) images of NGC 612 (and the other galaxies: NGC 5078, NGC 7172 and IC 5063) centred on the galaxies’ respective nuclei or geometric centers. The image sizes were selected by visual inspections to cover the entire galaxies’ emission regions seen in the WISE bands, and also making provision for appreciable background spaces around the image regions to facilitate the fitting. The sky background emission in the enhanced-resolution and cleaned images, which have virtually no visible bad pixels to mask, were first subtracted.

The AGN emission is explored in Section 5.2.1. Section 5.2.2 describes the models of the short-wavelength WISE images used to characterize the stellar emission distribution.

### 5.2.1 Nuclear Emission

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Nuclear Emission</th>
<th>Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W1 (mJy)</td>
<td>W2 (mJy)</td>
</tr>
<tr>
<td>NGC 1316</td>
<td>16.39 ± 0.25</td>
<td>10.10 ± 0.15</td>
</tr>
<tr>
<td>NGC 612</td>
<td>0.70 ± 0.01</td>
<td>1.34 ± 0.02</td>
</tr>
<tr>
<td>NGC 5078</td>
<td>1.72 ± 0.03</td>
<td>1.66 ± 0.03</td>
</tr>
<tr>
<td>NGC 7172</td>
<td>0.07 ± 0.001</td>
<td>0.33 ± 0.005</td>
</tr>
<tr>
<td>IC 5063</td>
<td>1.20 ± 0.02</td>
<td>28.32 ± 0.42</td>
</tr>
</tbody>
</table>

Table 5.2: Emission from the nuclear regions of the galaxies in the respective WISE images. They were estimated by doing separate iterative fits to the individual nuclei of the images as described in Section 5.2.1. The last column is the central regional extent of the image used in the fitting. The pixel scale is 0.687″ for NGC 1316 and NGC 612, and 1.0″ for the other galaxies.

To estimate the emission from the nuclear regions of the galaxies, the approach taken by Lanz et al. (2010) in their analysis of the Spitzer images of NGC 1316 was followed. It is an iterative procedure with GALFIT to determine the locations of the central AGN in each band and measure the respective flux densities.
5.2 Resolved Maps and Components Separation

The centres of the Sérsic profile and AGN (nuclear point source) were first determined by repeatedly modeling the W1 and W3 images respectively. A two-dimensional Sérsic + PSF model was then fitted to the W1 image keeping the centers of the profiles fixed at the previously identified positions. The best-fit Sérsic parameters from the W1 fit and the iteratively identified point source centre from the W3 fit were held constant and subsequently fitted to all the images (i.e., W1, W2, W3 and W4). The PSF images obtained for NGC 1316 and NGC 612 from this process were used in masking their respective nuclei for the GALFIT fits in Sections 5.2.2 and 5.3.

The integrated flux densities of the GALFIT output PSF images from the various fits were measured and are recorded in Table 5.2 together with the regional extents of the respective images showing the image regions used in the fits. These fluxes are regarded as nuclear emission due to the central AGN and stars in the inner regions of the respective bands. In NGC 1316, although the W1 and W2 images are very close in wavelength, the noise is ~ 36% higher in W2. The galaxy is thus brighter in W1 by a factor of about 2 compared to W2, so the signal-to-noise is higher in the W1 image by a factor of about 2.5. This explains why the W2 flux is lower than for W1. The AGN is expected to be slightly fainter in W1 (by a factor of about 1.2, based on the estimates from the corresponding Spitzer images by Lanz et al. (2010) and is therefore less of a contaminant.

The nuclear flux measurements obtained for NGC 1316 are consistent, but a bit higher than those reported in Table 1 of Lanz et al. (2010) in their similar analysis of the Spitzer images of the galaxy. The fluxes range from 16 mJy (in W1, 3.4 µm) to 73 µm (in W4, 22 µm) in this study, compared to the range from 5 mJy (in IRAC 1, 3.6 µm) to 61 mJy (in MIPS, 24 µm) in the former. This may be due to the larger WISE PSF beam width, and the more stars that could possibly be picked up in the nuclear regions in the WISE compared to the Spitzer bands. Moreover, the images used here were background subtracted. Allowing GALFIT to subtract the background emission could lead to over-subtraction and subsequent under-estimation of the flux measurements as could be the case in Lanz et al. (2010).

This iterative technique for estimating nuclear emission outlined above worked well for the elliptical galaxy NGC 1316. The PSF fit accurately identified the center of the galaxy and picked up the nuclear emission. However, in the lenticular galaxies, the program did not find the geometric centers of the galaxies (representing the AGN locations), but rather fitted the PSFs at few arcseconds around the nucleus in each case. The nuclear emission measurements of the lenticular galaxies (NGC 612, NGC 5078, NGC 7172 and IC 5063) listed in Table 5.2 therefore represent the measurements of the most luminous points detected closely around the nuclei of the galaxies. Those excess emissions points could be unresolved star formation regions around the nuclei.

5.2.2 Stellar Emission Models of NGC 1316 and NGC 612

The emission in the WISE shorter wavelength W1 (3.4 µm) and W2 (4.6 µm) bands was modeled to estimate the stellar contributions. The nuclear regions were masked out (using the PSF-modeled masks generated in Section 5.2.1) to exclude the contributions from the
Table 5.3: Best-fit parameters obtained by fitting the listed models to the W1 map of NGC 1316. The size of the W1 image used for the fit and to measure the flux density of the components was 6′ × 6′ (35 × 35 kpc²) for NGC 1316. The statistical errors of the parameters quoted by GALFIT (also in Table 5.4) were very small (< 0.01%) and are therefore not given here. The uncertainties in flux density measurements here were set to 1.5% based on error estimations from the uncertainty maps of the galaxies, which is consistent with Vega spectrum-like WISE images (see Jarrett et al. 2011).

