ISM Conditions

in

Starburst Galaxies

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Proefschrift

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À Memória do Meu Pai

And so it begins. Magnetic fields make their presence felt by exerting forces on charged particles, which because of this will spiral around the field lines. Highly energetic cosmic rays spiralling around magnetic field lines emit radio waves that we detect with telescopes like the WSRT. In this thesis I study Faraday rotation of these radio waves to learn more about magnetic fields in the Milky Way. [CERN copyright]

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Chapter 1

Introduction

1.1 Starburst Galaxies

When the first galaxies were formed about 10 billion years ago, the Universe was much smaller and denser than today. It is thought that interactions between these first galaxies were very frequent. In deep observations of the sky one can see how the galaxies seem to be highly grouped in dense regions, where interactions are common. These interactions provoke the piling up of gas and dust, triggering the formation of large quantities of massive stars. In some of these objects, the star formation rate is so high that, if maintained, it would consume all the gas in the galaxy in less than a Hubble Time (**?** 87**?**). Such galaxies are called "Starburst Galaxies".

The successful Infrared Astronomical Satellite (IRAS), launched in 1983, showed that starburst galaxies may be a common mode of evolution for galaxies. Starbursts are intensely luminous at infrared wavelengths, reaching bolometric luminosities $L > 10^{11} L_{\odot}$ (**?**), and have star formation rates (SFR) up to 1000 times the SFR in our own galaxy (**?**). In the local Universe, starburst galaxies are responsible for approximately a quarter of all the massive star formation (**?**), and it is clear that they form an important phase of galaxy evolution. Scaled-down versions of starbursts are found in the Local Group of galaxies, like 30 Doradus in the LMC, and prototypical starbursts can be found in the local Universe, at distances shorter than 100 Mpc. These galaxies could be studied as local/recent counterparts to the first galaxies in the Universe.

Most starbursts (but not all) are clearly initiated by interactions, collisions or mergers of gas-rich galaxies (**?**). The impact of such interactions compress vast amounts of interstellar gas and dust and locally increase gas density. Molecular gas clouds eventually collapse and form massive stars in very energetic bursts (**?**). Stellar winds and supernovae sweep up the ISM, producing more shock waves, consequently forming more massive stars. In many starburst galaxies, the ionized gas escapes the star forming region, forming outflows that extend many kiloparsec outside of the galactic plane. As the molecular gas is used up or dispersed, the starburst period comes to an end. Other triggers of starbursts include inward gas flows in barred galaxies, or spontaneous global gravitational instability in dwarf galaxies.

The properties of a starburst depend upon a number of factors, including the stellar initial mass function (IMF) and the aging/evolution of the stellar population. The IMF is the number of stars that form per mass interval at the start of their main sequence lifetime. The low-mass stars dominate the stellar population, but the high-mass stars dominate both the luminosity and the ionization in a starburst.

A starburst region can contain up to hundreds of super star clusters (SSCs), each

Figure 1.1 — Left: composite image of the Antennae galaxies (NGC 4038/4039), made using the ACS instrument on the Hubble Space Telescope using several different filters: F435W (B) in blue, F550M (y) in green, F658N (Hα=[NII]) in pink, and F814W (I) in red (Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)). Right: composite image of the Antennae galaxies, made from 3.6 μm (in blue), 4.5μm (in green) and 8.0 μm (in red) images from the Infrared Array Camera on board Spitzer Space Telescope (Credit: NASA/JPL-Caltech/Z. Wang (Harvard-Smithsonian CfA)). See color supplement for a color version of this figure.

of which contain hundreds of stars surrounded by gas and dust. In starburst galaxies they are most commonly characterized by diameters greater than 100 pc and and stellar masses more than $10^6 M_\odot$. In the first 5 Myr of their lifetimes, SSCs are enshrouded in dust, making it impossible to be observed in the optical. In the interacting system the Antennae (NGC 4038/NGC 4039), seen in Fig. **??** (left), one can observe the super star clusters in its different evolution stages. At the rims of the system, one can see the ionized gas surrounding the massive clusters. However, in the region where the two galaxies encounter each other, there are large amounts of dust completely obscuring the light from the stars. In Fig. **??** (right), this obscured region lights up at 8μm, which is in the mid-infrared. The very young (< 5 Myr) SSCs formed during a starburst are typically enshrouded in dust, which absorbs the UV and optical radiation emitted by the massive stars, making them hard to study at these wavelengths. The properties of luminous starbursts can best be investigated by observing them in the infrared.

1.2 The ISM of starburst galaxies at infrared wavelengths

The infrared spectrum from starburst regions is emitted mainly by three kinds of sources corresponding to the main components in a star forming region: gas, dust, and stars. The variation of the emission flux of these three components with the wavelength is called a spectral energy distribution (SED). The near-infrared continuum emission (1-3μm) is dominated by photospheric radiation from red giant and red supergiant stars, with small contributions of bremsstrahlung radiation, hot dust and blue stars. Somewhere between 3-10μm, the continuum energy distribution begins to rise steeply with the increasing wavelength, as the SED is becoming dominated by radiation from dust heated to several hundred degrees by the young massive stars. The energy distribution reaches a maximum in the 80-100μm, falling off rapidly with wavelength thereafter.

1.2.1 Gas and Dust

The gas surrounding a massive cluster absorbs nearly all the stellar photons with energies sufficient to photoionize neutral hydrogen (E > 13.6 eV, or $\lambda < 91.2$ nm). The subsequent recombination of hydrogen ions and resulting radiative cascade produce hydrogen recombination emission lines, but the strongest lines are mainly in the visible and near-infrared part of the spectrum. In HII regions the gas is almost completely ionized and the free thermal electrons can also collisionally excite ions, whose radiative decay produces emission lines.

Fine structure transitions arise between levels with excitation temperatures of a few hundred degrees. These lines are "forbidden" lines because they are forbidden to electric dipole radiation and their excited states are relatively long-lived. The strength of these lines depends on collision rates and radiative transition probabilities. The ratios of various line strengths indicate gas densities and temperatures. Most infrared fine structure lines are little affected by interstellar extinction and are incisive probes of the most obscured regions.

Molecular hydrogen lines are also detected in the mid-infrared, mainly through transitions between pure rotational states. The H_2 molecule is thought to be excited either collisionally in shocks or by absorption of $91 - 111$ nm photons. Depending on which lines are observed, the observations can be used to determine values of the interstellar extinction, shock velocities, and UV energy densities.

Dust surrounding the massive stars absorbs UV radiation from the stars and reemits it in the infrared. The infrared continuum of the spectral energy distribution (SED) between $5 - 1000\mu$m is produced mainly by dust grains of various types. Dust is thought to be mainly formed around Asymptotic Giant Branch (AGB) stars. Stars with masses below 8 M$_\odot$ will go through the AGB phase, and lose significant mass into the ISM. AGB stars often have pulsational instabilities, leading to periodic variations in the physical conditions at a given radial distance, which may induce cyclic phases of grain nucleation, growth, and ejection (**?**). Once solid particles are formed, they are blown to the ISM by the radiation pressure from the star. As dust grains are injected into the ISM, they suffer a variety of ISM processes that result in their destruction, returning elements into the gas phase or further coagulation into bigger grains. These processes include: a) thermal sputtering in high velocity (> 150 kms^{-1}) shocks, b) shattering by grain-grain collisions in lower velocity shocks, c) evaporation near luminous stars and HII regions, and d) accretion in dense molecular clouds.

Dust grains can be divided into various types, according to size and composition. Sufficiently large grains can absorb UV photons without varying their temperature and therefore are at thermal equilibrium with the ionized gas. Smaller grains are no longer in thermal equilibrium with the ISM and its temperature can vary by up to a factor of 10. Dust grains are generally either silicate or carbonaceous in nature. For simplicity, these types are often grouped into three cathegories: BGs, VSGs, and PAHs.

The population of big silicate grains (BGs) of radius $a \sim 10 - 100$ nm is characterized by a single grain temperature T. It is usually modeled by one or more modified blackbody curves (MBB), which have the shape $F(\lambda) \propto \lambda^{-\beta} B(T_d, \lambda)$, in which $B(T_d, \lambda)$ is the Planck function, and β an emissivity factor that depends on the physical properties of the material. BGs usually account for most of the sub-millimeter ($\lambda > 100\mu$m) SED emission in the Milky Way and nearby galaxies, and also the SED peak (**? ?**). Therefore, with the advent of IRAS the assumption that the SEDs of galaxies are characterized by a population of BGs with a single temperature was quite reasonable, and the IRAS colors $60/100\mu$m have been used to determine T empirically.

Very small carbonaeous grains (VSGs) with $a < 50$ nm are stochastically heated rather than in thermal equilibrium with the ISM. When the grains are immersed in an interstellar radiation field, their temperatures fluctuate according to their size and the energy of the photons. Studies of the temperature spiking of very small grains of $5 - 50$ nm have suggested that the temperature spike associated with absorption of a 10 eV photon may approach 10^3 K (**?**).

Polycyclic aromatic hydrocarbon molecules (PAH) are thought to be responsible for the broad emission bands seen in the mid-infrared between $3.3 - 18\mu$m (**? ? ?**). They are the smallest of the dust grains considered here, with $a \sim 10$ nm, undergoing stochastic heating up to temperatures $T \gg 100$ K when excited by single photons in PDRs. There is wide variety of configurations of PAH molecules, with the main broad emission bands at 3.3, 6.2, 7.7, 8.6, and 11.3 μm being produced by C-C and C-H rotational, vibrational, and bending modes. The underlying continuum is produced by amorphous carbon VSGs, and also weaker PAH emission bands.

1.2.2 The phases of the ISM

Figure 1.2 — Schematic of one of the geometries considered in PDR models. The stars represent the central cluster.

All these phases of gas and dust exist in starburst regions, and are revealed by studying infrared spectral features. Fig. **??** is a schematic of a model of the structure of the ISM surrounding a massive cluster. Stellar winds from the cluster sweep the nearby gas and dust up to a radius R, where it ionises a thin gas shell known as an H II region. In this region, all of the present gas is ionized. The most common tracers of an HII region in the mid-infrared are fine-structure lines such as [ArII]6.99μm, [NeII]12.8μm, [NeIII]15.6μm, [SIII]18.3μm, and [SIII]33.5μm. Outside of an HII region is a photodissociation region (PDR). PDRs include all interstellar regions where the hydrogen gas is predominantly neutral but where FUV photons play a significant role in the chemistry and/or the heating. Most of the mass of the gas and dust in the Galaxy resides in PDRs and is significantly affected, either via chemistry or heating, by the FUV flux. Therefore, PDRs emit much of the IR radiation (line and continuum) in galaxies. Much of the gas is heated by the grain photoelectric heating mechanism. The most common tracers of PDRs in the mid-infrared are warm H_2 rotational emission lines, broad emission features caused by vibrational modes of polycyclic aromatic hydrocarbon molecules and some low-excitation fine-structure lines, such as [SiII]35μm. In Fig. **??**, a "template spectrum" of a starburst is presented, built averaging the mid-infrared spectra of 13 starburst galaxies (40). The figure illustrates the richness of the $5 - 35\mu$m wavelength range. Important features include PAH emission bands, silicate absorption features, and emission lines, in addition to the information contained in the slope of the spectral continuum.

With spatially resolved studies of the distribution of mid-infrared spectral features, one can resolve the ISM structure in starburst regions and study the impact of the UV field on the ISM, especially on dust. It is important to know how differences in metallicity affect the ISM structure and the link between dwarf galaxies such as NGC 5253 and starbursts with dense concentrations of SSCs such as M82. Differences in starburst density affect how SSCs influence the surrounding ISM through positive and negative feedback, enhancing or suppressing star formation. With a ring galaxy system like Arp 143, one can study how a system of coeval SSCs can develop in which SSCs are separated from each other by more than 5 kpc.

The range of luminosities and morphologies observed in starburst galaxies are related to the different properties of the interstellar medium. Dwarf galaxies, for example, have lower metallicities than spirals and merger systems. Whereas the metallicity of a prototypical starburst galaxy, such as M82, is about Solar (57), dwarf galaxies have typically much lower metallicities (**?**), which may be as low as 1/40 of the solar metallicity, as is the case of SBS 0335-052. This is reflected by the lack of PAH features observed in the spectrum of this galaxy (63). These galaxies contain only a few SSCs, and are therefore quite suitable for the study of spatial variation of ISM properties with the distance from the clusters.

Figure 1.3 — Average IRS spectrum from 13 galaxies (IC342, NGC 660, NGC 1097, NGC 1222, NGC 2146, NGC 3310, NGC 3556, NGC 4088, NGC 4194, NGC 4676, NGC 4818, NGC 7252, NGC 7714). All spectra have been normalized to a flux density of 1 at 15μm before co-addition (40).

In galaxies with higher mass there is enough gas to form dense starburst regions with dozens of SSCs, like the ones found in M82 or NGC 253, concentrated around the nuclear regions. A central starburst is formed as the gas is driven inwards from the disk to the nucleus as a result of tidal bars (**? ?**), interactions, or mergers (**? ?**). Once the gas reaches the inner kiloparsec, it can either fragment and form stars (at rates of typically 10-100 $M_\odot$ yr^{-1}), or continue to flow inwards and fuel an AGN, or a combination of both.

In galaxies without a dramatic inflow of gas into the nucleus, SSCs are spread out in the spiral arms. In cases of a head-on collision of galaxies, the gas is compressed by a powerful shock-wave, and a ring of SSCs can be formed around the nucleus with tens of kiloparsec in diameter. The most well-known example is the Cartwheel galaxy, in which the star-forming ring has a diameter of ~ 40 kpc (**?**). If the SFR is the same or less than the SFR of central starburst galaxies, this means that disk starbursts and ring systems have much lower starburst densities. A decrease in the starburst density means a decrease on the interstellar radiaton field (ISRF) intensity. This would have important implications on the dust temperature, as the equilibrium temperature of a dust grain increases with the intensity of the ISRF (**? ?**).

1.3 This thesis

Figure 1.4 — Distribution of NGC 5253, M82, and Arp 143 according to metallicity and starburst area.

In this thesis I focus on two main questions:

- How are starbursts triggered at different scales?
- How do different areas occupied by SSCs affect ISM conditions?

For this purpose I studied in detail the ISM properties of three starburst galaxies that cover a wide range of metallicities and star formation areas. These galaxies are NGC 5253 (a low-metallicity dwarf galaxy), M82 (a prototypical central starburst galaxy), and Arp 143 (a collisional galaxy system). Fig. **??** shows how these three galaxies are distributed according to metallicity and starburst area.

In **Chapter 2** I first study the effect of a single cluster on the ISM, using fine-structure line ratios. The abundance of PAHs is influenced mostly by two factors: radiation field hardness and metallicity. Mid-infrared studies of Blue Compact Dwarf (BCD) galaxies (112; 20,e.g.) revealed that the abundance of PAH is definitely correlated with metallicity. However, the PAH abundance also decreases with the hardness of the radiation field, which varies with the distance to a young SSC. Moreover, in low-metallicity environments, the hardness of the radiation field is enhanced (75). NGC 5253 is a low-metallicity dwarf galaxy and its infrared luminosity is dominated by a single very young and massive cluster near the center. It is therefore adequate to use this galaxy to study the variation of PAH abundance with the distance to a single SSC. I present *Spitzer Space Telescope* data on the nearby starburst galaxy NGC 5253, from the Infrared Array Camera *IRAC* and the Infrared Spectrograph *IRS*. The spectra reveal for the first time PAH emission features at 11.3μm; the equivalent width of this feature increases significantly with distance from the cluster. The EW of the PAH 11.3μm feature increases by a factor of 15 at a distance of 250 pc from the central cluster. I find that the [Ne III]/[Ne II] ratio, which traces the hardness of the radiation field decreases by a factor of 3.4 over the same distance. The product [NeIII]/[NeII]*([NeIII]+[NeII]), which I call "strength" of the radiation field, accounts for the variation of the PAH EW, and thus PAH destruction up to 200 pc from the SSC.

As M82 is an example of a central starburst with multiple SSCs, in **Chapter 3** I analyze the variation of ISM properties with high spatial resolution (~ 35 parsec) $5-38\mu$m Spitzer-IRS spectra of the central region of M82. The [NeIII]/[NeII] ratio is on average low at $\sim$0.18, about 40 times lower than in the central cluster of NGC 5253. The [NeIII]/[NeII] ratio shows little variations across the plane, indicating that the dominant ionizing stellar population is evolved (5 - 6 Myr) and well distributed. This contrasts with NGC 5253, and reflects differences in both metallicity and age. There is a slight increase of the ratio with distance from the galactic plane of M82 which we attribute to a decrease in gas density. Our observations indicate that the star formation rate has decreased significantly in the last 5 Myr. The large quantities of dust and molecular gas in the central area of the galaxy argue against starvation and for negative feedback processes, observable through the strong extra-planar outflows.

There is also a good correlation of the spatial distribution of dust extinction in M82 with the CO 1-0 emission, which is to be expected since the molecular gas emission traces the densest star-formation sites, and these are the most extincted. The PAH emission, arising from the PDRs, follows closely the ionization structure along the galactic disk. The observed variations of the diagnostic PAH ratios across M82 can be explained by extinction effects, within systematic uncertainties. The $16-18\mu$m PAH complex is very prominent, and its equivalent width is enhanced outwards from the galactic plane. We interpret this as a consequence of the variation of the UV radiation field. The EWs of the 11.3μm PAH feature and the H_2 0-0 S(1) line correlate closely, and we conclude that shocks in the outflow regions have no measurable influence on the H_2 emission.

In systems where SSCs are separated by several kiloparsecs, feedback will no longer be possible. In **Chapter 4** I investigate how massive SSCs spread over a wide area of dozend of kpc^2 can be triggered by a large-scale shock wave. I present new mid-infrared ($5 - 35\mu$m) and ultraviolet (1539 – 2316 Å) observations of the interacting galaxy system Arp 143 (NGC 2444/2445) from the Spitzer Space Telescope and GALEX. The central nucleus of NGC 2445 is surrounded by knots of massive star-formation in a ring-like structure. There is unusually strong emission from warm H_2 associated with an expanding shock wave between the nucleus and the western knots. From the multi-wavelength data I conclude that the ring of knots was formed almost simultaneously in response to the shock wave traced by the H_2 emission. However, the knots can be further subdivided in two age groups: those with an age of 2–4 Myr (knots A, C, E, and F), which are associated with 8μm emission from PAHs, and those with an age of 7-8 Myr (knots D and G), for which 8μm emission shells are no longer observed. The reasons for this are unclear, as PAHs are observed at later stages in other systems like the Antennae.