<table>
<thead>
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<th>Parameter</th>
<th>Single Sérsic</th>
<th>1st Sérsic</th>
<th>2nd Sérsic</th>
</tr>
</thead>
<tbody>
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<td>Image center: (RA)</td>
<td>03h22m41.66s</td>
<td>03h22m41.66s</td>
<td>03h22m41.73s</td>
</tr>
<tr>
<td>(DEC)</td>
<td>−37°12′29.55″</td>
<td>−37°12′29.49″</td>
<td>−37°12′32.15″</td>
</tr>
<tr>
<td>Integrated magnitude</td>
<td>4.96 mag</td>
<td>4.69 mag</td>
<td>8.55 mag</td>
</tr>
<tr>
<td>Effective radius (Reff)</td>
<td>123″.5</td>
<td>254″.9</td>
<td>36″.6</td>
</tr>
<tr>
<td>Sérsic index (n)</td>
<td>5.27</td>
<td>8.06</td>
<td>0.33</td>
</tr>
<tr>
<td>Position angle (PA)</td>
<td>52°.7</td>
<td>52°.8</td>
<td>53°.7</td>
</tr>
<tr>
<td>Axis ratio (b/a)</td>
<td>0.70</td>
<td>0.67</td>
<td>0.98</td>
</tr>
<tr>
<td>Reduced chi-squared</td>
<td></td>
<td>21.8</td>
<td>15.7</td>
</tr>
<tr>
<td>Flux density (mJy)</td>
<td>3181.9 ± 47.7</td>
<td>4080.3 ± 61.2</td>
<td>116.6 ± 1.7</td>
</tr>
</tbody>
</table>

Figure 5.7: Characterizing the starlight distribution of NGC 1316: W1 image (left panel) and GALFIT residual maps for a single Sérsic model (middle panel), and a double Sérsic model (right panel). The contour levels are 0.01, 0.02, 0.04, 0.08 mJy/pixel (black) and 0.16, 0.32, 0.64 mJy/pixel [white] for the W1 image and 0.001, 0.004, 0.009 mJy/pixel for the residual maps. The double Sérsic model gives lower residuals and better represents the starlight distribution of NGC 1316 in the WISE bands.

central AGNs and other nuclear-related activity. Although, the procedure outlined in Section 5.2.1 could not identify the nuclear regions (the geometrical centers) of the lenticular galaxies with certainty, the regions around the nuclei with conspicuous emission were masked out.

From the analysis, the W2 images were quite similar to those of W1 in all the models in the respective galaxies, but the W1 images stand as better representatives of the starlight distribution in the galaxies. The W2 images will therefore not be individually displayed.

For each galaxy, two models were tested. For NGC 1316, a single Sérsic and a double Sérsic model were used. For NGC 612, a single Sérsic model and the superposition of a
Sérsic and an exponential disk model were tried. The choice of the models was informed by the morphological classes of the galaxies. The double model fits proved the better starlight representations in the galaxies. They produced appreciably lower residuals, reduced chi-squared values and better residual maps (see Tables 5.3 and 5.4, and Figures 5.7 and 5.8).

The double Sérsic residual of NGC 1316 still has some residuals; this suggests that the galaxy is disturbed due to the past merger events and is not necessarily ellipsoidal. Also, the twisting profiles shown in the residuals (especially in the Sérsic + exponential disk model) of NGC 612 are indications of the warping or distortion of the galaxy from the intervening interactions with the neighboring companion NGC 619 (Emont et al. 2008).

The best-fit parameters of the fits are listed in Tables 5.3 and 5.4. The Figures 5.7 and 5.8 show the W1 images in contours (left panels) and the resulting residual maps for the two models considered (middle and right panels). The residual maps are the left-over emission.
after subtracting the modeled starlight (in NGC 612), and starlight and nuclear emission (in NGC 1316).

The best-fit single Sérsic model values of NGC 1316 (see column 2 of Tables 5.3) match well with the ones found by Lanz et al. (2010) in their analysis of the Spitzer 3.6 μm image. The Sérsic index of 5.3 found here is comparable with the 5.8 identified by Côté et al. (2007) and the 6.1 determined by Lanz et al. (2010).

The effective radius of NGC 612 in the single Sérsic model is slightly lower than what was found in the R-band (12.′′7 instead of 16.′′7; Fasano et al. 1996; Govoni et al. 2000) and in the i-band (17.′′7; Veron-Cetty et al. 2001) at a fixed Sérsic index of 4. The values obtained here can be compared more directly to those found in the K-band by Inskip et al. (2010), who also included an edge-on disk and obtained an $R_{\text{eff}}$ of 20.′′5 for a fixed Sérsic index of 4, compared to the 23.′′6 and 2.9 respectively obtained in this study at the same disk scale-length of 3.′′4. Allowing the fit parameters to float freely leads to the realization of better and representative best-fit parameters.

A double Sérsic model had useful to capture different types of structures (a compact bulge and a more extended halo or a disk: see Sections 5.2.2 and 5.3).

5.3 WISE Dust Emission of NGC 1316 and NGC 612

Two different methods were used to extract the dust distribution from the long-wavelength W3 and W4 WISE maps. In the first method a constrained two-dimensional fit was performed to the W3 and W4 images, using the geometrical parameters obtained in the fits to the W1 images discussed in Section 5.2.2, keeping them fixed but allowing only the amplitudes to float (see Section 5.3.1). The W4 images are useful for global measurements but not for detailed analysis. This explains why there are negative pixel values (see Tables 5.3 and 5.4) representing over-subtraction of stellar emission. Moreover, the relatively isolated W4 image is not applicable for starlight extraction, especially by the GALFIT approach (see Helou et al. 2004).

For the second method the W1 images were simply scaled by appropriately derived factors and subtracted from the W3 and W4 images, having been smoothed and adjusted to their respective angular resolutions (also in Section 5.3.2). This approach is referred herein as the scaling method.

5.3.1 Constrained Fitting Method

The technique used here is similar to the one applied to the Spitzer maps of NGC 1316 by Lanz et al. (2010) to recover the distribution of dust. Given the results of the stellar emission models in Section 5.2.2, both the single Sérsic and double Sérsic models were used to represent the starlight in W1 for NGC 1316, and single Sérsic and the superposition of a Sérsic and an exponential disk models for NGC 612. The best-fit parameters obtained from the fits to W1 in each case (see Tables 5.3 and 5.4) were kept fixed, with the exception of
the amplitudes which were allowed to vary in the respective fits to the W3 and W4 images. 

The identified nuclear regions of the images were masked out to exclude all nuclear-related and starburst emission from the fits (explanation given in Section 5.2.1). There were however fit overestimates resulting in negative pixel regions (shown in white in the gray-image background) of the residual/dust maps (see Figure 5.10).

In NGC 1316, both the stellar and nuclear emission were subtracted leaving the residuals, which are regarded as the dust component of the W3 bands (see Figures 5.9). Figure 5.11 show great matches between the W3 dust maps and the dust seen in extinction in HST in NGC 1316. There is an over-subtraction of the stellar emission in the single Sérsic map (see Figure 5.9, middle panel). The right panel image of Figure 5.11 shows a better match with the HST image. Hence, the double Sérsic model serves as a better representation of the dust map in the galaxy.