Warm dust is associated with high starburst density and therefore with high ISRF intensity. Therefore, the dust temperature can be also an indicator of starburst density. The largest part of the dust mass existing in star-forming galaxies is made of large silicate grains, which mostly emit in the region $\lambda > 60\mu$m. This part of the spectrum is usually modeled with a sum of two modified blackbodies, a model that requires few free parameters. However, with all its parameters free, it can only model SEDs with at least seven datapoints. Many observed infrared SEDs of star-forming galaxies to date, including starbursts, have only three datapoints. This means that the dust properties such as temperatures and masses derived by modeling these infrared SEDs are largely uncertain. In **Chapter 5** I model the infrared SEDs of a sample of 126 star forming galaxies with modified blackbody (MBB) models in order to explore the possibilities of reducing the required fitting parameter space in the models. Most infrared SEDs are too broad to be modelled by a single MBB, and a cool dust component needs to be added. Modeling each galaxy with a two MBB components, we conclude that the SEDs can be adequately described with fixed emissivity exponents for both components ($\beta = 2$), leaving four parameters free: the temperatures of the cold and warm components, T_c and T_w, and the scaling parameters of the cold and warm components N_c and N_w. Six galaxies require a very cold MBB, with $T_c < 14$ K, and two of these, NGC 1614 and NGC 3310, have $T_c < 10$ K. Four of these galaxies are merger systems. An explanation for the very cold component could be either dust shielded in large molecular clouds in a high pressure environment such as the central regions of mergers. Other explanation would be tidally removed dust as a consequence of the merging process, of which NGC 1614 can be seen as an extreme example. We estimate the mass fraction between the cold dust and warm dust components as $M_c/M_w \sim 50$, which is very similar to the ratio derived from the two MBB model for NGC 1614, $N_c/N_w = 55$. Despite the outlying galaxies having a high mass fraction of Very Small Grains (VSGs) on average, a high VSG mass fraction is not a sufficient explanation for the very cold dust emission at the sub-millimeter. For the spiral NGC 3310, a higher fraction of VSGs is clearly preferred as the cause of very cold dust emission. Merger galaxies were also found to have higher T_w on average, associated with a higher ISRF intensity.

The main conclusions of this thesis are the following:

- It has long been argued that photo-destruction is an important cause for low PAH abundances in blue compact dwarf galaxies, in addition to the effects of low metallicity. In this thesis, I have shown that in the low metallicity blue compact dwarf galaxy NGC 5253, the relative strength (equivalent width) of the PAH emission increases with distance from the central, ionizing stellar cluster. Since one does not expect significant variations in metallicity over a few hundred parsecs within the same galaxy, this finding is taken as a strong support for an anti-correlation between the strength of the PAH emission and the UV radiation field. In other words, whether or not there are sufficient metals in the low density ISM of blue compact dwarf galaxies to form PAHs, their observed signatures will be weak as they get efficiently destroyed by UV photons.

- While in NGC 5253 the observed properties were mainly determined by a single, massive central cluster, the structure in more luminous starburst galaxies is a lot more complex. Extending my previous results, I examined the nuclear region of the classical starburst galaxy M82 and found two striking results. First, the UV radiation field across the central few hundred parsecs is, on spatial scales of about 30 parsecs, about 40 times softer than in NGC 5253 with very little spatial variation. Hence, for any given location, there must be a composition of older and younger clusters, with the former being the dominant population. Because of the high cluster density, the "sphere of influence" of any particular cluster is much smaller than in the case of NGC 5253 or Arp 143 (see below). Second, from the large amount of dense molecular gas still present in the center of M82 one would expect a very active phase of star formation. However, this is not observed in M82, with star formation strongly suppressed in the last 5 Myr, thus mechanisms that suppress the conversion of gas into stars must be at play. Supernovae shocks and stellar winds are likely to provide efficient but localized, negative feedback.
- On scales larger than a few kiloparsecs, supernova feedback cannot longer be a dominant factor in affecting the star formation efficiency on short timescales. Large scale events like galaxy interactions become then relevant. I have studied this for the ring galaxy Arp 143, which is characterized by a ring-like structure of super star clusters at kiloparsec distances from the nucleus. Unlike in M82, the massive clusters in Arp 143 are at distances from each other that prohibit their mutual influence and allow for a detailed cluster-by-cluster study. I found that their ages differ but the age spread is very small compared to the dynamical time across the ring of clusters. This is strong support for the scenario in which a radially expanding, large-scale shock wave from a head-on galaxy-galaxy collision has swept up the interstellar medium and triggered the formation of these clusters. Furthermore, I found that the strength of the PAH emission is anti-correlated with the cluster age, which is likely resulting from supernovae and stellar winds clearing out the surrounding ISM.
- Finally, I investigated the properties of the dust emission in starburst environments. The first step was to identify a simple and robust formalism and check its accuracy. The far-infrared (60μm $--1$ mm) SED of most starburst galaxies can be reasonably reproduced by two modified black bodies with constant emissivity. I investigated a sample of 126 galaxies which had observations at 850μm and IRAS pointings, along with all publicly available data in the far-infrared range. Most galaxies from that sample can be very well fitted with the sum of two black

bodies at ”normal” temperatures, which suggests that, globally, the dust properties of starburst galaxies are very similar. However, a small fraction of galaxies require a very cold component with $T < 14$ K. Most of these ”cold” galaxies are mergers and exhibit a high fraction of stochastically heated very small grains (VSGs). This finding opens two plausible explanations for the cold dust: either a large amount of big, very cold silicate grains in the diffuse ISM, or a significantly higher fraction of VSGs. In one case, the spiral NGC 3310, a higher fraction of VSGs is clearly preferred, but in most of the “cold galaxies”, spatially detailed sub-millimeter observations of the central regions of these galaxies are required in order to trace the origin of the 850μm emission.

1.4 Outlook

The forseeable future of starburst galaxy research is going to be associated mostly with the far-infrared and submillimeter. The *Herschel Space Telescope*, launched in May 2009 will allow a study of starburst galaxies with superior sensitivity, spatial and spectral resolution in the far-infrared. It has a 3.5 meter diameter mirror, and a science payload consisting on three instruments: PACS, a camera and spectrometer that allows Herschel to carry out photometric measurements at 75μm, 110μm, and 170μm and obtain spectra between $57 - 210\mu$m; SPIRE, a camera and spectrometer that peforms phtometric measurements at 250μm, 350μm, and 500μm, and obtain spectra between $197 - 672\mu$m; HIFI, a spectrometer with extremely high spectral resolution, with a wavelengths range between $157 - 625\mu$m. With these instruments one can perform detailed photometric studies of dust emission in nearby galaxies, with a resolution at 170μm comparable to MIPS 24μm maps. SPIRE will address also the scarcity of data from nearby galaxies between $160 - 450\mu$m. With PACS in particular, it will be possible to map ISM cooling lines such as [CII]157.7μm, [OI]63.2μm, [OIII]88.4μm, and [NII]$121.9, 205\mu$m, which allow spatially detailed physical studies of the cold ISM in nearby galaxies down to a resolution of $10''$. I will specifically be involved in KINGFISH, an imaging and spectroscopic survey of 61 nearby (D < 30 Mpc) galaxies, chosen to cover the full range of ISM properties and environments found in the local Universe.

The exploration of the mid-infrared Universe did not end with the Spitzer Space Telescope. The James Webb Space Telescope (JWST), scheduled to launch in 2014, will be the next instrument to be dedicated to this wavelength range. With a primary mirror of 6.5 meter in diameter and a payload of a near- and mid-infrared cameras and spectrographs, JWST will be dedicated to observe at wavelengths between $0.6 - 27\mu$m, with a spectral resolution up to R~ 3000 between $5 - 27\mu$m, about 5 times the maximum spectral resolution of Spitzer/IRS. The fact that it has near- and mid-IR instruments in one telescope allows the study of near-infrared features in starburst galaxies at high-z, such as hydrogen and helium recombination lines, which trace the ionized gas surrounding massive young stellar clusters. With increased sensitivity in relation to Spitzer/IRS, MIRI will be also especially useful to detect mid-infrared spectral features such as PAHs, thus tracing star formation in faint nearby sources.

Despite the high sensitivity of a space telescope such as JWST, spatially resolved observations of starbursts at high-z will only be possible with ALMA. At $z > 5$, the far-infrared peak moves to sub-millimeter wavelengths, where ALMA will be ~ 1000 times more sensitive than present equipment. This gives the possibility to study in detail high-z ULIRGs in the sub-millimeter and normal galaxies up to $z = 3$, which will contribute to a better knowledge of the star formation history of the Universe. It will also be possible to resolve Giant Molecular Clouds (GMC) and study their size and turbulence in galaxies out to distances of 100 Mpc, which allow us to study in the star formation processes on a large population of starburst galaxies on a scale only possible today on the most nearby examples such as M82. All this shows a bright future ahead for the research of starburst galaxies.

Chapter 2

Spatially Resolved *Spitzer* Spectroscopy of the Starburst Nucleus in NGC 5253

Chapter enhanced from P. Beirão, B. R. Brandl, D. Devost, J. D. Smith, L. Hao & J. R. Houck, Astrophysical Journal Letters, 643, L1 (2006)

We present new *Spitzer Space Telescope* data on the nearby, low-metallicity starburst galaxy NGC 5253, from the Infrared Array Camera *IRAC* and the Infrared Spectrograph *IRS*[1]. The mid-IR luminosity profile of NGC 5253 is clearly dominated by an unresolved cluster near the center, which outshines the rest of the galaxy at longer wavelengths. We find that the [Ne III]/[Ne II] ratio decreases from ~ 8.5 at the center to ~ 2.5 at a distance of ~ 250 pc. The [S IV]/[S III] follows the [Ne III]/[Ne II] ratio remarkably well, being about $4-5$ times lower at all distances. Our spectra reveal for the first time PAH emission features at 11.3μm; their equivalent widths increase significantly with distance from the center. The good anti-correlation between the PAH strength and the product between hardness and luminosity of the UV radiation field suggests photo-destruction of the PAH molecules in the central region. The high-excitation [OIV]25.91μm line was detected at 0.42×10^{-20}W cm^{-2}. Our results demonstrate the importance of spatially resolved mid-IR spectroscopy.

[1]The *IRS* was a collaborative venture between Cornell University and Ball Aerospace Corporation funded by NASA through the Jet Propulsion Laboratory and the Ames Research Center.

Figure 2.1 — *IRAC* color composite image of NGC 5253 at 3.6μm (blue), 4.5μm (green) and 8.0μm (red). The image is 4 arcmin aside. North is up and East to the left. See color supplement for a color version of this figure.

Figure 2.2 — Overlay of the SH and LH slits (top) and the extraction region for the SL+LL spectrum (bottom) on the *IRAC* 3.6μm image of NGC 5253. The image is 1 arcmin aside. The SH slit is highlighted at the most central position.

2.1 Introduction

NGC 5253 is a nearby, low-metallicity dwarf galaxy with a recent starburst, which is responsible for its infrared luminosity of $L_{IR} \sim 1.8 \times 10^9 L_\odot$ (2). Distance estimates vary from 3.3 ± 0.3 Mpc (8) to 4.0 ± 0.3 Mpc (27); here we will assume 4.0 Mpc, corresponding to 19.4 pc / ″. With its low metallicity of only about $1/6 Z_\odot$ (13) NGC 5253 is an excellent target to study starbursts in a low-metallicity environment. The spectral signatures of Wolf-Rayet (WR) stars suggest a very recent starburst (Beck et al. (2); Schaerer et al. (23)). Cresci et al. (3) detected 115 star clusters using optical and near-infrared VLT images at an age range of 3-19 Myr. Turner et al. (29) found a compact radio source representing a hidden super star cluster (SSC) in one of the earliest phases of SSC formation ever observed. Its ionizing flux corresponds to several thousand O7 V star equivalents within the central $2''$ (4; 106) and an infrared luminosity of $L_{IR} = 7.8 \times 10^8 L_\odot$ (4). Near-infrared observations with Hubble Space Telescope revealed the presence of a double star cluster in the nuclear region, separated by $6 - 8$ pc (1). There are indications that an interaction with M81 might have provoked the starburst (14).

NGC 5253 has also been studied in the mid-IR with the *Infrared Space Observatory (ISO)* by several authors, e.g., Crowther et al. (4), Thornley et al. (105) and Verma et al. (31). With *Spitzer*'s increased sensitivity (71) and the smaller slit apertures, the *IRS* can continue where *ISO* left off. In this letter we report on the spatial variations of the physical conditions in the central region of NGC 5253, based on *IRAC* images and *IRS* (63) spectral maps.

2.2 Observations and data reduction

The images were obtained on 2005 January 31 using IRAC (22) at all four bands ($3.6, 4.8, 5.8, 8.0\mu$m). The observations consist of 12 slightly dithered pointings of 3×12s exposures each. The data were pipeline processed by the Spitzer Science Center. Fig. **??** shows the *IRAC* color composite image of NGC 5253. To assess what fraction of the total luminosity of the central region is provided by the central cluster we compare the flux within the central 44 pc (2 pixel) to the total flux within a radius of 330 pc for each channel. The results in Table **??** show the increasing dominance of the starburst nucleus in luminosity with wavelength. We subtracted the *IRAC* instrumental PSFs from the nucleus for all four channels, and the residuals suggest that the central cluster remains unresolved in the *IRAC* images, which is consistent with its very compact size (106).

The mid-IR spectra were obtained on 2004 July 14, using high resolution (SH+LH;

Table 2.1 — IRAC Flux Table

λ (μm)	Central Flux (MJy/sr)	Total Flux (MJy/sr)	F_{44pc}/F_{600pc}
3.3	2616±12	6578±86	0.39
4.5	5069±16	7846±97	0.65
5.8	11640±29	17187±261	0.68
8.0	26869±33	37846±99	0.71

$R \approx 600$) and the low resolution (SL+LL; $R \approx 57 - 127$) modules of the *Infrared Spectrograph (IRS)* in spectral mapping mode. In the SH (short-high) mode, the map consists of 12 different pointings, overlapping by half a slit width and about one third slit length, covering an area of $18''.0 \times 23''.6$. In LH (long-high) mode the map consists of only 6 different pointings (due to the larger slit dimensions), covering an area of $22''.2 \times 33''.4$. At each pointing 7×6 s exposures were taken. Fig. 4.1 at the left shows the SH and LH slit positions overlaid on the *IRAC* image of the central region. Both maps are slightly off-center. Additional "sky" measurements, 6 arcmin from the nucleus were taken as well, with 5 cycles of 6 and 14 seconds for SH and LH, respectively. The basic processing of the data, such as ramp fitting, dark current subtraction and cosmic ray removal, was performed with versions 11.0 and 15.3 of the automated *IRS* pipeline at the Spitzer Science Center for the high resolution modules and low resolution modules, respectively.

Figure 2.3 — Complete *IRS* SH+LH spectrum of the cluster region of NGC 5253, which correspond to the highlighted slits in Fig. 4.1. Beyond 35μm the spectrum is dominated by noise and detector artifacts.

The high resolution spectra were extracted as follows: the background was subtracted using the sky images and the spectra were extracted in "full-slit" mode from pre-flat-fielded files using the *IRS* data reduction and analysis package SMART, version 5.5 (10). The extracted spectra were flux calibrated with an empirically derived RSRF (relative spectral response function) of α Lac. The spectral overlaps between orders were manually clipped, according to the local S/N. Finally, the SH spectra were scaled up by 16% to match the LH continuum fluxes at 19 μm. This discrepancy in the fluxes is due to the difference between the SH and LH slit sizes.

The low resolution spectra were extracted using CUBISM (96), an IDL-based software package designed to combine spectral mapping datasets into 3D spectral cubes. Bad pixels in the basic calibrated data (BCD) spectra were manually flagged and then automatically discarded when rebuilding the cube. Spectra from off-source positions 1 kpc to the south of the nucleus were used to subtract the background from the low-resolution spectra. A $14''.8 \times 18''.5$ region covering the infrared peak (see Fig. 4.1 at the right) was selected for extraction from a SL map built by CUBISM. Low resolution spectra of this region were extracted for all the low resolution modules.

Table 2.2 — Fine-Structure Lines and Ratios

distance (pc)	[SIV] $(10^{-20} W cm^{-2})$ $\lambda_{obs} = 10.52\mu$m EP=34.8 eV	Huα $(10^{-20} W cm^{-2})$ $\lambda_{obs} = 12.37\mu$m	[NeII] $(10^{-20} W cm^{-2})$ $\lambda_{obs} = 12.83\mu$m $\lambda_{obs} = 15.58\mu$m EP=21.6 eV	[NeIII] $(10^{-20} W cm^{-2})$ $\lambda_{obs} = 18.74\mu$m EP=41.0 eV	[SIII] $(10^{-20} W cm^{-2})$ EP=23.3 eV	[NeIII]/[NeII]	[SIV]/[SIII]
27	37.50 ± 0.21	2.11 ± 0.53	5.63 ± 0.14	47.40 ± 1.21	16.79 ± 0.58	8.41 ± 0.30	2.23 ± 0.08
30	33.22 ± 0.84	1.57 ± 0.28	5.90 ± 0.16	40.87 ± 1.90	17.24 ± 0.52	6.93 ± 0.37	1.93 ± 0.08
76	8.80 ± 0.21	0.43 ± 0.02	3.51 ± 0.08	16.94 ± 0.50	7.91 ± 0.24	4.83 ± 0.18	1.11 ± 0.04
121	2.25 ± 0.32	0.32 ± 0.10	2.02 ± 0.09	8.41 ± 0.31	4.54 ± 0.16	4.17 ± 0.24	0.50 ± 0.02
135	7.01 ± 0.45	...	2.62 ± 0.17	12.18 ± 0.33	6.30 ± 0.18	4.65 ± 0.18	1.11 ± 0.04
149	6.03 ± 0.51	...	2.75 ± 0.13	11.06 ± 0.25	6.00 ± 0.12	4.02 ± 0.21	1.01 ± 0.04
155	3.37 ± 0.24	...	2.58 ± 0.23	8.74 ± 0.14	4.98 ± 0.09	3.39 ± 0.08	0.68 ± 0.02
173	1.01 ± 0.08	...	1.09 ± 0.02	3.16 ± 0.11	2.38 ± 0.08	2.91 ± 0.14	0.43 ± 0.02
194	1.77 ± 0.04	...	2.17 ± 0.14	6.27 ± 0.09	4.03 ± 0.09	2.89 ± 0.08	0.44 ± 0.02
219	0.71 ± 0.01	...	0.60 ± 0.04	1.55 ± 0.06	1.10 ± 0.07	2.60 ± 0.08	0.64 ± 0.02
226	1.18 ± 0.18	...	1.36 ± 0.08	3.28 ± 0.11	2.35 ± 0.09	2.42 ± 0.07	0.50 ± 0.02
260	...	...	0.68 ± 0.12	1.76 ± 0.07	1.12 ± 0.05	2.59 ± 0.08	...

Figure 2.4 — IRS SH spectra of NGC 5253 sorted by decreasing distance from the central cluster (from left to right and from top to bottom). The distances are inserted in the lower right of each plot.

2.3 Discussion

2.3.1 Spectral properties

The complete $10-38\mu$m SH+LH spectrum at the most central position of our map is shown in Fig. **??**. The spectrum shows a smooth continuum with no significant absorption features, and turnover in the slope around 20μm. It is dominated by the strong emission lines of [SIV]10.5μm, [NeII]12.8μm, [NeIII]15.5μm, [SIII]18.7μm, [SIII]33.5μm and [SiII]34.8μm. Also detected are the signature of polycyclic aromatic hydrocarbons (PAH) at 11.3μm and Huα at 12.37μm up to a distance of ~ 120 pc.

The flattening at 20μm is also seen in the low metallicity blue compact dwarf galaxy SBS0335-052 (63) and also in the tidal dwarf galaxies NGC 5291 N and NGC 5291 S (9). We used SMART to fit a modified black-body to the continuum over the range $15-35\mu$m. Using a solid angle equal to the area of the region where the low resolution spectrum was extracted, which is 6.4×10^{-9}sr, the blackbody fit gives a temperature $T=132\pm8$ K. The derived optical depth at 0.55μm ($\tau_{0.55\mu m}$) is effectively zero, and $\alpha=0.04\pm0.14$, where $\tau=\tau_{0.55\mu m}(0.55/\lambda^{\alpha})$. This means that the dominant cooler $40-60$ K dust component, which is present in most starbursts and spiral galaxies, is notably absent here. (9) obtained a similar result with a temperature of $T=142\pm31$ K. The lack of cool dust component in NGC 5253 and in these galaxies is probably due to their common morphology. Their interstellar medium is heated by one or more unobscured HII regions. The dust distribution around these regions is diffuse enough that the dust temperature is $T>100$ K.

Fig. **??** shows eight representative SH spectra at decreasing radial distances. The distances were calculated from the central cluster to the center of each slit position. The remaining four spectra of our map are redundant and not shown to save space. The most prominent spectral features are labeled. The line fluxes for each radial position are listed in Table **??**.

From the SL map built with CUBISM we selected a region including the central cluster which is covered also by the LL slits. The complete low resolution $5-38\mu$m SL+LL spectrum is shown in Fig. **??**. The spectrum between $5-10\mu$m is dominated by the PAH features at 6.2μm, 7.7μm, and 8.6μm, and the [ArII]6.99μm and [ArIII]8.99μm emission lines are quite visible. Longwards 10μ, emission lines such as [SIV]10.5μm, [NeII]12.8μm, [NeIII]15.5μm dominate. The continuum flattening at 20μm observed in the high resolution spectra is confirmed.

2.3.2 PAH ratio maps

Figure 2.5 — Complete *IRS* SL+LL spectrum of the cluster region of NGC 5253, which correspond to the highlighted region in Fig. 4.1. Beyond 20μm the spectrum is dominated by residual fringes not elliminated by the pipeline.

Laboratory and theoretical studies have been proposing that the PAH emission bands at 6.2μm, 7.7μm, and 8.6μm arise mainly form photoionized PAH molecules, whereas bands at longer wavelengths, like the 11.3μm, arise mainly from neutral PAH molecules. Therefore, a ratio between these different types of PAH bands, such as $6.2/11.3\mu$m, will trace the ionization state of PAHs. A tool like CUBISM gives us the oportunity to create PAH ratio maps from the low resolution spectra. This allows us to study the spatial variations of PAH ionization for the first time in a dwarf galaxy.

In the upper plot in Fig. **??** we present a map of the $6.2/11.3\mu$m PAH ratio, which traces PAH ionization. The contours in white are from a $HST - NICMOS\ Pa_{\alpha}$ image (1), indicating the location of the young massive cluster. The $6.2/11.3\mu$m PAH ratio varies between 0.1 and 0.7. The ratio is clearly lower in the infrared peak region, and arises in a small region at the left and along the west side of the image. The ratio is the highest about 100 pc NW of the young cluster, as represented by the contours. The noise can be seen at both ends of the map.

There is no immediate association of the $6.2/11.3\mu$m PAH ratio with the cluster distribution in the galaxy. However, the ratio increase in the left side of the map could be associated with the dust lane observed by Cresci et al. (3) and with a faint CO emission peak (17). Moreover, the presence of a single young cluster dominating the radiation field in the galaxy will affect the equivalent width of the PAHs and we can study spatially this effect using the high-resolution spectra.

Figure 2.6 — Maps of the $6.2/11.3\mu$m PAH ratio and the [SIV]/[NeII] line ratio. The square indicates the region selected for extraction of the full SL+LL spectrum in Fig. **??**.

2.3.3 Gradients in the radiation field

The variation of the hardness of the radiation field can be studied using maps of ratios between two ionic lines tracing stars of different temperatures. In the wavelength regime covered by the SL1 slit we find two suitable ionic lines, [SIV]10.5μm and [NeII]12.8μm. Because [SIV] traces very young and massive O stars, and [NeII] older and cooler O and B stars, the [SIV]/[NeII] ratio is a good indicator of the hardness of the radiation field. In the lower plot in Fig. **??** we present a map of the [SIV]/[NeII] ratio. We can see how dominant is the radiation field from the central cluster and how it distributes throughout the region. However, given that we use different elements, the [SIV]/[NeII] ratio is not ideal, given possible abundance differences between S and Ne.

With ionization potentials of 21.56 eV and 40.95 eV for Ne and Ne^{+}, respectively, the [Ne III]/[Ne II] ratio is a better measure of the hardness of the radiation field, and traces the OB stars. Crowther et al. (4) measured a relatively low [Ne III]/[Ne II] ratio of $3.5 - 4.0$. However, the larger *ISO-SWS* slit apertures of $14'' \times 20''$ and $14'' \times 27''$, centered on the nucleus, may have also picked up significant line flux at lower excitation from the surrounding galactic population. With the smaller *IRS* slit aperture of $4''.7 \times 11''.3$ we can probe the influence of spatial resoluti'on on the measured spectral diagnostics. The upper plot of Fig. 5.16 shows the [Ne III]/[Ne II] and [S IV]/[S III] ratios as functions of the distance to the central cluster. Both ratios decrease by a factor of four over 250 parsecs, indicating a significant softening of the UV radiation field with distance from

Figure 2.7 — *Upper:* Variation of the [Ne III]/[Ne II] (full circles) and [S IV]/[S III] (diamonds) line ratios with distance to the galactic center. The error bars along the x axis represent the *IRS* slit length, which translates into a range in radial distance; they are the same for [S IV]/[S III] ratios. The error bars along the y axis represent flux uncertainties. *Center:* PAH 11.2μm equivalent widths (EWs) as a function of distance to the nucleus. The error bars represent EW measurement uncertainties. *Bottom:* Dependence of PAH 11.2μm EW $\times$ ([Ne II]+[Ne III]) $\times$ [Ne III]/[Ne II] with distance. For details see text. The bars indicate systematic errors.

the cluster core. Both ratios trace each other remarkably well, with the Ne ratio being about $4 - 5$ times higher at all distances.

Our high [Ne III]/[Ne II] ratio at the central cluster is comparable to those observed in nearby H II regions like 30 Doradus and low-metallicity dwarf galaxies like II Zw 40 (105). Rigby et al. (21) modeled Ne line ratios for star clusters at low metallicity $Z = 0.2Z_{\odot}$ and showed that a peak ratio of 7.0 is consistent with an upper mass cutoff of $100M_{\odot}$, at an age of $3 - 5$ Myr.

2.3.4 Dependence of PAH strength on the radiation field

It has often been asked if PAHs in low-metallicity starbursts appear to be weaker because of low abundance or because they get destroyed by the generally harder radiation fields in these environments (e.g., Wu et al. (112); Engelbracht et al. (6); O'Halloran et al. (20); Madden (16)). Neither of the previous *ISO-SWS* observations detected PAH features in NGC 5253. Our high S/N spectra clearly reveal, for the first time, the presence of the 11.3μm PAH feature in all SH positions on NGC 5253, which shows that PAHs can be present in a low metallicity environment. The center plot of Fig. 5 shows a steady increase of the PAH equivalent width (EW) with distance. The observed increase suggests either the photo-destruction of PAHs or the absence of photodissociation regions (PDR) near the cluster center. We assume constant metallicity throughout the galaxy, as no known dwarf has steep metallicity gradients (12).

In Fig. 5 we have investigated the correlation between the measured PAH strength and the "strength" of the UV radiation field, defined by the product of the hardness and the intensity of the radiation field, [Ne III]/[Ne II]$\times$([Ne III]+[Ne II]). The bottom plot shows the product between the UV field and the PAH strengths as a function of distance. This product stays almost constant out to a radial distance of 200 pc, meaning that the strength of the UV field and the strength of the PAH emission is strongly anticorrelated. The good anti-correlation over such a large distance (encompassing numerous H II regions) suggests that the photo-destruction of PAHs might be the dominant mechanism here.

2.3.5 [OIV] line emission

Of particular interest for characterizing the energetics in starbursts is the [O IV]25.89μm line. With an excitation potential of 54.9 eV, it fills the wide energetic gap of mid-IR fine-structure lines between lines that can originate from massive stars and lines that likely require an AGN. The [O IV] line has been attributed to various mechanisms, including very hot stars (24; 19) and energetic shocks for low-excitation starbursts (15).

Our high S/N spectra reveal a faint [O IV] line at two slit positions outside the central cluster, with fluxes of about 0.42×10^{-20} W cm^{-2} at a S/N of 7.1. This is higher than the limits given by Crowther et al. (4) (0.10×10^{-20} W), but below the upper limit of Verma et al. (31) (0.9×10^{-20} W cm^{-2}), and in reasonable agreement with the flux measured by Lutz et al. (15) (0.65×10^{-20} W cm^{-2}). Using the STARBURST99 code (Leitherer et al. 1999) assuming an instantaneous burst of star formation with a Salpeter (22) IMF at 1/5 solar metallicity, the observed OIV emission can be produced by roughly 125 WR stars (WC+WN), consistent with the wide range of O7 V star equivalents (4; 106) within the central $1 - 2''$. A detailed discussion is given in Martin-Hernandez et al. (18). However, as the [OIV] emission is only observed outside the nucleus, it is not obvious that the [OIV] line is predominantly photo-excited by the central WR stars. Other excitation mechanisms, such as shocks, need to be considered.

2.3.6 Conclusions

We studied spatially resolved mid-infrared spectra of the dwarf galaxy NGC 5253, a galaxy with its infrared luminosity dominated by a single very young and massive stellar cluster near the center. The spectra were taken by the *Spitzer* Infrared Spectrograph in both the $5 - 38\mu$m low resolution ($R \sim 65 - 130$) and the $10 - 37\mu$m high-resolution $R \sim 600$ modules. To study the spatial variation of the radiation field and its effect on the PAH molecules, we have built spectral maps as well as full spectra from the cluster regions and from regions placed at different radial distances from the cluster.

The spectra show a smooth continuum with no significant absorption features, and turnover in the slope around 20μm. They are dominated by the strong forbidden emission lines and the signatures of polycyclic aromatic hydrocarbons (PAH) at 6.2μm, 7.7μm, 8.6μm, and 11.3μm were detected for the first time up to a distance of ~ 120 pc. We modelled the continuum with a single blackbody curve with a temperature of $T = 132 \pm 8$ K, indicating a single hot dust component.

There is a possible correlation of the $6.2/11.3\mu$m PAH ratio with the faint CO emission and the dust lane, but there is no other obvious correlation with the morphology of the galaxy in other wavelengths. The radiation field, as traced by the [SIV]/[NeII] ratio, is harder in the cluster region. The [NeIII]/[NeII] and [SIV]/[SIII] ratios decrease by a factor of four over 250 parsecs, which indicate a significant softening of the UV radiation field with distance from the central cluster.

There is a steady increase of the PAH equivalent width (EW) with distance, suggesting either the photo-destruction of PAHs or the absence of photo-dissociation regions (PDR) near the cluster center. The "strength" of the UV radiation field, defined as the product of the hardness and the intensity of the radiation field, stays almost constant out to a radial distance of 200 pc, meaning that the strength of the UV field and the strength of the PAH emission is strongly anti-correlated. The good anti-correlation over such a large distance (encompassing numerous H II regions) suggests that the photo-destruction of PAHs might be the dominant mechanism here.

We observe a faint [O IV] line at two slit positions outside the central cluster, with fluxes of about 0.42×10^{-20} W cm^{-2} at a S/N of 7.1, which is in agreement with previous studies. This flux can be produced by roughly 125 WR stars (WC+WN). However, as the [OIV] emission is only observed outside the nucleus, we cannot say that photo-excitation is the predominant mechanism for the excitation of this line.

Chapter 3

Spatially Resolved *Spitzer-IRS* Spectroscopy of the Central Region of M82

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We present high spatial resolution (~ 35 parsec) $5 - 38\mu$m spectra of the central region of M82, taken with the Spitzer Infrared Spectrograph. From these spectra we determined the fluxes and equivalent widths of key diagnostic features, such as the [NeII]12.8μm, [NeIII]15.5μm, and H_2 S(1)17.03μm lines, and the broad mid-IR polycyclic aromatic hydrocarbon (PAH) emission features in six representative regions and analysed the spatial distribution of these lines and their ratios across the central region. We find a good correlation of the dust extinction with the CO 1-0 emission. The PAH emission follows closely the ionization structure along the galactic disk. The observed variations of the diagnostic PAH ratios across M82 can be explained by extinction effects, within systematic uncertainties. The $16 - 18\mu$m PAH complex is very prominent, and its equivalent width is enhanced outwards from the galactic plane. We interpret this as a consequence of the variation of the UV radiation field. The EWs of the 11.3μm PAH feature and the H_2 S(1) line correlate closely, and we conclude that shocks in the outflow regions have no measurable influence on the H_2 emission. The [NeIII]/[NeII] ratio is on average low at $\sim$0.18, and shows little variations across the plane, indicating that the dominant stellar population is evolved (5 - 6 Myr) and well distributed. There is a slight increase of the ratio with distance from the galactic plane of M82 which we attribute to a decrease in gas density. Our observations indicate that the star formation rate has decreased significantly in the last 5 Myr. The quantities of dust and molecular gas in the central area of the galaxy argue against starvation and for negative feedback processes, observable through the strong extra-planar outflows.

3.1 Introduction

M82 (NGC 3034) is an irregular galaxy located at 3.3 Mpc (58) in the M81 group. It is the closest starburst galaxy, seen nearly edge-on, with an inclination angle of about 80. At infrared wavelengths it is the brightest galaxy on the sky, with a total infrared luminosity of $3.8 \times 10^{10} L_{\odot}$ (43). Most of its luminosity originates from the inner 500 pc hosting intense starburst activity presumably triggered by a tidal interaction with M81

At the distance of M82, $1''$ corresponds to 15 parsec, which allows spatially resolved studies of the starburst region. Evidence of a stellar bar ~ 1 kpc long is shown by near-infrared studies (104; 68,e.g.), mid-infrared [NeII]12.8μm and millimetric CO emission studies (72). According to Larkin et al. (68) and Achtermann & Lacy (34), there is a rotating ring of ionized gas at a radius of ~ 85 pc, and on the inner side of a ring of molecular gas at ~ 210 pc. Two possible spiral arms were also identified by Shen & Lo (92) and Mayya et al. (76), at radii of ~ 125 pc and ~ 400 pc. The starburst of M82 drives a bipolar mass outflow out to several kiloparsecs perpendicular to the plane of the galaxy, especially evident in X-ray and Hα (39; 93; 69; 41; 100). Dust has also been detected in the outflow region (35; 59; 62; 54). The star forming regions of M82 are predominantly clustered in the volume enclosed by the molecular gas ring, indicated by the HII region tracers, like the [NeII]12.8μm line and the mid- and far-infrared continuum emission (104; 111; 68; 34; 71). Near-infrared hydrogen recombination lines also arise in these regions, but they are a more ambiguous tracer of star formation, as they can also be excited by shocks, though these are unlikely to dominate.

Near-infrared integral field spectroscopy and ISO-SWS mid-infrared spectroscopy by Förster Schreiber et al. (57) allowed a detailed modelling of starburst activity in the central region (55). These models are consistent with the occurrence of starburst activity in two successive episodes, about 10 and 5 Myr ago, each lasting a few million years. However, the spatial studies by Förster Schreiber et al. (57) and others covered only near-infrared wavelengths. The large aperture of the ISO-SWS provided a continuous $2.4 - 45\mu$m spectrum but covered the whole central region of M82. ISOCAM-CVF data (56) provided better spatial resolution but the spectra only had a spectral resolution of $R \sim 40$ and were shortward of 15μm.

Engelbracht et al. (54) published Spitzer-IRS low-resolution spectra of a 1 arcmin wide strip along the minor axis of M82, intersecting the disk at the eastern side. The spectra, taken as part of the SINGS Legacy project, were combined with Spitzer 8 and 24 μm images, and show that the emission by polycyclic aromatic hydrocarbons (PAH) and H_2 molecules extends far out from the disk (to 6 kpc) in both directions. Engelbracht et al. (54) suggest that the filamentary aromatic-dominated emission represents dust either expelled from the galaxy as a result of a powerful nuclear superwind, or that dust is in the halo being lit up by the starburst, perhaps coexisting with the extensive warm H_2 molecules. They suggest that this halo dust is probably a leftover from the interaction with M81.