The middle and right panels of Figure 5.10 are the non-stellar emission maps of NGC 612. They were created by subtracting the stellar emission discussed in Section 5.2.2. The Sérsic + exponential disk model presents a better fit with the lower reduced chi-squared value (see Table 5.4), but its non-stellar emission (see Figure 5.10, right panel) is over-subtracted in the central region. The stellar emission of disk galaxies is claimed to be better fitted by a combination Sérsic and exponential disk models (see Véron-Cetty & Véron 2001, Beletsky et al. 2011), but for NGC 612, the stellar emission component is better represented using a single Sérsic model (see Figure 5.10, middle panel); the stellar model parameters (see Tables 5.4 and 5.6) and map (Figure 5.8) pointed in favour of the double model. The overlay of the non-stellar emission map on the left panel of Figure 5.12 further shows a good match with the dust lane revealed in DSS image of the galaxy.

![Figure 5.9: Distribution of dust in NGC 1316. The W3 image (left panel), the dust from fitting a single Sérsic model (middle panel), and the image obtained from the double Sérsic model fit (right panel). Starlight and nuclear emission, which is mainly due to the central AGNs contributions have been subtracted. The contour levels are 0.008, 0.01, 0.02, 0.04 mJy/pixel (black) and 0.2, 0.3 mJy/pixel (white) for the W3 image and 0.0014, 0.003, 0.004, 0.008 mJy/pixel for the dust maps.]

In Tables 5.5 and 5.6, integrated flux densities of the stellar models, nucleus and the residuals/dust of the galaxies are presented. Negative fluxes denote over-subtractions. The stellar emission was over-estimated, particularly from the nuclear regions in the NGC 612
Figure 5.10: Distribution of residuals in NGC 612. The first row shows the W3 image (left panel), the residuals from fitting a Sérsic + exponential disk model (middle panel), and the image obtained from fitting Sérsic + exponential disk model (right panel). Starlight has been subtracted, but the nuclear emission is however not subtracted. The contour levels are 0.004, 0.008, 0.020, 0.08 mJy/pixel (black) and 0.2, 0.3 mJy/pixel (white) for the W3 image and 0.004, 0.008, 0.020 mJy/pixel for the residual maps.

Figure 5.11: W3 dust maps obtained from fitting a single Sérsic model fit (left panel) and double Sérsic model fit (right panel) in contours overlaid on the optical HST image. The contour levels are 0.0015, 0.003, 0.004, 0.008 mJy/pixel.

maps in the double model fit. The measurements from the scaling method outlined in Section 5.3.2 for NGC 1316 and NGC 612 and shown in Table 5.7, are also included in Tables 5.5 and 5.6 for comparison.

The GALFIT method of emission components separation works better in resolved nearby (≤ 20 Mpc) sources. It is ideal for unveiling the residual and dust maps in such sources (also see Lanz et al. 2010). However, the approach does not give realistic flux density measurements (e.g. Tables 5.5 and 5.6; and also Lanz et al. 2010). This is because there is a high potential for the program to over-subtract the stellar emission with an associated under-estimation of the residual components or vice versa. For instance, Dale et al. (2005) give the total flux of the Spitzer 24 μm as 360 ± 40 mJy, but Lanz et al. (2010) quotes
Figure 5.12: W3 non-stellar maps obtained from single Sérsic model fit (left panel) and the Sérsic + exponential disk model fit (right panel) in contours overlaid on the DSS grey-scale image. The contours are 0.002, 0.008, 0.040 mJy/pixel for the left image and 0.004, 0.008, 0.020 mJy/pixel for the right image.

<table>
<thead>
<tr>
<th>Band</th>
<th>Starlight</th>
<th>Nucleus</th>
<th>Residual/Dust</th>
<th>Scaled</th>
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<tr>
<td></td>
<td>Single Sérsic (mJy)</td>
<td>Double Sérsic (mJy)</td>
<td>Single Sérsic (mJy)</td>
<td>Double Sérsic (mJy)</td>
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<tr>
<td>W1</td>
<td>1808.9 ± 27.1</td>
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</tr>
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<td>W2</td>
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<td>1001.1 ± 15.0</td>
<td>10.1 ± 0.2</td>
<td>14.2 ± 0.2</td>
</tr>
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<td>W3</td>
<td>401.5 ± 6.0</td>
<td>392.6 ± 5.9</td>
<td>22.4 ± 0.4</td>
<td>16.9 ± 0.3</td>
</tr>
<tr>
<td>W4</td>
<td>404.0 ± 6.1</td>
<td>411.2 ± 6.2</td>
<td>73.1 ± 1.1</td>
<td>-80.4 ± 1.2</td>
</tr>
</tbody>
</table>

Table 5.5: Integrated flux densities of the stellar models, nucleus and the dust of NGC 1316. The measurements were made within elliptical aperture of position angle, PA = 34°7, axis ratio, AR = 0.75, centered at 03h22m41.60s –37°12′28.8′′ of the galaxy. The semi-major and semi-minor axes of the aperture were respectively 160″ and 120″. The residuals (in W1 and W2) and dust fluxes (in W3 and W4) are obtained by subtracting the modeled starlight and nuclear emission from the respective background-subtracted images.

<table>
<thead>
<tr>
<th>Band</th>
<th>Starlight</th>
<th>Non-Stellar Emission</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single Sérsic (mJy)</td>
<td>Sérsic + Expdisk (mJy)</td>
</tr>
<tr>
<td>W1</td>
<td>49.0 ± 0.7</td>
<td>53.3 ± 0.8</td>
</tr>
<tr>
<td>W2</td>
<td>30.8 ± 0.5</td>
<td>32.3 ± 0.5</td>
</tr>
<tr>
<td>W3</td>
<td>117.9 ± 1.8</td>
<td>107.6 ± 1.6</td>
</tr>
<tr>
<td>W4</td>
<td>158.7 ± 2.4</td>
<td>136.8 ± 2.0</td>
</tr>
</tbody>
</table>

Table 5.6: Integrated flux densities of the stellar models, nucleus and the non-stellar of NGC 612. The measurements were made within elliptical aperture of position angle, PA = 170°, axis ratio, AR = 0.60, and center 01h33m57.61s –36°29′36.0′′ of the galaxy. The semi-major and semi-minor axes of the aperture were respectively 60″ and 36″. The residuals (in W1 and W2) and dust fluxes (in W3 and W4) are obtained by subtracting the modeled starlight from the respective background-subtracted images.