In this paper we present mid-IR spectral maps at unsurpassed sensitivity and spatial resolution of the central ~ 0.5 kpc^2 of M82, covering the main contributors to the bolometric luminosity of the galaxy. Our goal is to provide a spatial and spectrally detailed description of the physical conditions within the central ~ 500 pc of M82,

Figure 3.1 — Left: Overlay of SL (red) and SH (blue) coverages and selected low-res extraction regions on an IRAC 8μm image. Regions A and B, represented in yellow, are regions where LL (14 - 35 μm) spectra were extracted. Right: Zoom-in of the IRAC 8μm image with an overlay of the SH map area in blue and the selected regions (in green) from where the SH+SL spectra were extracted. The ISO-SWS aperture used in the $12 - 27\mu$m range by Förster Schreiber et al. (57) is also overlayed in yellow on the image. Both figures are in logarithmic scaling. See color supplement for a color version of this figure.

to help us to give an insight on the evolution of the starburst activity in this region. This involves the study of the distribution of the radiation field, gas density, and the physical properties of PAHs. Of particular interest are the spatial variations of the fine-structure lines, the excitation of the molecular hydrogen, and the distribution of the PAH molecules. In section 2 we describe the observations and data reduction, in section 3 we present the data, and in section 4 we discuss the scientific results, followed by our conclusions.

3.2 Observations and data reduction

The observations were made with the Infrared Spectrograph (IRS)[8] spectrometer (63) on board the *Spitzer Space Telescope*, under the IRS guaranteed time observing program. The data were taken on June 6th, 2005 using the IRS "mapping mode" in all four modules: Short-High (SH; $10 - 19\mu$m), Long-High (LH; $14 - 38\mu$m), provide $R \sim 600$, while Short-Low (SL; $5 - 14\mu$m) and Long-Low (LL; $14 - 38\mu$m) give $R \sim 60 - 130$. Each of the SL and LL modules are further divided into two subslits, which correspond to diffraction orders: SL1 ($7.5 - 14\mu$m), SL2 ($5 - 7.5\mu$m), LL1 ($20 - 38\mu$m), and LL2 ($14 - 20\mu$m). The SH map consists of 30 pointings with 4 cycles each, and each subsequent pointing is offset by half a slit width parallel to the slit and about one third of the slit length along the slit. The SH map covers an area of $28'' \times 23''$. The LH data consists of 12 pointings, with 5 cycles each, covering an area of $38'' \times 33''$. The offsets are equivalent to the SH map. The SL data consists of 120 pointings, with 2 cycles each, covering an area over the M82 central region of $55''.5 \times 57''$. The LL data consists of 22 pointings with 2 cycles each. Both SL and LL maps follow the same offseting scheme as SH. Because of the high brightness of M82 it was unavoidable that the LL1 data became saturated near the center of M82, but the LL2 data are still usable. Fig. 3.1 (left) shows the areas covered by the IRS SL, LH, and SH maps overlayed on the IRAC 8μm image from Engelbracht et al. (54). The total integration times range from 12 (for SL exposures) to 31 sec (for LH exposures). Due to issues concerning the extraction, the LH spectra were not used in this analysis. The boxes 'A' and 'B' are the regions where the complete low-res (SL+LL) spectra were extracted.

The data were processed with version 13.2 of the Spitzer reduction pipeline (version 14 for LL). Observations taken at each position were combined into spectral cubes using CUBISM (96), an IDL-based software package designed to combine spectral mapping datasets into 3D spectral cubes. Bad pixels in the basic calibrated data (BCD) spectra were manually flagged and then automatically discarded when rebuilding the

[8]The IRS was a collaborative venture between Cornell University and Ball Aerospace Corporation funded by NASA through the Jet Propulsion Laboratory and the Ames Research Center

Table 3.1 — Characteristics of the Selected Regions

	Region 1	Region 2	Region 3	Region 4	Center	Total	Region A	Region B
RA (J2000)	9:55:52.42	9:55:50.63	9:55:52.74	9:55:50.22	9:55:51.19	9:55:51.32	9:55:52.17	9:55:52.68
Dec (J2000)	+69:40:32.1	+69:40:45.6	+69:40:48.5	+69:40:58.60	+69:40:46.8	+69:40:45.30	+69:41:12.5	+69:40:22.2
Size	$6''.8 \times 6''.8$	$6''.8 \times 6''.8$	$6''.8 \times 6''.8$	$6''.8 \times 6''.8$	$11''.3 \times 11''.3$	$24''.9 \times 24''.9$	$14''.8 \times 20''.3$	$14''.8 \times 20''.3$

cube. Spectra from off-source positions 1 kpc to the NE of the nucleus were used to subtract the background from the low-resolution spectra. For the high-resolution spectra we did not subtract a background since there was no suitable "sky" spectrum available and the high source fluxes strongly dominate any background emission. The spectral analysis was done using SMART (60) and PAHFIT (96).

3.3 Analysis

On the basis of the SH spectral map coverage we defined six sub-regions for which we extracted the spectra from SL and SH with CUBISM. The location of these regions is shown in Fig. 3.1 (right) overlayed on the IRAC 8μm image from Engelbracht et al. (54). The ISO aperture is also shown to illustrate the increase in spatial resolution obtained with $Spitzer$-IRS. Regions 2 and 3 coincide with the peaks of the [NeII] emission, regions 1 and 4 are offset to both sides of the galactic disk, the slightly larger region C covers the nominal center of the galaxy, and the last region corresponds to the entire area mapped with the SH spectrograph. The exact coordinates and sizes are listed in Table 3.1.

Fig. 3.2 shows the SL ($5-14\mu$m), and SH ($10-19\mu$m) spectra extracted for these six regions. The noise is negligible and the spectra exhibit the classical features of starburst galaxies (40), such as strong emission features of the PAHs, fine-structure lines, and emission from molecular hydrogen, in addition to the broad silicate absorption features around 9.7μm and 18μm, with an underlying continuum of very small grain emission (VSGs). The 5-38 μm wavelength range contains many important diagnostic lines, such as [ArII]6.99μm, [ArIII]8.99μm, [SIV]10.51μm, [NeII]12.81μm, [NeIII]15.56μm, [SIII]18.71μm. All of the detected features are labelled in Fig. 3.2. The fluxes and ratios of the most relevant fine-structure and H_2 emission lines are listed in Table **??**. These lines were measured using Gaussian fits to the line and linear fits to the local continuum. The [NeII] line was measured after subtracting the 12.6μm PAH feature. [SIV] at 10.5μm is hard to detect on regions 1 and 4 due to low S/N ratio, and [ArIII], at 8.99μm is too close to the 8.6μm PAH feature to be detected in a low resolution spectrum. Due to saturation of the LL1 module and extraction issues of the LH spectra, we could not measure the [SIII] 33.6μm line.

Numerous PAH emission features are easily detectable in our spectra. The fluxes and equivalent widths (EWs) of the strongest features at 6.2μm, 7.7μm, 8.6μm, 11.3μm, 12.6μm, 14.2μm, and the $16-18\mu$m complex are listed in Table 3.3. Their values were derived using PAHFIT (96), an IDL tool that decomposes low-resolution spectra of PAH emission sources using a physically motivated model. This model includes starlight, thermal dust continuum, resolved dust features and feature blends, prominent emission lines, and dust extinction. In our case, we merged SL and SH spectra in order to have one spectrum for each region with the widest wavelength coverage possible. Weaker PAH features at 5.2 μm, 5.6 μm, 12.0 μm, and 13.55 μm are present in the spectra in Fig. 3.2, but are not further utilised in this paper. In Fig. 3.3 we present an example of a fit to a combined SL+SH spectrum of region 2. In the overall spectrum (green) we distinguish the continuum component (red), PAH component (blue), ionic lines (purple), and dust absorption (dashed line).

Figure 3.2 — SL (left) and SH (right) spectra of the six selected regions within the central starburst region of M82. The "Total" region corresponds to the total SH map in Fig. 3.1.

Figure 3.3 — Decomposition of SL+SH spectrum of Region 2. Red solid lines represent the thermal dust continuum components, the thick gray line the total continuum, blue lines are dust features, while the violet peaks are atomic and molecular spectral lines. The dotted black line indicates the fully mixed extinction which affects all components, with axis at right. The solid green line is the full fitted model, plotted on the observed flux intensities and uncertainties. See color supplement for a color version of this figure.

Silicate absorption affects mainly the wavelength interval from $7-12\mu$m. In PAH-FIT we have the option to include or exclude silicate absorption, and the difference between these two cases can be up to 50% in flux of the 11.3μm feature. In section 4.3 we discuss the methods to estimate the magnitude and distribution of extinction. Also there is a significant difference in the 11.3μm flux between the SH and SL spectra, which can also reach 50%. This difference can be attributed to a poor fit to the silicate absorption feature in SH, as this module only covers wavelengths $> 10\mu$m. In this paper we use the SH+SL measurements for this reason and to include the 17μm complex.

We also extracted combined SL+LL spectra ($5-38\mu$m) from two $15'' \times 20''$ regions, A and B (see Fig. 1 left), at a distance of 200 pc above and below the galactic plane of M82, where saturation did not compromise the LL measurements. Their positions are listed in Table 1. The spectra from regions A and B were virtually identical in shape, and an average of these spectra is shown in Fig. 3.4. The spectrum is clearly dominated by strong PAH emission features and a steeply rising continuum, characteristic of classical starburst galaxies (e.g. 40). The wiggles observed longwards 20μm are fringes that originate from interferences in the detector substrate material. At the low spatial resolution presented by the LL modules, we cannot see any unusual features in the SL+LL spectra of regions A and B. Also, as the LL1 slit is saturated at the central region of M82, we cannot extract any full low-res spectra of this region, connecting it to regions A and B. For these reasons, we will not make further analysis of LL1 module spectra in this paper.

3.4 Results and discussion

The main gain of our observations over previous work on the starburst in M82 is the availability of spatially resolved mid-IR spectroscopy of the central region. Despite their overall similarity the spectra show distinct variations in the relative strengths of the spectral features, in particular in the neon fine structure lines and PAH features. These variations and their physical causes will be described in the following sections.

3.4.1 The morphology of the starburst region

The discovery of a series of compact radio supernova remnants along the galactic plane of M82, extending over 600 pc (67; 78), is an indication of very recent and presumably ongoing star formation. The detection of the ionic high excitation lines [NeIII] and

Figure 3.4 — Average of the $5-38\mu$m low-resolution IRS spectra of the regions A and B, located approximately 200 pc above and below the galactic plane of M82.

[SIV] confirms the presence of very young massive stars in M82. Ratios using ionic lines of the same species and different ionization potentials such as [NeIII]/[NeII], [SIV]/[SIII], and [ArIII]/[ArII] are a useful measure of the hardness and intensity of the radiation field and radiation density, and are therefore sensitive to the presence of young massive stars.

Our measurements of the [NeIII]/[NeII] ratio are shown in Table **??**, for each of the six selected regions. We find $0.13 \leq$ [NeIII]/[NeII] ≤ 0.21, with a median of [NeIII]/[NeII] = 0.18, which is consistent with the spatially integrated ratio of [NeIII]/[NeII] = 0.16 ± 0.04 determined by Förster Schreiber et al. (57). These values are 30% lower than the average value of 0.26 for the ISO-SWS sample of starburst galaxies (105), and more than an order of magnitude below the value of 8.5 found in the center of NGC 5253 (see Chapter 2), a low metallicity starburst galaxy at about the same distance as M82.

Other ratios such as [SIV]/[SIII] and [ArIII]/[ArII] could be used to confirm the results on the [NeIII]/[NeII]. However, as mentioned in Chapter 3, our measurements of [SIV] in regions 1 and 4 have large errors from noise, and [ArIII], at 8.99μm is too close to the 8.6μm PAH feature to be measured accurately from the low resolution spectrum, precluding the use of these ratios.

The Spitzer/IRS spectral maps allow a study of the spatial variation of the radiation field, based on the [NeIII]/[NeII] ratio. Due to the presence of several luminous star clusters in the central region, one might expect strong variations of [NeIII]/[NeII] between regions. In Fig. 3.5 we present spectral maps of the two strongest neon emission lines, and a ratio map, overlayed by the 12μm continuum contours from Achtermann & Lacy (34). For both line maps, CUBISM was used to subtract a fitted continuum map from a total line+continuum map at the same wavelength on a pixel-by-pixel basis. The [Ne II] emission in the upper map shows two peaks to either side of the nucleus, a weaker and a stronger peak, which correspond to the E and W peaks in Achtermann & Lacy (34) respectively. After a close inspection, we identify the strong W peak in our maps with the two continuum emission peaks. The E and W [NeII] emission peaks are identified as a "ring" of ionized gas in Achtermann & Lacy (34). The morphology of the [NeII] emission follows the Brγ emission in Satyapal et al. (90) and Förster Schreiber et al. (57). The [NeIII] map also reveals two emission peaks at the same positions, but with the eastern peak brighter relative to the western peak.

The lower map in Fig. 3.5 presents the [NeIII]/[NeII] ratio. The ratio varies from $0.08 - 0.27$ throughout the map. The lower value corresponds to the location of the westernmost clusters and there is a significant increase in the ratio further out from the galactic plane of M82, from 0.15 to 0.27. Statistical 1σ errors are $\sim 15\%$ and arise mostly from baseline determination errors. The grey line represents the direction of the X-ray outflow observed in M82 (101; 100). It originates from the nucleus (marked with a plus sign) and is perpendicular to the plane of the galaxy. The peak of X-ray emission is offset from the outflow axis by 30 pc. Although the gradient in the [NeIII]/[NeII] ratio does follow the outflow axis, it appears offset by $5''$ to the east, and associated with the

Figure 3.5 — Spectral maps in the [NeII] (top), [NeIII] (center), and [NeIII]/[NeII] (bottom) lines from the IRS SH module, with contour overlays of the 12μm continuum emission from Achtermann & Lacy (34). The regions shown are $\sim 26'' \times 26''$. At the bottom map, the line is the direction of the of the X-ray outflow, which is perpendicular to the plane of the galaxy. The cross represents the nucleus.

eastern cluster.

The overall morphology of the ionizing radiation in the region as revealed by the spectral maps seems to be in agreement with ground observations of the continuum and [NeII] emission by Achtermann & Lacy (34). However, the [NeIII]/[NeII] ratio varies only by a factor of three throughout the region and these variations do not correspond to the position of the emission peaks. An increase of the [NeIII]/[NeII] ratio is observed further out of the galactic plane, but due to the limited spatial coverage of the map, we cannot determine if this increase is connected to the outflows. The origins of the observed emission morphology and the variation of the [NeIII]/[NeII] ratio are discussed in the following subsection.

3.4.2 Origins of the variation of the radiation field

The [NeIII]/[NeII] ratio measures the hardness of the radiation field, which is a function of stellar age and metallicity, and often parameterized by the effective temperature T_{eff}, and the radiation intensity as measured by the ionization parameter U[1]. Given the strength of the [NeII] and [NeIII] lines in M82, and their proximity in wavelength which minimises the effects of extinction, [NeIII]/[NeII] is the most reliable measure of the hardness of the radiation field. With the help of starburst models, it is possible to use the [NeIII]/[NeII] ratio to estimate the ages of the massive clusters in the region.

Observations with ISO/SWS have been used previously for this purpose. Förster Schreiber et al. (57) determined a spatially integrated ratio of [NeIII]/[NeII] = 0.16 for the inner 500 pc of M82. Using the photoionization code CLOUDY and solar metallicity stellar atmosphere models by Pauldrach et al. (81), Förster Schreiber et al. (57) modelled the variations of line ratios with T_{eff}. Adopting an electron density $n_e = 300$ cm^{-3} and an ionization parameter log$U = -2.3$, Förster Schreiber et al. (55) found for the ISO value for [NeIII]/[NeII] an effective temperature of 37400±400 K and a burst age of 4 -6 Myr. Other observed ratios were also modelled, such as [ArIII]/[ArII] and [SIV]/[SIII], giving similar T_{eff} (within uncertainties). Independent estimations of cluster ages were done at longer wavelengths. Colbert et al. (43) analysed far-infrared spectra from ISO/LWS and fitted line ratios to a combined HII region and PDR model. Their best fit model is an instantaneous starburst of 3 - 5 Myr old massive stars, in agreement with Förster Schreiber et al. (55).

If the infrared emission peaks correspond to massive clusters of stars, we can determine their ages from the measured [NeIII]/[NeII] ratio and compare them with the above results, using the photoionization models by Snijders et al. (98). As input, Snijders et al. (98) used massive cluster spectra modeled with Starburst99, assuming a

[1] U is defined as $U = \frac{Q}{4\pi R^2 n_H c}$, where Q is the production rate of ionizing photons from the stars, R is the distance between the ionizing cluster and the illuminated gas cloud, n_H is the hydrogen number density of the gas, and c is the speed of light.

Salpeter IMF, $M_{up} = 100M_{\odot}$, $M_{low} = 0.2M_{\odot}$, and a gas density of 100 cm^{-3}. This value of gas density is a factor of three lower than the Förster Schreiber et al. (57) value, but this has a small effect on the [NeIII]/[NeII] ratio. Fig. 3.6 show the results for a range of ionization parameters. The selected regions are represented by horizontal lines. The value of log$U = -2.3$ derived by Förster Schreiber et al. (57) corresponds to a ionization front speed of $q = 1.6 \times 10^8$cm s^{-1}. For a typical value of q, there are two possible solutions for the ages of the clusters in each region range: ~ 2.5 Myr, and $5 - 6$ Myr. Former studies based on bolometric and K-band luminosities (55) and CO equivalent widths (90) put a lower limit for the ages of the cluster at 3 Myr. Therefore, we conclude that the cluster ages range from $5 - 6$ Myr, in agreement with the previously determined burst ages. These clusters dominate the central region of M82 and may be similar to those observed further out in M82 in the optical, studied in detail by Smith et al. (97) using HST/ACS, which were found to have an average age of 6.4 ± 0.5 Myr.

As shown in Fig. 3.5, the [NeIII]/[NeII] ratio increases from 0.15 to 0.27 with increasing distance from the galactic plane of M82. This is counterintuitive, as one might expect a harder radiation field at the location of the most luminous regions along the plane. Away from the plane, a decrease of gas density, relative to the number of ionizing photons, leads to an increase of the ionization parameter, which then causes an increase of the [NeIII]/[NeII] ratio, as discussed in Thornley et al. (105). Indeed, Fig. 3.6 shows that the [NeIII]/[NeII] scales with the ionization parameter. The variation we observe in the [NeIII]/[NeII] ratio implies a variation of a factor of five in the ionization parameter. This is equivalent to saying that the gas density decreases five times faster than the radiation field which decreases as $\sim R^{-2}$ with R being the distance to the ionization source. Shocks could also contribute to the increase of the [NeIII]/[NeII] ratio in the outflow region, but in Section 4.5 we show that to be minimal. This hypothesis could be tested using the [SIII]18.6μm/[SIII]33.6μm. Unfortunately, due to the problems reported in Sec. 2, we could not derive an accurate flux for the [SIII]33.6μm line in both LL and LH spectra.

It is important to emphasize that, even at higher angular resolution, the [NeIII]/[NeII] ratio in M82 remains quite low for an active starburst. We would have expected a larger variation with higher ratios locally corresponding to younger clusters and lower elsewhere. A comparison with the ISO-SWS sample of starburst galaxies (Thornley et al. (105)) shows that it is actually lower than most starbursts, despite being closer and better resolved. The low [NeIII]/[NeII] ratio could be caused by an aged stellar population where the starburst activity ceased more than half a dozen Myrs ago - although this possibility seems unlikely given the large amounts of molecular gas still present at the center of M82. An edge-on view of the galaxy could also contribute to the low variation of [NeIII]/[NeII] ratio.

As a comparison, we examined the $4''.5 \times 4''.5$ area with the highest [NeIII] flux (Fig. 3.5), comparing the measured [NeII] and [NeIII] luminosities with the models to determine the enclosed stellar mass. A single super star cluster of 5 Myr would have a cluster mass of $10^6 M_{\odot}$ which is twice the mass of the super star cluster in NGC 5253 (107). A single cluster in a $4''.5 \times 4''.5$ area would correspond to a cluster number density of $\sim 200/$kpc^2, which is comparable to the cluster density found in the fossil starburst region of M82 by de Grijs et al. (45).

While the average age of the starburst population in M82 appears to be ∼5 Myr, ongoing star formation (≤1 Myr) could possibly be obscured by recent contributions of older stellar populations (> 5 Myr) to the neon ratio. Considering this possibility, we explore the region with the highest [NeIII] flux, a strong indicator of the presence of O stars, as an illustrative case to set an upper limit on the ongoing star formation in M82. This region has a [NeIII]/[NeII] of ~ 0.10, with a total [NeIII] luminosity of $1.41 \times 10^6 L_\odot$. Assuming $q \sim 1.6 \times 10^8$cm s^{-1}, a typical young cluster of 1 Myr has [NeIII]/[NeII]~ 5 and can contribute ∼50% to the total [NeIII] luminosity or ∼2.5% per mass relative to the older 5−6 Myr old population. This means that the 1 Myr old population only emits ∼5% of the total [NeII]+[NeIII] luminosity of the older 5−6 Myr old population. Even as an upper limit, this value indicates that the activity of the starburst has substantially declined relative to the high star formation rate that existed 5 Myr ago.

Despite the reduced starburst activity, the presence of CO emission all over the central region (Fig. 3.7) shows that the starburst in M82 still has a large gas reservoir, as pointed out by Thornley et al. (105) and Förster Schreiber et al. (55). It appears therefore unlikely that the starburst activity ceased because of lack of fuel. On the other hand, negative feedback mainly through strong stellar winds and supernovae explosions can play an important role in determining the star formation rate in starbursts. Förster Schreiber et al. (55) calculated a feedback timescale of $1 - 10$ Myr, which is in good agreement with the age of the older super star clusters in the central region of M82.

In summary we find that [NeIII]/[NeII] ratio is low on average, and increases with distance from the galactic plane of M82. The increase can be explained by an increase of the ionization parameter through a drop in gas density. The low [NeIII]/[NeII] ratio indicates that the dominant population consists of older clusters (> 5 Myrs). We cannot rule out the presence of younger clusters in the central region, but at a much reduced rate ($< 5\%$) of star formation compared to previous epochs. The large amount of molecular gas still present in the central region argues against a starvation of starburst activity, due to lack of gas. Instead, we believe that negative feedback processes are responsible for the observed decline in the star formation rate.

Figure 3.6 — Effect of the cluster age on the [NeIII]/[NeII] ratio. The data for our selected regions in M82 is shown by the horizontal lines. The model curves are computed for a cluster of $10^6 M_\odot$, assuming Salpeter IMF, $M_{up} = 100 M_\odot$, and $M_{low} = 0.2 M_\odot$. Each curve represents a different ionization parameter, and the solid curve is the one that approaches the value found by Förster Schreiber et al. (57), log$U = -2.3$. The horizontal lines indicate the [NeIII]/[NeII] for each selected region, from region 1 to region 4. The first dip in [NeIII]/[NeII] represents the ageing of the stellar population, after which WR stars are produced, increasing the [NeIII]/[NeII] ratio. The dip at 6 Myr occurs as most massive stars die through supernova explosions.

3.4.3 Extinction

One of the most noticeable features in the spectra in Fig. 3.2 is the absorption feature at $9 - 11 \mu$m, caused by silicate grains. This feature can be extremely deep especially in ULIRGS (e.g 99), and affects the observed fluxes of spectral lines and features in this region. The strength of this feature is characterized by the optical depth at 9.8μm ($\tau_{9.8}$)

assuming a simple geometrical dust distribution. For our analysis it is important to estimate the intensity of this feature and its spatial variation in order to investigate its influence on the PAH strengths, which we discuss in the following subsections.

To study the distribution of $\tau_{9.8}$ in the SL region, we selected an area of 20×12 pixel in the center of the SL1 map. Within that area we extracted spectra from 60 spatial resolution elements (2×2 pixel each).

The apparent optical depth $\tau_{9.8}$ is then estimated from the ratio of the interpolated continuum to the observed flux at 9.8μm. For the central region of M82, $\tau_{9.8}$ ranges from 0.3 - 3.1, assuming a foreground screen attenuation. We built an extinction map of 10×6 resolution elements from the simple fit method, which is shown in Fig. 3.7. The qualitative distribution of $\tau_{9.8}$ observed in this figure is very similar to the qualitative results from the PAHFIT fitting method. There is a good correlation between the $\tau_{9.8}$ distribution and the CO 1-0 emission, indicating that dust and molecular gas coincide in this region. The enhanced $\tau_{9.8}$ in the northwest region of the map indicates an increase of silicate dust above the galactic plane.

For an independent, and possibly more accurate, estimate of $\tau_{9.8}$, we used PAHFIT on 15 SL+LL1 spectra ($5 - 20\mu$m), each corresponding to 4 resolution elements fitted only with SL. With the PAHFIT method, $\tau_{9.8}$ ranges from 0 - 2.52, with a median is 1.34.

The combined SL+LL spectrum is necessary to better constrain the parameters in PAHFIT. Fitting only SL spectra with PAHFIT can result in large errors in the calculation of $\tau_{9.8}$. Unfortunately, due to saturation at wavelengths longward of 20μm, we have an insufficient spatial coverage of LL data in the central region. In addition, the LL slits are $\sim 10\,\mathrm{sec}.$ wide, providing low spatial resolution.

For the higher spatial resolution, we used the simple method described by Spoon et al. (99) to estimate $\tau_{9.8}$. In this method we approximate the mid-IR continuum at 9.8μm by a power law fit to the flux pivots at 5.5μm and 14.5μm, avoiding the PAH emission features.

The values derived from both SL+LL and simple fit methods agree qualitatively well, but in regions where $\tau_{9.8} < 1$, the difference between the two methods is greater than a factor of two. Using a mixed attenuation law with $A_v/\tau_{9.8} = 16.6$ (86), the range of $\tau_{9.8}$ corresponds to $0 < A_v < 41.8$ for the SL+LL method. The values of $\tau_{9.8}$ from the power-law interpolation method give $5.0 < A_v < 51.5$. These values are in agreement with Förster Schreiber et al. (57), which derive $23 < A_v < 45$ for their selected regions in M82, which cover an area closer to the infrared peaks.

Figure 3.7 — Map of $\tau_{9.8}$, determined from a simple continuum fit to the SL spectra, with overlay of CO 1-0 emission contours from Shen & Lo (92). The crosses indicate the [NeII] emission peaks. The image was rotated by 55 degrees and interpolated.

We conclude that both methods, besides their significant uncertainties in the magnitude of $\tau_{9.8}$, have consistently revealed significant variations in the amount of dust extinction across the central region. These variations are strong enough to affect the following interpretation of PAH features.

3.4.4 Variations of PAH emission features

Polycyclic Aromatic Hydrocarbons (PAHs) are thought to be responsible for a series of broad emission features that dominate the mid-infrared spectra of starbursts (e.g. 83). They are observed in a diverse range of sources with their strongest emission originating in photodissociation regions (PDRs), the interfaces between HII regions and molecular clouds.

The relative strength of the different PAH bands is expected to vary with the size and the ionization state of the PAH molecule (52; 51). Observations of Galactic sources (e.g. 110; 65; 109) have shown that the relative strengths of individual PAH features depend upon the degree of ionization: C-C stretching modes at 6.2μm and 7.7μm are predominantly emitted by PAH cations, while the C-H out-of-plane bending mode at 11.3μm arises mainly from neutral PAHs (52). Thus the ratios $6.2/11.3\mu$m and $7.7/11.3\mu$m may be used as indicators of PAH ionization state. Joblin et al. (65) have found that the 8.6/11.3 μm ratio can also be linked to variations in the charge state of the emitting PAHs, which is supported by laboratory experiments (64). Smith et al. (96) found band strength variations of factors of 2–5 among normal galaxies.

Figure 3.8 — IRS spectral map of the PAH ratio $6.2/11.3\mu$m, with overlay of CO 1-0 emission contours from Shen & Lo (92). The map is in logarithmic scaling. This map was done using CUBISM maps of baseline-subtracted flux at $6.0 - 6.5\mu$m and $11 - 11.7\mu$m.

Studies of PAHs in M82 have been done previously using ISO. Observations with ISOCAM (56) revealed a decrease in the $6.2/7.7\mu$m ratio and an increase in the $8.6/11.3\mu$m PAH ratio from the nucleus outwards along the galactic plane. The observations also showed a good spatial correlation of the $8.6/11.3\mu$m ratio with the CO (1-0) emission. These ratio variations are attributed to real differences in the variation of physical characteristics of PAHs across M82, specifically a higher degree of PAH ionization within the most intense starburst sites.

We use CUBISM to build maps of ratios of PAH features that exist in the 6 - 14 μm SL spectra. The 7.7μm feature is split between the two SL orders, and the 8.6μm feature is largely influenced by the 7.7μm feature, making the local continuum determination difficult. For these reasons the 6.2μm feature map was chosen to be compared to the 11.3μm feature map. In Fig. 3.8 we present the $6.2/11.3\mu$m PAH ratio map, overlayed with the CO (1-0) contours from Shen & Lo (92).

Obviously, the distribution of the $6.2/11.3\mu$m PAH ratio correlates well with the molecular ring defined by the CO (1-0) map. The molecular emission forms two lobes ~ 200 pc from the nucleus whereas the ionized emission is concentrated around the nucleus, in the regions where the [NeII] and [NeIII] emissions peak.

However, the $6.2/11.3\mu$m PAH ratio may be affected by extinction. Comparing the CO emission with the extinction map in Fig. 3.7 and with the PAH ratio map we see that they correlate well. Hence, we investigate the effects of extinction on the observed PAH ratios in the next subsection.

Figure 3.9 — Baseline subtracted IRS spectra of the selected regions from Fig. 1. The gray line is the Chiar & Tielens (42) extinction law, applied to a normalized flux of 1.75, and assuming $\tau_{9.8} = 2$.

3.4.4.1 Influence of silicate absorption on PAH ratios

The fluxes of the PAH bands at 6.2μm, 7.7μm, 8.6μm, and 11.3μm are all affected by dust absorption. However, as the 11.3μm is significantly more affected by the 9.8μm silicate feature than the 6.2μm feature, this will affect the measured PAH ratio in Fig. 3.8. To illustrate this influence, we show in Fig. 3.9 the baseline subtracted spectra of the selected regions around the nucleus in M82, normalized to the flux at 7.7μm to emphasize the relative flux variations of the 11.3μm PAH feature. The gray line is the Chiar & Tielens (42) extinction law, applied to a normalized flux of 1.75, and assuming $\tau_{9.8} = 2$. For this figure, the baseline was removed by subtracting a second order polynomial fitted to the following wavelengths: 5.5μm, 6.8μm, 8.0μm, 13.2μm, and 14.5μm. These wavelengths were chosen to avoid the silicate feature at 10μm and the PAH features. The effect of extinction on the 8.6μm and 11.3μm PAH features is similar, meaning that the $8.6/11.3\mu$m ratio could possibly be used to study PAH ionization with minimal concern for extinction, as the difference in flux correction between 8.6μm and 11.3μm is $\sim 15\%$. However, the 8.6μm feature is influenced by the broad PAH feature at 7.7μm, which makes the local continuum fitting more difficult compared to the 6.2μm feature.

Fig. 3.9 suggests that the variations of PAH feature ratios involving the 11.3μm feature will be heavily affected by extinction and contributing to the distribution of the $6.2/11.3\mu$m PAH ratio in Fig. 3.8. The 7.7μm PAH feature is affected by extinction to a similar level as the 6.2μm feature, as shown in the Fig. 3.9. Draine & Li (52) use the $6.2/7.7\mu$m ratio for PAH size diagnostic and $11.3/7.7\mu$m for a PAH ionization state diagnostic. Variations of these ratios reflect real variations of the physical properties of PAHs in M82 only if their variations are not due to extinction effects. Fig. 3.10 presents the $6.2/7.7\mu$m and $11.3/7.7\mu$m PAH ratios calculated from PAHFIT measurements of the same sub-regions as in the extinction map. The data in Fig. 3.10 is corrected for extinction. We took the average of the extinction methods (continuum fit method and the PAHFIT fit on SL+LL1 spectra (see 4.3)) for correction. The points are dispersed between the tracks representing totally ionized and neutral PAH populations, and the error bars show the average of the difference between the extinctions derived by the two methods. The triangles are points from the areas where [NeIII]/[NeII]> 0.24 in the [NeIII]/[NeII] map from Fig. 3.5. These are regions with harder radiation field, where a greater number of ionized PAH are expected to be observed. The squares are points from areas in the map where [NeIII]/[NeII]< 0.13. To preserve the clarity of the plot, only the error bars at these points are represented, as they are typical for all the points. The arrow represents the effect on the ratios of a silicate absorption feature with $\tau_{9.8} = 1.34$, which is the median optical depth for the region as explained in section 4.3.

The $11.3/7.7\mu$m PAH ratios are dispersed between 0.2 and 0.5. However, the error bar can account for this dispersion, demonstrating how silicate absorption can affect the diagnostic of PAH ionization state based on this ratio, on scales of the size of the IRS resolution elements, ~ 35 pc. This implies that the average variations in the ionization state of the grains are relatively small on scales of 35 pc. These results are to

Figure 3.10 — The $6.2/7.7\mu$m PAH ratio vs. $11.3/7.7$ PAH ratio, for the same sub-regions as in the absorption map in Fig. 3.7. The triangles are points from the areas where [NeIII]/[NeII]> 0.22 and the squares are points from the areas where [NeIII]/[NeII]< 0.13. Error bars represent average uncertainties, related to extinction correction and fitting uncertainties. The arrow represents the effect of a silicate absorption feature with $\tau_{9.8} = 1.34$. The tracks represent the ratios of a population of neutral and ionized PAHs.

be compared to SINGS results, in which the $11.3/7.7\mu$m PAH ratio is found within the same range as in the central region of M82 for galaxies dominated by HII regions (96).

The $6.2/7.7\mu$m ratio varies between ~0.2 and ~0.3. This is well in the range of $0.2 - 0.4$ reported by Smith et al. (96) for SINGS galaxies dominated by HII regions. We observe no significant difference in the $6.2/7.7\mu$m ratio between regions with high [NeIII]/[NeII] ratio and regions with less [NeIII]/[NeII] ratio. Extinction and fitting errors affect the $6.2/7.7\mu$m ratio only by $\sim 1\%$, and errors from fitting residuals from PAHFIT amount to less than 2%. However, there are significant uncertainties arising from the continuum fitting by blackbody curves with effective temperatures between $35 - 300$K. Modifying the number of blackbody components and their temperatures results in changes of the PAH ratios in excess of $8 - 12\%$. The horizontal error bar represents the average uncertainty of 10%.

The range of $6.2/7.7\mu$m ratios implies an environment composed by a warm ionized medium and photodissociation regions (PDRs) (52). The dispersion in the data could reflect a real variation of this ratio. The general significance of the variation of the $6.2/7.7\mu$m is discussed on Draine & Li (52). Assumptions about the stellar radiation intensity, which affect the $11.3/7.7\mu$m ratio as well, account for these variations in the number of C atoms, Following (52), our observed ratios correspond to a number of carbon atoms in a PAH grain between 100-140 ($6.2/7.7\mu$m~ 0.3) and 240-320 ($6.2/7.7\mu$m~ 0.2).

However, there is no correlation between the $6.2/7.7\mu$m ratio with radiation hardness (symbols in Fig. 3.10) or with any other resolved spatial structure in the central region. Since the variations are comparable to the uncertainties in the measurement the results are not (yet) significant enough to support PAH size variations at parsec scales. Similarly, the variations of the $11.3/7.7\mu$m ratio are mostly due to extinction and show little support for variations in PAH ionization throughout the region. However, if PAH sizes would vary on parsec scales one would expect a strong emission from the larger grains which radiate predominantly at larger wavelengths, such as the $17/mu$m complex.

3.4.4.2 The 17μm PAH complex

The $16 - 18\mu$m wavelength range contains the H_2 S(1)17.03 μm line and the 17μm PAH complex. This complex is attributed to a blend of emission features (16.45μm, 17.03μm, and 17.37μm) which are possibly due to PAH C–C–C bending modes (e.g. 108), and also emission from PAH clusters, amorphous carbon particles, and other PAH-related species (82). Following the Draine & Li (51) models, the 17μm complex is mostly emitted by large PAH molecules with 1000 - 2000 carbon atoms, while the 6.2μm feature is emitted mostly by smaller PAH molecules with only 200 - 300 carbon atoms. The rela-

Figure 3.11 — Zoom-in on the PAH dominated emission features in the $16-18\mu$m spectral range of the SH spectra. The spectra were normalized to the average flux between 16.2μm and 17.6μm and rebinned to a resolution $R = 300$, to diminish the noise. The error bars indicate noise at three wavelengths.

tively narrow features at 16.45μm and 17.37μm have been detected by ISO in Galactic (77) and extragalactic sources (102). Only with Spitzer-IRS has the whole 17μm PAH complex been identified and routinely detected in both normal and starburst galaxies (e.g. 95; 44; 40), including the outer regions of M82 (54). However, the spatial variation within galaxies other than the Milky Way has not yet been studied. Engelbracht et al. (54) detected this complex in the disk and in the halo of M82, but their spectral coverage did not include the central regions. Here we report the characteristics of this complex in the central kpc of M82.