400 ± 12 mJy as starlight contribution in the same image region using the GALFIT approach; the dust map obtained was rather a good representation and comparable to that seen in the
optical. The GALFIT procedure is useful for revealing the stellar, residual and dust maps of resolved images, but not for accurate photometric measurements.

In order to quantify the dust emission in NGC 1316 and compare to other estimates, we measured the flux density in the two elliptical regions defined by Lanz et al. (2010) and shown in their Figure 8. Interestingly, the two regions have very comparable flux densities in $W3$: $25.3 \pm 0.5 \, \text{mJy}$ in the north-west region and $26.0 \pm 5.1 \, \text{mJy}$ in the south-east one. At $5.8 \, \mu \text{m}$ and $8.0 \, \mu \text{m}$, Lanz et al. (2010) had measured $\sim 6.5 \, \text{mJy}$ and $13.8 \, \text{mJy}$ in the north-west region, and $\sim 4.2 \, \text{mJy}$ and $18.8 \, \text{mJy}$ in the south-east region. Without a spectrum it is not possible to be certain that the higher $12 \, \mu \text{m}$ to $8 \, \mu \text{m}$ flux ratio in the north-west region is due to a different $11.3 \, \mu \text{m}$ to $8 \, \mu \text{m}$ PAH flux ratio. The north-west region is known to be about 2.5 times richer in molecular gas (Horellou et al. 2001). This is also where the inner jet ends abruptly and it may have affected the physical conditions of the interstellar medium.

5.3.2 Scaling Method

Based on the stellar spectral energy distribution (SED) extrapolations from Brown et al. (2014b) for an appropriate early-type system, synthetic integration was performed using the WISE filter responses. This gave the photometric measurements for the respective bands. And by comparing the emission in $W3$ and $W4$ separately to $W1$, the factors 0.158 and 0.059 were arrived at as the respective ratios of the continuum contribution (from old stars) of $W1$ in $W3$ and $W4$. These are formulated and presented as Equations 5.3 and 5.4. They may be used to quantify dust (non-stellar) emission or infrared excesses in the longer wavelength WISE images. The dust map obtained by this scaling method is referred to as scaled dust map.

To create the scaled dust maps of the galaxies (see Equations 5.3 and 5.4), the $W1$ images were scaled by the factor 0.158 before smoothing to the resolution of the $W3$ images, and subtracting from the $W3$ images. The $W1$ images were similarly scaled by the factor of 0.059, smoothed to $W4$ images resolution, and subtracted from the $W4$ images:

$$f_{\text{scaled dust}}(W3) = f(W3) - 0.158 f(W1)$$

$$f_{\text{scaled dust}}(W4) = f(W4) - 0.059 f(W1)$$

The infrared excess estimation using the above expressions is mainly due to star formation in the ellipticals. There are however contributions from old asymptotic giant branch (AGB) populations in the case of lenticular galaxies.

Adopting this approach defined by Equations 5.3 and 5.4, scaled dust maps of NGC 1316 and NGC 612 were created (see Figures 5.13 and 5.14). Figures 5.13 and 5.14 show the respective scaled dust maps of NGC 1316 and NGC 612: the left images are $W3$, and the right ones are $W4$. 
5.3 WISE Dust Emission of NGC 1316 and NGC 612

Figure 5.13: Distribution of dust in the NGC 1316 WISE images obtained with the scaling method: W3 (left panel) and W4 (right panel). The contour levels are 0.0034, 0.006, 0.009, 0.020 mJy/pixel for the W3 image and 0.0048, 0.009, 0.020, 0.050 mJy/pixel for the W4 image.

Figure 5.14: Distribution of dust in the NGC 612 WISE images obtained with the scaling method: W3 (left panel) and W4 (right panel). The contour levels are 0.0038, 0.01, 0.03, 0.1 mJy/pixel for the W3 map and 0.009, 0.03, 0.09 mJy/pixel for the W4 map.

The W4 images are not well resolved by WISE as mentioned earlier. In addition to the poor resolution of the W4 image of NGC 612, the reconstructed super-resolution image of the galaxy have artifacts along the minor axis, which are showing up in the W4 scaled dust map (see Figure 5.14, right panel).

The dust distributions revealed by the W3 scaled dust maps are analogous to the dust emission shadowed in their optical images (see overlay maps in Figure 5.15). The W3 scaled
dust map of NGC 1316 coincides well with the dust seen in extinction in the \textit{HST} image (Figure 5.15, left panel). The map of NGC 612 reproduces the dust lane revealed in the \textit{DSS} image of the galaxy (Figure 5.15, right panel).

Similar analysis was done with the NGC 5078, NGC 7172 and IC 5063 images, and their respective scaled dust maps are shown in Figures 5.16, 5.17 and 5.18. In the Figures 5.16, 5.17 and 5.18, the top images are the \textit{W3} (left panels) and the \textit{W4} (right panels), and the bottom ones are the \textit{W3} (left panels) and \textit{W4} (right panels) scaled dust maps. The orientations of the dust seen in these maps (bottom panels) agree well with the dust lanes seen in the Carnegie-Irvine Galaxy Survey \textit{CGS} images of the respective galaxies (shown in Figure 2.7).

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Resolution-enhanced Images</th>
<th>Scaled Dust Maps</th>
<th>Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\text{W1})</td>
<td>(\text{W3})</td>
<td>(\text{W4})</td>
</tr>
<tr>
<td>NGC 1316</td>
<td>(1849.8 \pm 27.7)</td>
<td>(440.7 \pm 6.6)</td>
<td>(400.2 \pm 6.0)</td>
</tr>
<tr>
<td>NGC 612</td>
<td>(58.5 \pm 0.9)</td>
<td>(117.8 \pm 1.8)</td>
<td>(149.3 \pm 2.2)</td>
</tr>
<tr>
<td>NGC 5078</td>
<td>(569.7 \pm 8.5)</td>
<td>(693.3 \pm 10.4)</td>
<td>(871.2 \pm 13.1)</td>
</tr>
<tr>
<td>NGC 7172</td>
<td>(233.6 \pm 3.5)</td>
<td>(311.0 \pm 4.7)</td>
<td>(595.9 \pm 8.9)</td>
</tr>
<tr>
<td>IC 5063</td>
<td>(152.2 \pm 2.3)</td>
<td>(871.5 \pm 13.1)</td>
<td>(3317.6 \pm 49.8)</td>
</tr>
</tbody>
</table>