As seen in Table 3.3 the ratios between the 17μm complex and the 11.3μm PAH feature, as measured with PAHFIT, range from 0.39 in regions 1 and 3 to 0.49 in the center region, and do not show clear spatial correlations. However, the $17/6.2\mu$m varies from 0.21 in region 3 to 0.57 in region 4. The ratios between the regions in the plane and the outward regions vary by a factor of 2. The latter numbers suggest a significant variation possibly due to different PAH sizes. However, correcting for an optical depth of $\tau_{9.8} = 2$ for the regions around the [NeII] peaks (Fig. 3.7), the ratio increases by $\sim 67\%$, yielding values of 0.37 for region 2 and 0.35 for region 3. While substantially increased, the values are still more than 20% below the values for region 1 and 4. However, due to uncertainties on the determination of $\tau_{9.8}$ we cannot diagnose any variation of PAH sizes based on this difference.

Fig. 3.11 shows a baseline-subtracted spectrum of the 17μm PAH complex normalized to the average flux between 16.2μm and 17.6μm and rebinned to $R = 300$, to enhance the broad components. In this figure we can see the flux variation in these three main PAH features between the regions. The differences in the strength of these features are consistent within the uncertainties, with exceptions being region 4 at 16.45μm and regions 2 and 3 at 17.37μm. Moreover, these discrepancies could be explained by errors in baseline subtraction, which are in the order of 10%. The 17μm PAH complex is also seen in the LL spectra as far as 2 kpc from the galactic plane. The model of Draine & Li (51) predicts that the relative strength of the individual components is not sensitive to ionization state or grain size. Our observations are in good agreement with an invariant shape of this PAH complex.

3.4.4.3 The difference between PAH emission and VSG emission

Very small grains (VSGs) are dust particles larger on average than PAHs, with typical sizes in the range of 1 - 150 nm (46). They are excited by stochastic heating and are thought to be responsible for most of the mid-infrared continuum emission. The properties of these grains with relation to PAHs have been studied previously in galactic sources (110; 70) and in dwarf galaxies (75; 112). These studies focus on the behavior of VSGs in conditions where PAHs are destroyed, mainly by intense stellar radiation in HII regions or a low metallicity environment. Flux differences between VSGs and PAHs are reported in Galactic HII regions by (e.g. 70), where the PAH/VSG emission ratio increases with the distance from the cluster.

As shown in Table 3, there are significant differences in EWs of the PAH features between the regions in the galactic plane and the regions outside the galactic plane. However, the EW shortwards of 10μm behaves differently from the EW longward of 10μm. Longwards of 10μm, we observe that the EWs of the PAH features increase outwards the galactic plane. The 11.3μm EW, for example, increases from 0.660μm in region 2 to 2.27μm in region 1. The EWs of the 6.2μm and 7.7μm decrease outwards the galactic plane. For example, the 6.2μm EW decreases from 1.10μm in region 2 to 0.308μm in region 1. The EW of the 8.6μm feature decreases up to a factor of two, from 0.865μm in region 3 to 0.437μm in region 2. This could be due to the contribution of the stellar continuum to the local continuum shortwards of 10μm. The stellar continuum contribution decreases with wavelength and with the distance from the galactic plane.

The continuum longwards of 10μm is composed by thermal emission from VSGs. As the PAH flux does not increase outwards from the galactic plane, this can only be due to a decrease of the local continuum emission relative to the PAH strength. This decrease can be explained by several different factors: photo-destruction, abundance differences between VSGs and PAHs, and different heating opacities between VSGs and PAHs with a varying radiation field.

Decreasing PAH flux with the hardening of the radiation has been observed in galactic star forming regions (110; 70), on small spatial scales near the luminous clusters ($\sim$2 pc), where the PAH destruction largely surpasses PAH excitation. Wether the conditions that lead to PAH destruction on 2 pc scales can be maintained over much larger scales, corresponding to the resolution of our maps ($\sim$35 pc), cannot be derived from our data, but has been observed in NGC 5253 (see Chapter 2). Using the SINGS sample of galaxies, Draine et al. (50) have shown that the fraction of PAH abundance over the total dust abundance decreases with metallicity. Hence, abundance differences between PAHs and VSGs could be observed in cases of a strong metallicity gradient. M82 has a metallicity gradient, but it becomes noticeable only at distances larger than 1 kpc from the center (84), which is greater than the distance from our regions 1 and 4 to the galactic plane (400 pc).

Our favored explanation is the difference in excitation between PAHs and VSGs, enhanced by variations of the radiation field. The mid-infrared PAH features are produced by vibrational-rotational modes of the PAH molecules, while the VSG continuum emission is mainly produced by thermal radiation. VSGs are bigger than PAHs, so thermal radiation becomes dominant over vibrational-rotational transitions. Following Draine & Li (52) models, the opacity of the cross-section peaks at FUV wavelengths, where hot dust is needed to emit at $10-20\mu$m. However, at the distance from the galactic plane of regions 1 and 4, the radiation field is still intense enough to excite PAHs, but no longer of a high enough intensity to excite the dust to the same temperatures as in the plane of the galaxy. This provokes the PAH EW enhancement observed in these regions.

3.4.5 Excitation of the warm H_2

Molecular hydrogen is the most abundant molecule in the Universe and can be used to probe the properties of the warm molecular gas in M82. It can be traced in the mid-infrared through rotational emission lines, which may arise through three different mechanisms: UV excitation in PDRs surrounding or adjacent to the HII regions; shocks that accelerate and modify the gas in a cloud, collisionally exciting the H_2 molecules; hard X-ray photons capable of penetrating the molecular clouds and heating large ionizing columns of gas.

Vibrational-rotational H_2 line emission in M82 was studied in the near-infrared by Pak et al. (80). By correlating the emission flux from these lines with [CII] 157μm and far-infrared luminosity, they showed that the H_2 emission comes mainly from the PDRs. ISO observations of M82 detected S(0), S(1), S(2), S(6), and S(7) rotational lines (88), excited by UV radiation from massive stars.

The S(1) and S(2) rotational transition lines of H_2 are clearly detected in our SH spectra. The fluxes and temperatures of these lines are listed in Table **??**, as well as the S(1)/S(2) ratios. The temperatures were calculated from the S(1)/S(2) ratios using the method described by Roussel et al. (89), assuming an ortho- to para- ratio of three. Our derived temperatures are in agreement with the average temperature value of 450 K, derived with ISO (88). The H_2 S(0) line could not be detected in any of the LH spectra, as its equivalent width is very low, supporting our finding that the H_2 temperature is indeed relatively high.

If H_2 emission is excited mainly by UV radiation in PDRs, the fluxes of H_2 lines and PAH lines should correlate closely, since PAH emission features arises from the same mechanism in PDRs. To look for secondary effects, like shocks, we plot in Fig. 3.12 the PAH 11.3μm vs. H_2 S(1)17.03μm fluxes, both divided by the continuum flux at $14.8 - 15.2\mu$m to reduce the range covered by the figure. Each data point corresponds to a resolution element of the CUBISM flux maps taken from SH spectra. The stars correspond to region 1, squares to region 2, diamonds to region 3, and triangles to region 4. The error bars represent the line uncertainties from the measurement. The correlation in Fig. 3.12 shows that the excitation mechanisms for both species coincide at least on spatial scales of the resolution of the map, which is 35 pc. While there is wider dispersion of data points corresponding to regions 1 and 4 (the regions associated with outflows) the systematic measurement errors account largely for this dispersion. We conclude that shocks in the outflow regions have no measurable influence on the H_2 emission. However, we cannot distinguish between UV- and local shock excitation as produced by supernovae or energetic outflows, on scales smaller than the resolution of our pixels (35 pc).

Figure 3.12 — The PAH 11.3μm feature over the 15μm continuum versus H_2S(1) over the 15μm continuum, based on a pixel-by-pixel correlation between SH maps. The values corresponding to each of the selected regions are represented by different symbols. The error bars represent line flux measurement errors.

3.5 Conclusion

We presented spatially resolved mid-infrared spectra of the central region of M82. The spectra were taken with the Spitzer Infrared Spectrograph in both the $5 - 38\mu$m low-resolution ($R \sim 65 - 130$) and the $10 - 37\mu$m high-resolution $R \sim 600$ module. The high signal-to-noise and the continuous spatial and spectral coverage allowed us to study the nucleus of a starburst galaxy in unsurpassed detail. Our goal was to study the physical conditions of the interstellar medium and their spatial variations within the central kpc of M82.

Overall, the spectra show the typical features of a starburst: prominent PAH features, silicate absorption, fine-structure lines, and a steeply rising continuum. We built a spectral map with high-resolution spectra, selected six representative regions for spectral extraction, and studied the variations of the neon ionic lines and PAH feature emission among the regions.

We attempted to trace the structure of the ionizing radiation, and therefore the young stellar population of M82 through the diagnostic emission lines, [NeII]12.8μm, and [NeIII]15.5μm. The overall morphology of the ionizing radiation in the region as revealed by the spectral maps appears to be in agreement with previous ground-based observations (34). There is surprisingly little spatial variation of the [NeIII]/[NeII] ratio across the disk, and it varies only by a factor of three throughout the central region, with these variations not corresponding to the position of the emission peaks. We observed an increase of the [NeIII]/[NeII] ratio by a factor of 2 outwards the galactic plane, which may be associated with the outflows. We suggest that the increase of the [NeIII]/[NeII] ratio with distance to the galactic plane is due to a decrease in gas density rather than a hardening of the field.

The [NeIII]/[NeII] ratio is low on average, which indicates that the dominant population consists of already evolved clusters (> 5 Myrs). We cannot rule out the presence of ongoing star formation in the central region, but it must occur at a much reduced rate ($< 5\%$) compared to previous epochs. This drop is unlikely to be caused by starvation, as there is still a large amount of molecular gas present in the central region. It is more likely due to negative feedback processes causing a decrease in the star formation rate.

There are significant variations in the amount of dust extinction, which strongly correlate with the CO 1-0 emission across the central region. These variations are strong enough to affect the interpretation of PAH features, but due to limited spectral coverage the extinction estimates are uncertain.

The flux of the main PAH features correlates spatially with the flux of the neon ionic lines, and with previous IRAC observations. Variations in the PAH ratios such as $6.2/11.3\mu$m were observed across the disk. However, they are strongly affected by the silicate feature at 10μm. We studied the variations the $6.2/7.7\mu$m and $11.3/7.7\mu$m PAH ratios, which are diagnostics for the size and the degree of ionization of PAHs. We found no correlation between the $6.2/7.7\mu$m ratio with radiation hardness or with any other resolved spatial structure in the central region. Since the variations are comparable to the uncertainties in the measurement the results are not (yet) significant enough to support PAH size variations at parsec scales. Similarly, the variations of the $11.3/7.7\mu$m ratio are mostly due to extinction and show little support for variations in PAH ionization throughout the region.

The 17μm PAH complex is very prominent in the center of M82. We did not find any relative variations within the complex, which is in agreement with predictions. The variations of the $17/6.2\mu$m ratio are most likely due to extinction effects. Due to the uncertainties on the determination of extinction, we did not consider the remaining variations as a clear indicator of PAH size variation.

We observed an enhancement of the EWs of the 11.3μm and the other PAH features longwards of 10μm outwards from the galactic plane. Several explanations exist for this, but we favor the variation of the UV radiation field, which excites differently PAHs and VSGs, given their different sizes.

The S(1) and S(2) rotational transition lines of H_2 have been detected in our spectra throughout the central region. H_2 and PAHs coincide at least on spatial scales of the resolution of the map, which is 35 pc. We conclude that large scale shocks in the outflow regions have no measurable influence on the H_2 emission. However, we cannot distinguish between UV- and local shock excitation as produced by supernovae or energetic outflows, on scales smaller than the resolution of our pixels (35 pc).

The Spitzer-IRS observations of the central region of M82 complements previous studies, not only in mid-infrared, but also in other wavelengths. Our results demonstrate the importance of spatially resolved spectroscopy in starburst studies. They helped to constrain the age of the starburst and confirm results from other studies and also stressed the importance of a thorough study of extinction to investigate possible variations of PAH properties. Further research of the starburst feedback and quenching processes will elucidate the sharp decrease in star formation in the last 5 Myr. It would be interesting to see if higher spatial resolution, as expected from the MIRI on board of JWST will discover a wider variation of the radiation field or signs of variation of PAH sizes an/or ionization. In addition, spatially more extended spectral studies of M82 are necessary to study the connection of the ionic line ratios with the outflows.

Table 3.2 — Main Emission Line Strengths in units of 10^{-19}W cm^{-2}

Region	[ArII] 6.99μm	[SIV] 10.5μm	[NeII] 12.8μm	[NeIII] 15.6μm	[SIII] 18.7μm	H_2 S(1) 17.0μm	H_2 S(2) 12.3μm	S(1)/S(2)	T (S(1)-S(2)) (K)	[NeIII]/[NeII]
1	0.30±0.03	0.04±0.01	1.04±0.03	0.22±0.01	0.38±0.01	0.12±0.01	0.07±0.01	1.71±0.46	381±44	0.21±0.02
2	7.82±0.23	0.31±0.01	25.3±0.9	3.42±0.09	8.5±0.19	0.23±0.04	0.25±0.03	0.92±0.30	586±117	0.13±0.01
3	5.77±0.10	0.33±0.01	18.4±0.4	3.58±0.06	5.92±0.18	0.25±0.04	0.27±0.03	0.93±0.28	583±109	0.19±0.02
4	0.44±0.02	0.03±0.01	1.73±0.04	0.36±0.01	0.66±0.02	0.08±0.003	0.06±0.003	1.33±0.13	439±31	0.21±0.02
Center	17.1±0.47	0.72±0.08	55.4±0.97	8.53±0.15	18.6±0.37	0.51±0.07	0.67±0.07	0.76±0.21	700±129	0.15±0.01
Total	44.8±1.49	2.16±0.13	141.2±3.10	23.6±0.38	49.0±0.83	2.53±0.09	2.47±0.11	1.02±0.09	536±32	0.17±0.02

Table 3.3 — Main PAH Feature Strengths as Measured with PAHFIT

Region	6.2μm Flux[1] EW[2]	7.7μm Flux[1] EW[2]	8.6μm Flux[1] EW[2]	11.3μm Flux[1] EW[2]	12.6μm Flux[1] EW[2]	14.2μm Flux[1] EW[2]	17μm complex Flux[1] EW[2]	F(17μm complex)/ F(6.2μm)	F(17μm complex)/ F(11.3μm)
1	8.9±0.1	29.9±0.1	6.2±0.1	10.9±0.1	6.0±0.1	0.62±0.01	4.2±0.03	0.47	0.39
	0.308	0.254	0.437	2.27	2.06	2.13	1.97		
2	154.7±0.1	528.0±0.2	99.3±0.1	77.9±0.1	64.5±0.1	6.1±0.1	34.6±0.1	0.22	0.44
	1.10	0.866	0.848	0.660	0.734	0.717	0.753		
3	136.3±0.1	478.2±0.2	83.6±0.1	73.7±0.1	57.2±0.1	5.5±0.1	29.1±0.1	0.21	0.39
	0.827	0.884	0.865	0.784	0.877	0.850	0.720		
4	13.3±0.1	49.6±0.1	11.3±0.1	15.7±0.1	7.7±0.1	0.67±0.10	7.6±0.1	0.57	0.48
	0.390	0.320	0.575	1.86	1.52	1.30	2.16		
Center	375.0±0.2	1320.0±0.5	242.4.0±0.5	202.5±0.6	156.3±0.3	14.3±0.1	99.0±0.2	0.26	0.49
	1.22	0.991	0.937	0.758	0.791	0.750	0.907		
Total	1158.0±1.0	4121.7±3.4	743.9±1.5	736.0±1.7	535.8±0.7	52.2±0.2	327.8±0.5	0.28	0.45
	1.00	1.00	1.00	1.00	1.00	1.00	1.00		

[a]Flux in units of 10^{-19}W cm^{-2}. The quoted errors are only the PAHFIT fit residuals. EWs are normalized to the EWs for the whole SH slit.
[b]Equivalent width in units of μm

Chapter 4

Powerful H_2 Emission and Star Formation on the Interacting Galaxy System Arp 143: Observations with *Spitzer* and *GALEX*

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We present new mid-infrared (5 - 35 μm) and ultraviolet (1539 – 2316 Å) observations of the interacting galaxy system Arp 143 (NGC 2444/2445) from the Spitzer Space Telescope and GALEX. In this system, the central nucleus of NGC 2445 is surrounded by knots of massive star-formation in a ring-like structure. We find unusually strong emission from warm H_2 associated with an expanding shock wave between the nucleus and the western knots. At this ridge, the flux ratio between H_2 and PAH emission is nearly ten times higher than in the nucleus. Arp 143 is one of the most extreme cases known in that regard. From our multi-wavelength data we derive a narrow age range of the star-forming knots between 2 Myr and 7.5 Myr, suggesting that the ring of knots was formed almost simultaneously in response to the shock wave traced by the H_2 emission. However, the knots can be further subdivided in two age groups: those with an age of 2–4 Myr (knots A, C, E, and F), which are associated with 8 μm emission from PAHs, and those with an age of 7-8 Myr (knots D and G), which show little or no 8 μm emission shells surrounding them. The reasons for this are unclear, as PAHs are observed at later ages in other systems like the Antennae.

4.1 Introduction

Figure 4.1 — Overlay of the SL (sparse) and LL (complete) maps on a V-band image of Arp 143. North is up. See color supplement for a color version of this figure.

The direct study of warm molecular hydrogen emission from galaxies has been improving considerably through the advent of more sensitive space-bourne spectrometers on the *Infrared Space Observatory* (e. g. Rigopoulou et al. (88); Lutz et al. (39))

and more recently on the *Spitzer* Space Telescope[1]. With the Infrared Spectrograph (IRS[2]) (63) on *Spitzer* (71) it has been possible to improve upon systematic studies of the mid-IR pure-rotational lines of molecular hydrogen in a variety of environments, from nearby normal galaxies (54), to galaxies in more extreme environments, like groups and clusters (46; 21; 23) and ULIRGS (8; 30) (see also a review on molecules by Omont (48)).