Table 5.7: Flux measurements within elliptical apertures for \textit{W3} and \textit{W4} images and scaled dust maps of the galaxies. The semi-major axis and centers for the respective elliptical aperture photometry were \(160^\circ\) and \((03^h22^m41.49^s, \,-37^\circ12^\prime27^\prime.51^\prime)\) for NGC 1316, \(60^\circ\) and \((03^h33^m57.61^s, \,-36^\circ29^\prime36^\prime.04^\prime)\) for NGC 612, and \(180^\circ\) and \((13^h19^m49.98^s, \,-27^\circ24^\prime36^\prime.46^\prime)\) for NGC 5078. Those of NGC 7172 and IC 5063 are respectively \(120^\circ\) and \((22^h02^m01.89^s, \,-31^\circ52^\prime10^\prime.57^\prime)\) and \(120^\circ\) and \((20^h52^m02.21^s, \,-57^\circ04^\prime07^\prime.51^\prime)\).

The same technique was adopted by Hedou et al. (2004) in their analysis of the local galaxy NGC 300, and by Dale et al. (2005) in their study of dust emission from the nearby
Figure 5.16: Distribution of scaled dust in the *WISE* images of NGC 5078. The first row shows W3 (left panel) and W4 (right panel) images of the galaxy, and the second row are the respective scaled dust maps. The contour levels are 0.02, 0.06, 0.13, 0.32, 0.44 mJy/pixel for the images, and 0.02, 0.06, 0.2 mJy/pixel for the dust maps. The inner two contours of the images are in white (as in all the *WISE* images of the galaxies).

galaxies NGC 3031, NGC 5194 and NGC 7331 using *Spitzer* data. In both studies, the factors 0.232 and 0.032 were used in scaling the 3.6 μm images of the starburst spiral galaxies to remove the stellar components in the 8 μm and 24 μm images respectively. These factors are comparable to the 0.158 and 0.059 used in this study for the early-type galaxies, which have a little less stellar emission in W3 than the 8 μm image, and a little more stellar emission in W4 than the 24 μm image (as discussed in Section 5.2). Draine et al. (2007) also scaled the *Spitzer* 3.6 μm emission by 0.0326 and subtracted from the MIPS 24 μm emission of the SINGS galaxies to measure their non-stellar emission.

In order not to underestimate the non-stellar emission in the W1 image, a variant of
Figure 5.17: Distribution of scaled dust in the WISE images of NGC 7172. The first row shows W3 (left panel) and W4 (right panel) images of the galaxy. The second row are the respective scaled dust maps. The contour levels are 0.02, 0.06, 0.13, 0.8, 1.2 mJy/pixel for the images, and 0.02, 0.04, 0.08, 0.2, 1.2 mJy/pixel for the dust maps.

The scaling method was tried by subtracting the scaled best-fit models of the W1 maps (described in Section 5.2.2) from the W3 and W4 maps. The resulting dust maps and fluxes were identical within 2% to those obtained by scaling W1 image. This meant that non-stellar emission in the W1 images of NGC 1316 and NGC 612 is merely within 2% of the total emission in the image.

The measurements in Table 5.7 are fluxes within the specified regions of the images after subtraction of the stellar components. They look more feasible compared to those from GALFIT reported in Tables 5.5 and 5.6. The ratios W3/W1 and W4/W1 are lower (< 1.0) in the NGC 1316, but larger (> 1.0) in the star forming S0 galaxies which have possible contributions from AGBs. Dust emission increases longwards of 8 µm, so the dust component
Figure 5.18: Distribution of scaled dust in the WISE images of IC 5063. The first row shows W3 (left panel) and W4 (right panel) images of the galaxy, and the second row are the respective scaled dust maps. The contour levels are 0.025, 0.08, 0.4, 1.6, 3.0, 5.2 mJy/pixel for the W3 image, 0.06, 0.6, 1.0, 2.6, 6.0, 9.0 mJy/pixel for the W4 image, 0.025, 0.08, 0.4, 1.6, 5.2 mJy/pixel for the W3 dust map, and 0.06, 0.6, 1.0, 2.6, 9.0 mJy/pixel for the W4 dust map.

Propportion in the W4 images must be higher than that for W3 as seen in Table 5.7. Stellar contribution in the W4 band is minute with over 97% of the total emission in the band from dust re-emission.

To recall, PAHs dominate the W3 band and the W4 image is dominated by warm small dust grains. The ratios of the fluxes of the scaled dust maps measured in the W3 images and W4 in the Table 5.7 range from 0.26 in IC 5063 to 0.74 in NGC 612. This small proportion of PAH emission (i.e., W3) in IC 5063 suggests PAHs destruction in the galaxy be due to the intense radiation coming from the activity (mainly star formation) on-going in the galaxy.

The stellar and dust properties of galaxies relate to their morphologies and metallicities
(e.g., Fontanot et al. 2009. Skibba et al. 2011), which play significant roles in galaxy evolution (see Draine et al. 2007). Using the W1 (stellar component) and W3 or W4 (dust contribution) flux measurements within the specified regions in Table 5.7, the dust-to-starlight flux ratios for the elliptical (< 1.0) and the S0 galaxies (> 1.0) relate directly to the current star formation rates of the galaxies (see Table 4.11). IC 5063, which has the highest star formation rate has the largest dust-to-starlight flux ratio, and NGC 1316, which has the lowest star formation rate, has the lowest dust-to-starlight flux ratio.

The W3 dust maps of NGC 1316 from the GALFIT (see Figure 5.9, right image) and the scaling method (see Figure 5.13, left image) are in good agreements with the HST image of the galaxy shown on the left panels of Figures 5.11 and 5.15 respectively. Similarly, the W3 non-stellar emission maps of NGC 612 from the GALFIT (see Figure 5.10, middle image) and the scaling method (see Figure 5.14, right image) align well with the DSS image of the galaxy (see right panels of Figures 5.12 and 5.15 respectively). However, the maps from the GALFIT approach appear to be over-subtracted thereby underestimating the non-stellar emission from the galaxies (see Tables 5.5 and 5.6). The Scaling method is a preferred approach for presenting the non-stellar maps and analysis of nearby sources.

5.4 PAHs and Line Emission of NGC 1316

Thermal dust continuum and dust emission features (lines) are the two major dominant dust emission components in NGC 1316. The dust emission features are dominated by PAHs especially at 8.0 µm and 11.3 µm (see Kennicutt et al. 2003). Dale et al. (2009) estimated the nuclear and extra-nuclear emission line fluxes (both molecular hydrogen and ion forbidden lines) of NGC 1316. The reported fluxes included those of the AGN tracer lines SiII (14.87 ± 0.78 × 10\(^{-9}\) Wm\(^{-2}\)sr\(^{-1}\); at 34.82 µm), OIV (3.16 ± 0.18 × 10\(^{9}\) Wm\(^{-2}\)sr\(^{-1}\); at 25.89 µm) and NeII (13.43 ± 0.47 × 10\(^{9}\) Wm\(^{-2}\)sr\(^{-1}\); also at 15.56 µm). In the Dale et al.’s sample of 11 SINGS galaxies, NGC 1316 has the strongest emission of the high excitation line OIV produced by the AGN, and among the top 20% of the galaxies in the sample with many strong emission lines.

In an attempt to see the matches between these emission and the scaled dust maps in Figure 5.13, the PAHs 8.0 µm and 11.3 µm, and the AGN emission line SiII and NeII images were retrieved from the SINGS legacy database\(^a\) (see Figure 5.19), and overlaid on the scaled dust maps (see Figures 5.20 and 5.21). Although the beams of the WISE and Spitzer IRS are different, Figure 5.20 shows a good match between the scaled dust and the PAH maps (top panel). The resolution of the 34.82 µm is poor compared to the mid-infrared wavelength, but a bit better at the 15.56 µm line (see Figure 5.20, bottom panel; and also Figure 5.21).

The implications here are that NGC 1316 is a merger remnant with the dust injection from the merger event. The cohabitation of the dust continuum (and clumps) and the emission lines in the central region revealed by Figures 5.20 and 5.21 are attestation of the

\(^a\)http://irsa.ipac.caltech.edu/data/SPITZER/SINGS/galaxies/ngc1316.html
Figure 5.19: PAHs and line emission images of NGC 1316. From top, PAH 8.0 µm (first image), PAH 11.3 µm (second image), NeII at 15.56 µm (third image) and SiII at 34.82 µm (fourth image).

star formation (Table 4.11) and AGN activity (also see Table 5.2) in the galaxy.
Figure 5.20: Overlays of PAHs and line emission (in green contours) on the WISE NGC 1316 W3 scaled dust map (in red contours of levels 0.004, 0.007, 0.010, 0.013 mJy/pixel in the background). The first row shows the PAH 8.0 μm (left panel) and the PAH 11.3 μm (right panel). The second row shows the NeIII at 15.56 μm (left panel) and the SiII at 34.82 μm (left right). The contour levels for the PAH 8.0 μm emission are 2.2, 4.8, 7.4, 10.0 MJy/sr and those of PAH 11.3 μm emission are 3.60, 9.07, 14.53, 20.0 MJy/sr. The contour levels for NeIII and SiII range from $1.8 \times 10^{-9}$ - $85 \times 10^{-8}$ MJy/sr and $1.5 \times 10^{-9}$ - $13 \times 10^{-9}$ MJy/sr respectively in steps of four.
Figure 5.21: Line emission NeIII at 15.56 $\mu$m (left map) and SiII at 34.82 $\mu$m (right map) in green contours on the WISE NGC 1316 $W_4$ scaled dust map (in red contours of levels 0.0045, 0.0122, 0.02 mJy/pixel in the background). Contour levels are the same as in Figure 5.20 for the NeIII and SiII emission.
Chapter 6

Conclusions

The aim of the study was to characterize and study the dust and stellar properties of merger-remnant radio galaxies in the mid-infrared and submillimeter parts of the electromagnetic spectrum using WISE, Spitzer and APEX-LABOCA observations. The radio-loud NGC 1316 and NGC 612 were studied in both the mid-infrared and submillimeter, and the compact radio-cored NGC 5078, NGC 7172 and IC 5063 in the mid-infrared only. The mid-infrared component of the study has been presented in a paper submitted to Astronomy & Astrophysics (Duah Asabere et al. 2016).

A brief summary and the main results of the dissertation are summarised below:

1. Enhanced-resolution images of all four WISE bands of the galaxies were produced and photometric measurements were performed in the WISE and Spitzer bands. The integrated flux density measurements of the enhanced-resolution WISE images of NGC 1316 compare very well with those from the corresponding Spitzer bands listed in Dale et al. (2005). For NGC 612, the measurement of $137 \pm 2\text{ mJy}$ in W4 is in agreement with the IRAS value at 25 $\mu$m ($130 \pm 33\text{ mJy}$; NED); the W3 isophotal flux of $114 \pm 1\text{ mJy}$ is significantly lower than the 12 $\mu$m IRAS flux ($200 \pm 35\text{ mJy}$; NED) and the 9 $\mu$m AKARI flux of 135 mJy (Ichikawa et al. 2012). The mid-infrared WISE and Spitzer band flux densities for NGC 5078, NGC 7172 and IC 5063 are reported herein for the first time. They are consistent with their corresponding bands.

2. Stellar mass and star formation rate estimates of the galaxies were made using calibrations based on the WISE W1 and W4 luminosities respectively. Of the sample, NGC 1316 has the largest stellar mass of $75.8 \times 10^{10}\ M_\odot$, which is about twice that of NGC 612 ($40.7 \times 10^{10}\ M_\odot$) and IC 5063 has the lowest stellar mass of $0.8 \times 10^{10}\ M_\odot$. The star formation rate ranges from $0.7\ M_\odot\ yr^{-1}$ in NGC 1316 to $19\ M_\odot\ yr^{-1}$ in IC 5063. The specific star formation rates of the galaxies range from $9.8 \times 10^{-13} \ yr^{-1}$ in NGC 1316 to $2.5 \times 10^{-9} \ yr^{-1}$ in IC 5063. For the lenticular galaxies, the star formation rate is proportional to the amount of H\textsc{i} gas measured therein (Wiklind, Combes & Henkel 1995, Emons et al. 2008). The nucleus of NGC 1316 is currently dormant.
and the galaxy is likely to evolve into a passive elliptical. The lenticular galaxies (especially the IC 5063 and NGC 612) have ongoing star formation throughout their disks. This may lead to the growth of larger star-forming disks and/or enough accreted gas to sustain the active nuclei in their centres.