Recently unusually strong mid-IR H_2 lines have been discovered in the giant shock-wave structure in Stephan's Quintet (1), and in over a dozen low-luminosity radio galaxies (46; 45), where H_2 lines are often the strongest in mid-infrared wavelengths. Strong H_2 equivalent widths were also found near the "overlap" region in the Antenna interacting galaxy (27). These systems have extremely large H_2 equivalent widths and line luminosities ($L_{H_2} > 10^{41-42}$ ergs/s), and relatively low star formation rates. Another defining characteristic is the large ratio of H_2 luminosity to PAH line strength, and the large (0.1 to 30%) fraction of H_2 luminosity to the total bolometric luminosity of the objects. Even larger H_2 line luminosities have been found associated with several massive galaxies in X-ray clusters (e. g. Egami et al. (21)). This new class of powerful H_2 emitting galaxy appears to be shock excited, and models of Stephan's Quintet, where a large-scale shock is strongly implicated suggest that a significant fraction of the bulk kinetic energy in the shock must be funnelled into the H_2 line in order to explain the results (11; 26). In this context, it is of considerable interest to find other examples of the same kind of emission in nearby systems. This paper describes strong H_2 emission from the strongly interacting galaxy pair Arp 143.

Arp 143 is an interacting pair of galaxies (NGC 2444/2445) with many of the necessary ingredients for a study of shocks generated by galaxy collisions. The southern gas-rich component of the pair, NGC 2445, is notable for the ring of stellar clusters and HII regions, whereas the nothern companion is devoid of activity. It is possible that NGC 2445 shares some similarities with collisional ring galaxies (like the Cartwheel ring), because the powerful star-forming knots lie along a crescent-shaped wave of HI emission (4), and there is kinematic evidence that the structure is expanding through the disk (32). Early unpublished spectroscopy by Jeske et al. (36) and optical and near-IR photometry of the knots (4) suggest the star clusters are quite young $< 30-60$ Myr, much younger than the dynamical age of the expanding HI wave–thus providing evidence that they are triggered by a collision with NGC 2444. Jeske et al. (36) estimated sub-solar (LMC-like) metallicity in the disk knots in the range 12+log[O/H] = 8.56-8.77, similar to other known collisional ring galaxies (see Bransford et al. 1996). The nucleus has mildly super-solar values of 12+log[O/H] = 9.18 – similar to nuclear starbursts. However, this simple picture is complicated by the unsolved mystery of the large 150 kpc-long HI plume (5) which extends just to the north of NGC 2444. The existence of such a long plume implies that the two galaxies involved in the collision have had a previous major tidal encounter in the past (29; 28). Perhaps the simplest interpretation

[1]This work is based, in part, on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. Support for this work was provided by NASA through a GO2 award issued by JPL/Caltech.

[2]The IRS was a collaborative venture between Cornell University and Ball Aerospace Corporation funded by NASA through the Jet Propulsion Laboratory and the Ames Research Center.

of the system is that NGC 2444 may have experienced an initial close passage with NGC 2445 ∼100 Myr ago, stripping HI into the plume from NGC 2444. After an initial non-pentrating encounter, the main stellar body of NGC 2444 has returned to collide recently with the disk of NGC 2445 in a manner similar to collisional ring galaxies (3).

In this paper we will present new multi-wavelength imaging and spectroscopic data of Arp 143, another example of a galaxy with very strong mid-IR H_2 emission. Our goal is to connect the recent dynamical events in Arp 143 with the shock and star formation history of the galaxy. The paper will use *Spitzer*, *GALEX*[3], and new ground based optical and near-IR images as well as mid-IR spectroscopy to explore the physical conditions in Arp 143. This will include the study of the dust and HII region properties, ages and luminosities of star formation regions and the excitation conditions of the warm H_2 gas. After a description of the images and spectra in §2, we will present in §3 the multiwavelength photometry and the spectral analysis. In §4, the discussion of the results will follow two main directions: the analysis of the shock region using mainly results from the spectral analysis, and the star formation history of the knots based on an interpretation of the UV-infrared SEDs of each knot. We will assume a distance to Arp 143 of 56.7 Mpc based on its corrected Virgo-centric velocity of 4142 km/s and an assumed H_0=73 km/s/Mpc. At this distance, 1 arcsec corresponds to 275 pc.

4.2 Observations and data reduction

4.2.1 Spectra

Figure 4.2 — Images of Arp 143 in 12 different bands: GALEX FUV, GALEX NUV, B, V, R, Hα, K, IRAC 3.6 μm, IRAC 4.5 μm, IRAC 5.8 μm, IRAC 8 μm, and IRS LL map at 24 μm. The different apertures used for photometry are overlayed on the FUV image.

The spectra were taken on October 24, 2004 using the IRS (63) on board of the Spitzer Space Telescope. All spectral data were processed using IRS pipeline version S15. Fig. **??** shows an overlay of the IRS low- and high-resolution slits on a V-band image. We have a completely sampled map in the Long-Low (LL; 15 - 37 μm) spectral mapping mode, consisting of 17 pointings (each with a 32 second exposure): a total LL exposure time of 544 seconds. A sparsely-sampled map was obtained with Short-Low (SL; 5 - 14 μm) which did not fully sample the galaxy as shown in the figure. It consisted of 30 pointings with 61 second exposures each: a total SL exposure time 1891 s. Since the LL and SL observations are composed of two sub-slits, each observed separately, convenient off-source "background" exposures were automatically obtained during the observations. These observations were selected to be free of line emission and were subtracted from each on-source exposure.

High-resolution spectra of the nucleus were taken in two nods with two 31 second exposures each for short and long wavelengths (SH and LH), resulting in a total integration time of 248 seconds. For each module we averaged the exposures for both nod

[3]GALEX (Galaxy Evolution Explorer) is a NASA small explorer launched in 2003 April. We gratefully acknowledge NASA's support under Guest Investigator program no. 45.

positions. After the removal of bad pixels, we extracted the spectra for each module, using SMART[4] (60), a tool for the extraction and analysis of Spitzer-IRS spectra, written in IDL. For the high-resolution spectra we did not subtract a background since there was no suitable "sky" spectrum taken. These observations were made early-on in the Spitzer mission before it was realized that obtaining a "sky" observation away for the target was useful for rogue-pixel removal (especially LH). Therefore, our SH and LH observations contain low-level zodiacal light in addition to the continuum from the galaxy. This does not affect the measurements of line fluxes (see later) but potentially can affect the measurement of the absolute continuum. The source was sufficiently bright that rogue-pixel removal was not a large issue in the case.

Extraction of all the in-target low-resolution spectra was performed using CUBISM (58), an IDL tool for the construction and analysis of spatially resolved spectral cubes using *Spitzer/IRS* spectra. Bad pixels in the BCD images were manually flagged in each cube pixel, and then automatically discarded when rebuilding the cube.

4.2.2 Images

Fig. 4.2 shows images of Arp 143 at 12 different wavelengths: far- (λ 1540Å) and near-UV (λ 2320Å) continuum; optical B- V-, and R-band continuum; H_α emission; K-band, the mid-infrared 3.6 μm and 4.5 μm bands, sensitive to the emission of the red stellar population; the mid-infrared 5.8 μm and 8.0 μm bands, specially sensitive to PAH and dust emission; and a 24 μm continuum image, built from a IRS LL spectral map. In the FUV image we show the apertures chosen for photometry, matching the main star forming knots visible on FUV, marked from A to G, and the nucleus. Each image was obtained as follows.

Figure 4.3 — Low resolution spectra of six regions coinciding with the selected knots.

4.2.2.1 FUV and NUV

Ultraviolet images of Arp 143 were obtained on January 28, 2005 (FUV) and December 26, 2006 (NUV) using the Galaxy Evolution Explorer (GALEX) satellite (41). The galaxy was imaged in the FUV and NUV bands, covering the wavelengths $1344 - 1786$Å and $1771 - 2831$Å. The total integration time was 3040 seconds for the FUV image and 219 seconds for the NUV. GALEX uses two 65 mm diameter, microchannel plate detectors, producing circular images of the sky with $1^\circ.2$ diameter at $5''$ resolution. The GALEX image was reduced and calibrated through the GALEX pipeline.The fluxes were converted to magnitudes on the AB system (47). The data was constructed with version 6 of the GALEX pipeline. We coadded two All Sky imaging visits to obtain the 219 seconds of exposure in the NUV image.

[4]SMART was developed by the IRS Team at Cornell University and is available through the Spitzer Science Center at Caltech.

Figure 4.4 — Low resolution spectrum of the gas ring in NGC 2445.

4.2.2.2 Optical and near-infrared

We obtained optical images on February 3, 2003 using the Palomar $60''$ telescope. The observations were made with a FOV of $12'.9 \times 12'.9$ (2048×2048 pixel) CCD imaging system with an RCA chip. The pixel scale is $0''.38$/pixel The data were taken in three filters, Johnson B, Johnson V, and Johnson R, and exposure times of 500 seconds for each filter. The night was moonless and transparent and the seeing was $0''.7 - 1''.0$. We used the star RU 152 for calibration. The Hα image was published in Romano et al. (52) and was taken in the Guillermo-Haro 2.1 m Telescope using a narrowband filter centered at 6635 Å(FWHM ~ 97 Å, which also contains the [NII]λ6583 line. We corrected the Hα flux for [NII] by assuming Hα/[NII]~ 3, typical of HII regions (49). The near-infrared images were obtained with good ($< 1''$) seeing through a K$_s$ (λ = 2.15 μm) filter using the WIRC camera on the Palomar $200''$ telescope in November 30 2004. WIRC is a 2048×2048 pixel wide-field $8.5 \times 8.5'$ HgCdTe camera with a pixel scale of $0.25''$/pix operated by Caltech.

4.2.2.3 Mid-infrared

Arp 143 was imaged with the Infrared Array Camera (IRAC, Fazio et al. (22)) on *Spitzer* at 3.6, 4.5, 5.8, and 8.0 μm on March 28, 2005. The IRAC detectors consist of two 256×256 square pixel arrays with a pixel size of $1''.22$ resulting in a total field of view of $5''.2 \times 5''.2$. For each of the four channels, 47 12 s exposures were taken, with a total integration time of 564 seconds for each channel. The data were reduced using standard procedures (i.e., dark-current subtraction, cosmic ray removal, non-linearity correction, flat-fielding and mosaicing) using pipeline version 14.0 of the Spitzer Science Center.

Figure 4.5 — Full high resolution spectrum of the nucleus of NGC 2445. The SH part was scaled up by 1.8 to match the LH spectrum.

4.3 Analysis

In Fig. 4.3 are five low-resolution spectra of $21'' \times 21''$ regions coinciding with knots B, C, E, F, and the nucleus. In these spectra we can see broad features attributed to Polycyclic Aromatic Hydrocarbons (PAHs), such as 6.2 μm, 7.7 μm, 8.6 μm, 11.3 μm, 12.6 μm features. Also noticeable is the distinctive PAH 17 μm complex. In the regions E and F, the H_2 lines at 9.7 μm, 12.2 μm, 17 μm, and 28.2 μm are especially strong. The ionic lines observed are [ArII]6.9μm, [NeII]12.8μm, [NeIII]15.6μm, [SIII]18.8μm and 33.5μm, and [SiII]34.8μm. The spectrum of knot D is extremely noisy, and therefore it is not shown in Fig. 4.3. This means that there is no continuum flux detected at this wavelength. However, the PAH features are detected above the sensitivity level. The peak of the 6.2 μm PAH feature, for example, is at 4 mJy, well above the 3σ sensitivity of the SL slit at this wavelength, which is 0.6 mJy. In Fig. 4.4 is a low resolution spectrum from the region where a ring of HI emission was observed by Appleton et al. (4); Higdon et al. (32), which is delimited in the B-band image in Fig. 4.2. This spectrum is very similar to the spectra of knots E and F, but it has some differences. It is even more dominated by distinctive H_2 lines, especially the H_2 S(1) line at 17 μm, although PAH features can also be seen, especially at 11.3 μm. The ionic lines are not so prominent, as the spectrum was taken in a region not dominated by star forming clusters.

4.3.1 H_2 lines

Figure 4.6 — H_2 excitation diagrams for knots E, F, G, the nucleus, and the gas ring . The plots are labelled with the fitting temperatures (T), column densities N(H_2) and molecular gas masses M(H_2) in units of K, cm^{-2}, and M$_\odot$ respectively. The points that are not labeled are upper limits and are not included on the fit.

Using the pure rotational H_2 lines we can probe the physical conditions of the warm molecular hydrogen in the star forming knots. The pure rotational lines originate from the warm (T > 100 K) gas. We measured the H_2 rotational line fluxes using SMART, and derived their excitation temperatures, column densities, and masses of their temperature components. Fig. 4.6 shows the excitation diagrams of the detected H_2 transitions and upper limits for the knots E, F, G, the nucleus, and the ring. Each excitation diagram consist on a plot of the natural logarithm of the column density N divided by the statistical weight g in the upper level of each transition against the upper level excitation temperature T_{ex}. The column density follows from the Boltzmann equation:

$$\frac{N_i}{N} = \frac{g(i)}{Z(T_{ex})} \times exp\left(-\frac{T_i}{T_{ex}}\right) \tag{4.1}$$

where N(i) is the molecular column density of the ith transition, N is the total column density of H_2, g(i) is the statistical weight for the ith transition, and $Z(T_{ex})$ is the partition function at the excitation temperature T_{ex}. The values of g for odd and even transitions are different because of the ortho and para transitions. Ortho transitions occur in molecules where the spins of both the nuclei are in the same direction. Para transitions occur in molecules where the spins of both the nuclei are in the opposite directions. At a gas temperature of $T \sim 300$ K, the ratio of ortho- to para-hydrogen is at its maximum of 3 : 1. The excitation temperature of the line-emitting gas is the reciprocal of the slope of the excitation diagram, and corresponds to the kinetic temperature in local thermodynamic equilibrium (LTE). However, the nonlinear decline of log (N/g) with upper-level energy, commonly seen in shocks within the Galaxy, as well as in external galaxies (39; 88), is an indication that no single-temperature LTE model fits these data.

The H_2 line fluxes, and the molecular gas temperatures, column densities and masses are listed in Table 4.1. The lowest temperatures are measured in knots E and G, using S(0) and S(1). The temperatures for knots F and H were derived from higher excitation transitions, S(1) and S(2), as S(0) was not detected. The measured temperatures are 137 K for knot E, 280 K for knot F, 178 K for knot G, and 309 K for the nucleus.

We can see that the molecular gas is hotter in knot F (280 K) and in the nucleus (309 K), but denser in knot E, where most of the warm molecular gas is concentrated. It is important to note that the temperatures for knots E and G were derived using only the S(0) and S(1) transitions, whereas higher transitions were used in other knots resulting in a higher average temperature of the gas. The derived excitation temperature is also dependent on the ortho-to-para ratio for H_2. During the fit to a multi-temperature model through the preferred data points, we constrain the warm gas by the S(0)/S(2) [para] ratio and allowing the higher order S(3) and S(5) [ortho] transitions to provide a very rough guide to the temperature of a hotter component, resulting in ortho-to-para ratios of 2.2 for knot E, 2.7 for knot G, and ~ 3 for knot F, the nucleus, and the ridge. These ratios agree with LTE models (13). The various masses are derived multiplying the column density by the physical area of the aperture corresponding to the knot.

4.3.2 PAH features

We used PAHFIT (96) to measure the PAH emission features for each of the knots. Some PAH features are decomposed by PAHFIT into gaussian components, such as the 7.7 μm and 11.3 μm features, and merged for the calculation of their total flux and EWs. The results of the PAH feature fits are listed in Table 4.2. Most of the PAH features lay on the SL part of the spectrum, meaning that the sparse map only has a 2 pixel wide coverage of the knots. We therefore make an extrapolation of the results taken with these observations to the total area of the knots.

The overwhelming majority of the PAH emission comes from the nucleus, which is also the region with the most emission at 8 μm (Fig. 4.2). From the star forming ring, Knots A, C, E, and F have PAH associated with the star clusters. Knot E is the one with the highest PAH emission, and this is also expected from the 8μm IRAC image in Fig. 4.2).

4.3.3 Ionic lines

In Table 4.3 we present the fluxes of the main ionized gas lines in the low resolution spectra, as measured using SMART. The errors listed reflect the S/N ratio at the wavelengths where the lines were measured. With these fluxes we calculated the ionic line ratios [NeIII]/[NeII], [SIII]18.7/[SIII]33.5 μm, and also [SiII]/[SIII].

The [NeIII]/[NeII] rate, because it is a rate between two ionization states of the same element, it is sensitive to the effective temperature of the ionizing stars, and therefore can be used as a measure of the hardness of the radiation field. This ratio varies typically between 0.05 and 1 in starburst galaxies and HII regions in normal galaxies, and is typically greater than 1 in dwarf galaxies (105). We could only measure the [NeIII]/[NeII] ratio for knots E, F, and for the nucleus, and the results are 0.52, 0.67, and 0.08. The ratios for knots E and F are compatible with very young massive clusters, and are similar to those found in very young clusters in other interacting systems such as the Antennae, where star forming regions with [NeIII]/[NeII] ratios between 0.30-0.73 are found Snijders (60). The ratio for the nucleus is much smaller than the ratios for the ring knots and are similar to the ratios found in the nuclei of starburst galaxies, like NGC 253 (0.07; Devost et al. (47)).

The [SIII]18.7/[SIII]33.5 μm ratio, as it is a ratio between two lines of the same ionization state, but with different critical densities for collisions with electrons (49). Therefore it is sensitive only to the density of the ionized ISM. The [SIII]33.5 μm line was detected in all knots, but the [SIII]18.7 μm was detected only in knots E, F, G, and in the nucleus. As seen in Table 4.3, the values for [SIII]18.7/[SIII]33.5 μm ratio for these knots vary between 0.50 in knots E and F and 1.34 in knot G although with a large measurement error for the last case.