3. The WISE filters have been used to estimate the current star formation rates of the galaxies; ranging from NGC 1316 as a gas-poor elliptical to IC 5063 as an active star-forming Seyfert. The star formation potential and dust content increase along the horizontal, and heating activity (such as AGN) increases along the vertical on the WISE color-color diagram. The diagram is useful as a tracer of star formation rate and nuclear activity in early-type galaxies.

4. NGC 1316 was detected by LABOCA 870 µm, and a non-synchrotron emission contamination flux density of $113 \pm 17$ mJy measured in the central $2'$.0. The measured flux is slightly lower than the $170 \pm 50$ mJy reported by Galametz et al. (2014) but consistent within the error bars. The nearby companion galaxy to the north, NGC 1317 was detected at a flux density of $34 \pm 13$ mJy. NGC 612 was also detected as a point-like source with flux density of $35 \pm 5$ mJy, unresolved due to its distance. A few other point sources (4 in NGC 1316 and 1 in NGC 612) were detected in the LABOCA maps which are potential high redshift submillimeter galaxies. An overlay of the LABOCA map of NGC 1316 on the optical HST image shows a good agreement between the northern and the southern dust concentrations, implying that, the dust seen in extinction in the optical has been shown in emission in the submillimeter.

5. A two-temperature model was used to fit homogenized flux measurements of NGC 1316 and NGC 612 from NED and the study, to separate the cold and warm dust components. In both galaxies, cold dust (of mass $M_{\text{cold dust}} = 5.3 \times 10^6 \, M_\odot$ in NGC 1316 and $M_{\text{cold dust}} = 5.3 \times 10^7 \, M_\odot$ in NGC 612) dominates the warm dust components (i.e., $M_{\text{warm dust}} = 8.3 \times 10^3 \, M_\odot$ for NGC 1316 and $M_{\text{warm dust}} = 5.3 \times 10^4 \, M_\odot$ for NGC 612) by a factor of 1000. The respective gas-to-dust mass ratio estimates of 94 and 149 for NGC 1316 and NGC 612 are measures of their star formation potentials. NGC 612 has warmer dust due to the relatively high radiation field created by the current star formation and the AGN activity. Cold dust is associated with the molecular gas phase. NGC 1316 with lower molecular gas content has a smaller cold dust fraction compared to NGC 612.

6. Spitzer IRS spectra of the two-radio-lobed galaxies differ strongly at short wavelengths, where the Rayleigh-Jeans part of the stellar light is clearly seen for NGC 1316, whereas NGC 612 shows strong emission lines especially around the 12 µm PAHs and 35 µm AGN tracer lines SIII and SII. They also differ at long wavelengths, the NGC 1316 spectrum being significantly steeper than that of NGC 612. The integrated mid-infrared flux measurements show infrared excesses, and their spectra are redder compared to global SEDs (E-galaxy for NGC 1316 and S0 for NGC 612). A major differ-
ence in the Spitzer IRS spectra of the central regions of the galaxies is the strength of the 7.7 μm PAH feature, which is suppressed relative to the 11.3 μm PAH feature in NGC 1316, as observed in samples of dusty elliptical galaxies (Kaneda et al. 2008) and low-luminosity AGNs (Smith et al. 2007), but is strong in NGC 612 due to the relatively high intensity of ongoing activity in the nuclear region.

7. GALFIT, a two-dimensional image decomposition software, was used to characterize and separate the stellar, AGN and dust contributions to the mid-infrared WISE emission of the galaxies. The stellar component (in the W1) was modeled using simple geometrical models (in NGC in 1316, a single and double Sérsic profile were tested; and in NGC 612, Sérsic and Sérsic + Exponential disk were tried). The AGN was modeled by a point spread function. The dust component (in the W3 and W4) which mostly traces star formation, thermal dust continuum, emission lines and contribution from the asymptotic giant branch in the case of S0 galaxies was obtained by subtracting the stellar and AGN components.

8. Two different approaches (i.e., GALFIT and Scaling) were used to extract the dust distribution from the long-wavelength W3 and W4 WISE images. In the GALFIT method a constrained two-dimensional fit was performed to the W3 and W4 images to model and subtract the starlight component leaving the dust (together with the AGN) component. In the scaling method the W1 images were simply scaled by appropriate factors and subtracted from the W3 and W4 images, having been smoothed and adjusted to their respective angular resolutions. The W4 images are useful for global measurements but not for detailed analysis such as the GALFIT modeling due to the poor resolution. Moreover, the relatively isolated W4 images are not applicable for starlight extraction, especially by the GALFIT approach.

9. By testing different models, it was found that the superposition of a double Sérsic is a reasonable representation of the starlight of NGC 1316, which dominates the emission in the W1 band. The double Sérsic model is useful to capture different types of structures (a compact bulge and a more extended halo, or a disk). For NGC 612, a better fit is obtained by the superposition of a Sérsic model and exponential disk. However, those models have their limitations, especially in the central regions, but also to represent the disk of NGC 612 that is strongly warped. Therefore a simple scaling model was used to separate the stellar from the non-stellar emission of the galaxies in the long-wavelength bands. Both methods reveal the morphology of the dust distribution in the galaxies. In NGC 1316, the 12 μm emission coincides with the dust patches seen in the HST image in two regions to the north-west and south-east of the nucleus and observed at 8 μm with Spitzer (Lanz et al. 2010). In NGC 612, the 12 μm and 22 μm emission comes from a warped disk.

10. Those two bright radio-lobed galaxies with low-luminosity optical AGN have very different mid-infrared properties, which are presumably related to their formation pro-
cesses and evolutionary stages. The dust in NGC 1316 is likely due to the recent infall of one or several small gas-rich companions, while in NGC 612, gas must have been accreted more continuously to settle in a rotating star-forming disk. Radio continuum measurements from the literature (Morganti et al. 1993) indicate that the nucleus of NGC 1316 is currently more dormant than that of NGC 612. While the nucleus of NGC 1316 may be momentarily revived if the dusty material from the north-west and south-east clumps makes it to the center, the galaxy is very likely to evolve into a completely passive elliptical with no sign of past activity within a few 0.1 Gyr. when the synchrotron emission from the nucleus and the lobes will have faded away. NGC 612, on the other hand, because of its own larger reservoir of molecular and atomic gas and the nearby presence of a gas-rich companion (Emonts et al. 2008) may grow a larger star-forming disk and/or sustain a level of activity in its nucleus. Numerical simulations of the growth of galaxies through accretion and mergers and high-resolution observations of dust and gas in radio-loud galaxies will help shed light on the evolution of those fascinating sources.

11. Observation of NGC 1316 at higher angular resolution with the ALMA in Chile or the Submillimeter Array in Hawaii will be suitable for making a detailed comparison with the HST image. The point-like sources detected in the LABOCA fields may also be followed up. Again, the galaxies are mergers at different levels of relaxation after the merger event. They could be part of a whole sample of galaxies selected across the Hubble sequence to observationally assess the merger-formation hypothesis and dust contribution in merger-driven galaxy evolution. Radio continuum measurements may be obtained by the future Square Kilometer Array and the African VLBI Network (AVN), that will include the Ghana telescope (see Duah Asabere et al. 2015).
Appendix A

Infrared Radial Profiles of WISE Images

The WISE elliptical-radial surface brightness profiles figures of NGC 5078, NGC 7172 and IC 5063 are presented here. The figures show infrared surface distributions of the galaxies.

A.1 Elliptical-Radial Surface Brightness Profiles
Figure A.1: Azimuthal elliptical–radial surface brightness profiles of NGC 5078 WISE images. Caption is the same as in Figure 4.2.
Figure A.2: Azimuthal elliptical-radial surface brightness profiles of NGC 7172 WISE images. Caption is the same as in Figure 4.2.
Figure A.3: Azimuthal elliptical–radial surface brightness profiles of IC 5063 WISE images. Caption is the same as in Figure 4.2.
Appendix B

Submillimeter Galaxy Candidates

B.1 High-redshift Submillimeter Galaxy Candidates in the LABOCA Maps of NGC 1316 and NGC 612

![NGC 1316 and NGC 612 maps](image)

Figure B.1: Shows the point sources (indicated by the red circles) detected in the LABOCA maps of NGC 1316 (left) and NGC 612 (right). At the 3.4σ threshold search, 5 point sources (including NGC 1317) were detected in the NGC 1316 map, and 1 detection (Source A) in the NGC 612 map at the 4.1σ threshold search (see Section B.1; and also Table B.1).

The detect utility in the Crush software package was used to search for point sources in the LABOCA maps. For NGC 1316, the search was done peaking at 3.4σ in the map area of $4.63 \times 10^{-2}$ square degree which contained about 1392 instrument beams. The point source detection searches were conducted within $3.77 \times 10^{-2}$ square degree of the NGC 612 map at
<table>
<thead>
<tr>
<th>Source(^{a})</th>
<th>RA [J2000](^{b})</th>
<th>DEC [J2000](^{c})</th>
<th>Flux(^{d})</th>
<th>S/N(^{e})</th>
<th>Confidence(^{f})</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1316</td>
<td>03:22:40.593</td>
<td>-37:12:30.05</td>
<td>13.19 ± 2.68</td>
<td>4.92</td>
<td>100</td>
</tr>
<tr>
<td>NGC 1317</td>
<td>03:22:43.972</td>
<td>-37:06:15.17</td>
<td>18.77 ± 5.76</td>
<td>3.26</td>
<td>88</td>
</tr>
<tr>
<td>NGC 1316(^{Source, A})</td>
<td>03:23:08.551</td>
<td>-37:11:11.14</td>
<td>15.77 ± 4.01</td>
<td>3.94</td>
<td>97</td>
</tr>
<tr>
<td>NGC 1316(^{Source, C})</td>
<td>03:22:24.922</td>
<td>-37:05:56.88</td>
<td>64.32 ± 17.20</td>
<td>3.74</td>
<td>95</td>
</tr>
<tr>
<td>NGC 1316(^{Source, D})</td>
<td>03:22:24.755</td>
<td>-37:07:00.26</td>
<td>37.70 ± 8.74</td>
<td>4.31</td>
<td>99</td>
</tr>
<tr>
<td>NGC 612</td>
<td>01:33:57.710</td>
<td>-36:29:38.65</td>
<td>57.09 ± 4.70</td>
<td>12.14</td>
<td>100</td>
</tr>
</tbody>
</table>

Table B.1: Possible high-redshift submillimeter galaxy candidates detected in the LABOCA maps of NGC 1316 and NGC 612. \(^{(a)}\) Detected source, \(^{(b)}\) and \(^{(c)}\) its spatial location. \(^{(d)}\) Measured uncorrected flux, \(^{(e)}\) signal-to-noise ratio and \(^{(f)}\) the confidence level of the detection.

4.1σ, which also contained about 1133 instrument beams. From the search, 5 point sources (including NGC 1317) were detected in the NGC 1316 map within the 3.4σ threshold at confidence level range of 88 - 100%. In the NGC 612 map, 1 point source was detected at the 4.1σ search at confidence level of 98% (see Table B.1). There were no negative detections.

These detected point sources are possible high-redshift submillimeter galaxies which need further probes with high resolution instruments to ascertain their authenticity and redshift information. The most probable ones are \(\text{Sources A and B}\) in the NGC 1316 map (see Figure B.1, left image), and \(\text{Source A}\) in the NGC 612 field (see Figure B.1, right image). The \(\text{Sources C and D}\) are at the outskirts of the NGC 1316 field. They could be background excess emission or noise.
B.2 Searching for Counterparts in the WISE Fields

Figure B.2: The extracted point sources (red circles) from the LABOCA map are matched on the NGC 1316 WISE images. The detections are not clearly visible in the WISE images, with the exception of NGC 1317, which is located in the cleaned spot.

The point sources detected in the LABOCA maps of NGC 1316 and NGC 612 (see Figures B.1) were superimposed onto the WISE images to check if they have counterparts. In NGC 1316 (see Figures B.1), there are no clear matches of the detected sources in the WISE images, with the exception of NGC 1317 seen in the cleaned spot north of the NGC 1316 (see Figure B.2).

However, in the NGC 612, the detected source in the LABOCA map coincides with suspected excess emission in all the four bands (see Figure B.3). There is a good possibility that it could be a high-redshift submillimeter galaxy.
Figure B.3: The extracted point sources (red circle) from the LABOCA maps are matched on the *WISE* images of the galaxy. The detection is visible in all the *WISE* images, with the exception of W3, which is not very clear.
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