The [SiII]/[SIII] line ratio is used as a starburst/AGN diagnostic (44). This is because the [Si II]34.82 μm line is a significant coolant of X-ray ionized regions or dense photodissociation regions (33), more commonly associated with AGN, whereas the [S III]33.48 μm line is a strong marker of H II regions. The typical value found in AGNs is around 3, whereas for nuclear starbursts is around 1 (44). We measured this ratio for all knots, varying from 0.82±0.22 in the nucleus to 1.97±0.51. The low signal-to-noise ratio in clusters B, C, and D is reflected in the high errors of the [SiII]/[SIII] measurements, and therefore all the values for this ratio are compatible with the values for nuclear starbursts found in (44).

4.3.4 High resolution spectrum of the nucleus

To study the ISM conditions in the nucleus with greater accuracy we took a high resolution spectrum of the nucleus of NGC 2445, which is presented in Fig. 4.5. We scaled up the SH spectrum by multiplying it by a factor of 1.7 to match the LH spectrum flux at 20μm. This factor is much lower than the difference between the SH and LH slits, but that is simply due to the fact that the nucleus is practically a point source. The LH and SH spectra were then joined together, resulting in a single 10 - 35 μm high resolution spectrum of the nucleus. The main features present are the ionic lines, like [NeII], [NeIII], [SIII], and [SiII]. PAH bands are also visible, as the 11.3 μm band, and the 16 - 18 μm feature. Also present are the H_2 rotational lines. These features allow a physical characterization of the ISM of the nucleus, and they can be used to diagnose electron temperature and density and H_2 gas temperature. The measured line ratios are listed in Table 4.3, along with the lines measured in the same knot using the low resolution spectrum. We can see that the low resolution line fluxes have roughly half the flux as the high resolution lines. This is due to the difference in the extraction apertures. The area of the LH slit is 231 arcsec^2, nearly twice the area of the low resolution extraction aperture chosen for the nucleus, which is 104 arcsec^2. This gives a ratio of 2.22, whereas the ratio between low and high resolution apertures for both the [NeII] and [NeIII] flux is 2.04, meaning that the surface brightness of the lines decreases with a wider aperture. However, to do a comparison of the continuum fluxes one has to estimate the background flux. We measured the background flux from an off-source SL slit, which gives 116 mJy and 95 mJy for 15 μm and 24μm, after scaling for aperture sizes. That means that the background accounts for $\sim 55\%$ of the high-resolution continuum at 15 μm and $\sim 32\%$ of the high-resolution continuum at 24 μm. The ratio of the continuum flux at 15 μm is thus 1.6, meaning that the surface brightness of the warm dust decreases with the aperture. The ratio for the 24 μm continuum is 2.2, meaning that the surface brightness of cooler dust does not vary with slit size.

Comparing the ratios derived from high resolution with the low resolution ratios, we find a remarkable match for the [NeIII]/[NeII] ratio, being 0.08 for both spectra, but for the [SIII]18.7/[SIII]33.5 μm ratio there are significant differences, being 0.73 for the high resolution spectrum and 0.49 for the low resolution spectrum. This reflects the different flux ratios between high and low resolution apertures: [SIII]18.7μm has a flux ratio of 2.38±0.16 thus maintaining its surface brightness, whereas [SIII]33.5μm has a flux ratio of 1.61±0.09 thus decreasing its surface brightness. This difference possibly reflects a decrease of the ionized gas density as the distance to the nucleus increases. Note that the LH slit could be contaminated by emission form the "shocked" gas region, and thus it can affect the line ratios that use lines [SiII] and [SIII]33.5μm and overestimate the nuclear H_2 component.

4.3.5 Photometry

Photometry of each knot was performed using *aper*, an IDL tool from the IDL Astronomy Library. We used the FUV GALEX image to set an aperture size for each knot, as seen in Fig. 4.2. We used circular apertures of $4''.5$ for knots C, F, and the nucleus; $6''$ for knots B and D; and $7''.5$ for knots A, F, and G. The sky background was determined using circular apertures of the same size as the ones used to measure each knot. With these apertures, we measured the flux within selected regions inside Arp 143 – but avoiding the knots – and averaged the results. We applied extended source corrections for IRAC photometry. These corrections depend on the size of the aperture and do not exceed 6.8%. The resulting fluxes of each of the knots are listed in Table 4.4.

Arp 143 was not observed with the MIPS instrument at 24 μm. However, in order to allow us to use some of the well known star- formation indicators (e. g. Calzetti et al. (14)) associated with the knots based on MIPS observation, we decided to create pseudo-MIPS 24μm photometric points by extracting 24μm data from the full-IRS LL map (see Fig. 4.2–last panel) using the CUBISM-extracted spectra, and the MIPS 24μm filter response curve. These values are tabulated in Table 4.4.

4.4 Results

Our goal is to characterize the physical origin of the H_2 line emission, its role on the appearance of the ring of star formation around the nucleus of NGC 2445, describe how the ISM in the knots evolves as they age. To achieve this goal we now analyze the observations described in the past chapter according to the following points: a) the study of the morphology of the system, describing it in the present state, in order to compare it to the present theories on the evolution of ring galaxies; b) the study of H_2 excitation region and comparison with predictions, in order to study its physical origin; c) the ISM properties of the knots and its evolution, using the mid-infrared spectra to study the ISM in the knots, and UV to K-band photometry to study their ages; and d) the star formation rates in the knots, and the future of star formation in the system.

4.4.1 Morphology

In Fig. 4.7 we present a composite of FUV (blue), V-band (green), and 8 μm emission (red), which traces emission from hot dust. Most of the luminosity in the V-band comes

Figure 4.7 — Composite of FUV (blue), V-band (green), and 8 μm (red) images of Arp 143. See color supplement for a color version of this figure.

from the nuclei of the two galaxies, NGC 2444, and NGC 2445, and a ring of star formation knots that surrounds the nucleus of NGC 2445. The nucleus of NGC 2445 dominates the emission in the infrared, indicating the presence of large amounts of warm dust, but it also has a large unobscured population of main sequence and old stars, as it has also significant optical and near infrared components. For a more quantitative comparison, the 8 μm flux from from the nucleus is about 5 times the combined 8 μm flux from the knots. The knots are located along the outer edge of an HI crescent (4). The knots are composed by several massive young clusters, visible in blue, and some are surrounded by PAH emission, visible in red. There are some mid-infrared "arms" connecting the nucleus to some of these regions. These arms are connected to the collisional nature of the ring – spokes are expected in gas that is collecting downstream of the ring (62). The only other galaxy with similar features reported in the literature is the Cartwheel galaxy (62).

NGC 2445 is about 20 kpc across. Some peculiarities reveal a connection between the massive star clusters and the dust, like the easternmost knot at about 12 kpc from the nucleus, identified in the FUV image in Fig. 4.2 as knot A. In Fig. 4.7 this FUV emitting knot seems to be surrounded by 8 μm mid infrared emission (in red), as it is brighter around the knot and less bright inside a radius of ~ 1 kpc from the center of the knot. This can be interpreted as a shell of warm dust heated by the massive stars. Other knots have 8 μm counterparts, like knot B, C, E, and F. For knots C and F, the 8 μm emission can be seen at the same site as the optical cluster, whereas in knot E, the 8 μm is found somewhat offset to the SE. Since the 8 μm IRAC band is dominated by PAH emission features, this means that the knots can be divided into two groups: those with associated PAH emission (A, C, E, and F), and "bare" knots, for which little or no PAH counterpart is observed (B, D, and G). This confirms what is observed in the spectra of Fig. 4.3, where PAH features are barely observed in knot D. The nucleus of NGC 2444 also shows substantial 8 μm emission, reflecting substantial massive star formation. The FUV emission comes mainly from knots A, E, and G, showing emission from young massive stars, whereas the IR-bright knot F emits little UV. An even more striking difference between mid-infrared and UV brightness, and Fig. 4.2 shows it clearly, is seen in the nucleus, the brightest region in 8 μm, with very little UV emission.

The companion lenticular galaxy NGC 2444 is prominent only in the optical and K-band, and is rather weak at longer wavelength. This supports the idea that much of the gas has been swept out of the galaxy in the past and it is dominated by an old inactive stellar population. It is possible that a faint "arm" extended from NGC 2444 behind NGC 2445, but this is hard to prove without kinematic data.

4.4.2 The shock front

Rotational emission lines of H_2 may arise through three different mechanisms: UV excitation in PDRs surrounding or adjacent to the HII regions (**?**); shocks that accelerate

Figure 4.8 — Contour maps of the H_2 S(0) (left) and H_2 S(1) (right) emission in Arp 143, overlayed on an IRAC 8 μm image. Contour levels are at 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.5 , 2, and 3 MJy/sr for H_2 S(0) and 1, 1.4, 1.8, 2, 2.5, 3, 4, 6, and 8 MJy/sr for H_2 S(1). See color supplement for a color version of this figure.

and modify the gas in a cloud, collisionally exciting the H_2 molecules (**?**); and hard X-ray photons capable of penetrating the molecular clouds and heating large ionizing columns of gas (**?**). Several rotational H_2 lines were detected in the wavelength range of our observations and they are listed in Table 4.1. Given that these lines trace the molecular gas at different temperatures, studying the spatial distribution of these excitation lines may give us a clue about the main excitation mechanism.

In Fig. 4.8 we present contour maps of the H_2 S(0) (left) and H_2 S(1) emission (right) in Arp 143, overlayed on the IRAC 8 μm emission color map. The H_2 emission in Fig. 4.8 is concentrated in two clumps–from the nucleus and in a crescent-shaped ridge (including knot F) west of the nucleus corresponding to the HI-crescent seen in VLA observations. The emission also is similar, but not identical to CO (1-0) interferometry distribution(32). These latter observations trace the distribution of cool H_2 emission through collisional excitation of the CO molecule. The main difference between the Spitzer (warm) H_2 observations and the CO (cool H_2 tracer) is that the warm gas seems to better define a crescent-shape. Indeed it is precisely here that a shock wave would be expected to heat up the H_2, supported by the fact that the S(1) map more clearly defines the crescent shape than the S(0) line, which is dominated by cooler excitation. This is compatible with the theoretical scenario illustrated in Fig. 4.9, taken from Appleton et al. (5), which represents the density wave formed after an off-center collision between two galaxies (the site of the collision is marked with an X), which expands outwards from the center and also grows in length. It is also worth noting that the area chosen for the spectrum of the gas ring, demarcated in Fig. 4.2 coincides with the area of the shocked H_2 emission. Therefore we can consider this spectrum, in Fig. 4.4 as representative of the shocked H_2 region.

The shape of the H_2 emission in Fig. 4.8 is promising but by itself does not settle the case for either PDR or shock origin. A way to investigate the origin of the excitation of rotational transitions of the H_2 molecule is to make a spatial comparison between the H_2 emission and PAH emission. The H_2 emission-line strength should track the PAH emission-line and IR continuum strength in the case where the most common H_2 excitation mechanism is UV excitation at the PDR interface with star formation regions. However, we see a remarkable transition in Arp 143, from the nucleus, where PAH emission is quite strong, to the non-nuclear H_2, which remains strong in the H_2 lines, but is very weak in PAH (and continuum) emission.

Roussel et al. (54) calculated the logarithm of the average ratio of the power emitted in the sum of the S(0) to S(2) transitions to the power emitted by the PAH features within the IRAC4 band, for HII nuclei and Seyferts from the SINGS survey. The average ratio for HII nuclei -2.19 ± 0.10 and for the Seyferts is -1.80 ± 0.34. We measured these ratios for the knots where H_2 lines from S(0) to S(2) have been measured. We take 7.7 μm and 8.6 μm as the PAH features inside the IRAC4 band. For the nucleus of Arp 143, the ratio is -2.26, which puts it in the average of the HII nuclei. However, for

Figure 4.9 — Schematic scenario of NGC 2445 where the knots are situated at the leading edge of the density wave. The contours are from the off-center collision model E from Fig. 7 in Appleton et al. (5), representing a stage of the expansion process of a density wave. The arrows represent the expansion of the wave. Solid contours indicate elevation above the initial unperturbed disk values and dotted contours represent depressed levels. The nucleus is marked with a square. The site of the collision is marked with a cross.

knots E, F, and, G, the ratios are -1.22, -0.90, and -0.94, respectively. This puts them well above the averages for HII nuclei and also for Seyferts. For the gas ring region, which largely coincides with the H_2 crescent, this ratio rises up to -0.36. So the difference we observe in the H_2/PAH ratio between the nucleus and the ring region in Arp 143 is a strong indication that the H_2 emission ridge seen in Fig. 4.4 is mostly due to shocks. X-ray emission is unlikely to be a strong contribution to the H_2 heating, since the ratio of the [SiII]/[SIII] lines in Arp 143 (even in the nucleus) suggests an insignificant contribution to the excitation of [SiII] from X-rays. (X-rays can significantly enhance this ratio–as discussed by Dale et al. (44)). This strongly suggests shock-excitation within the crescent-shaped structure. A very strong H_2 emission in the absence of strong PAH emission is seen in the shock wave in Stephan's Quintet (1) and in the spectrum of 3C326 (46), where strong shocks are implicated. The lack of a correspondingly large continuum is also one of the characteristics of the shocked H_2 seen in the radio galaxy sample, and the Stephan's Quintet, as well as low-excitation emission lines.

We can interpret the excitation diagrams in Fig. 4.6 also in the context of the different origins of the H_2 emission. The temperatures derived in the excitation diagrams are compatible with either a PDR origin or a shock origin for the H_2 excitation. The H_2 temperature derived for the nucleus is higher than the temperature for the knots associated to the H_2 ridge, and to the H_2 ridge as a whole, still does not reach the level required to rule out PDR origin, and the comparison with the PAH emission is crucial. However, these temperatures are just average gas temperatures, and it is possible the presence of a warmer gas component in the H_2 shock region. The column density of the gas is lower in the H_2 ridge than in the knots, which is expected, since the warm H_2 emission from the ridge is more diffuse, whereas the H_2 emission peak coincides with knot F.

4.4.3 The properties of gas and PAHs in the knots

The knots in the ring of star formation are very young and are expected to have similar characteristics to young massive clusters discovered in starburst galaxies. We use our observations to study the components of the ISM in these knots, which consist of the molecular gas, ionized gas, and dust.

The properties of the warm molecular gas, as presented in Sect. 4.4.2, can be compared with the properties of the cold molecular gas as studied in (32) using CO observations. CO probes molecular gas up to a temperature of 100 K, but provides no information on the "warmer" gas which might be more directly linked to the source of activity. However, we can estimate what fraction of the total gas mass lies in higher temperatures. The fraction H_2 (warm) to H_2 (cool) is 4.8 % for knots F and G, 2.6 % for the nucleus, but 64 % for knot E, assuming a CO-H_2 conversion factor for the LMC. On average, the fraction of warm to cool H_2 amounts to 10 %, which is nearly the same found by Rigopoulou et al. (88) for a sample of starburst galaxies.

Forbidden ionic lines can be used as indicators of the conditions of the ionized gas in the knots and the shock region. The ratio [NeIII]/[NeII] is a measure of electron temperature of the ionized gas, and is used to estimate the knot ages; the [SIII]18.7/[SIII]33.5 μm ratio is used as a measure of electron density. These ratios are compared to modeled ratios derived using photoionization diagnostics by Snijders et al. (98), assuming Salpeter IMF, stellar mass cutoffs $M_{up} = 100M_{\odot}$ and $M_{low} = 0.02M_{\odot}$ and solar metallicity.

From the [SIII]18.7/[SIII]33.5 μm ratio we can estimate the density of the knots for which these lines are measured. This ratio is insensitive to the ionization parameter Q and age. As seen in Fig. **??** (right), for any Q and age, knots E, F, G, and the nucleus have electron densities in the order of $10^2 - 10^3$ cm^{-3}. This is the average electron density encountered in the center of the starburst galaxy M82 (57). However Knot E, for example has a diameter of ~ 1 kpc, about two times the size of the central region of M82 (see Chapter 3), and it is composed of individual clusters that could have much higher densities.

Fig. **??** in the left shows the evolution of the modeled [NeIII]/[NeII] with age, for a given value of the ionization parameter. Due to difficulties in measuring the [NeII] line in the low resolution spectra, as it is merged with a PAH feature at 12.8 μm, we could only measure the ratio for knots E, F, and for the nucleus. We can see that the measured ratios correspond to knot ages of 1 - 4.5 Myr. The difference in the [NeIII]/[NeII] ratio between the nucleus (0.08) an the ring knots (0.5-0.7) means that population of recently formed massive stars in the nucleus is older than the young bursts in the ring, having an estimated age of 5 - 6 Myr. The fit to the low resolution spectrum of the nucleus gives an A_V of 0.02, which is too low to have any effect on the ratios, and therefore extinction does not affect the ratios significantly.

PAH molecules with different physical characteristics produce different bands. The 6.2 μm, 7.7 μm, and the 8.6 μm bands are produced preferentially by ionized PAHs whereas the 11.3 μm band is produced primarily by neutral PAH molecules. Therefore, the ratio 11.3/7.7 μm may indicate the effect of PAH ionization. We calculate this ratio for all the knots. Given the uncertainties in the PAH flux measurements, we could only derive a reliable 11.3/7.7 μm ratio for knots F and H. We cannot see significant differences between the two ratios, at least not bigger than the uncertainties for knot F.

4.4.4 The ages of the knots

With the fluxes listed in Table 4.4, we built SEDs of the main knots, in order to further constrain their physical characteristics. To achieve this, we compare the SEDs with synthetic spectra modeled with Starburst99 Leitherer & Heckman (38). There are several parameters we need to consider when fitting the model SEDs to our observations:

- The mode of star formation. The star formation may occur continuously (continuous star formation model, or CSF model) or in a single, almost instantaneous, burst (instantaneous burst model, or ISB). We will adopt the ISB model for the star-forming knots, as there is no evidence that star formation has been ongoing for any considerable time in these knots.

- The stellar initial mass function (IMF). We adopt a Kroupa IMF with an upper-mass cutoff of 100 $M_\odot$ and a lower mass cutoff of 0.02 $M_\odot$.
- The initial gas metallicity (Z). We assume sub-solar metallicity $Z = 0.4Z_\odot$, which is similar with the metallicity reported by Jeske et al. (36).
- The age of the star clusters. This is a free parameter ranging from 0 to 1×10^9 yr.
- The effect of extinction. We use the Calzetti starburst extinction law (16) on the synthetic spectra,
- Dust emission.

With these conditions, we fitted the synthetic spectra to the measured SEDs of each knot. The fluxes listed in Table 4.4 were converted to units of ergs^{-1}Å^{-1}. We compensated the optical and UV fluxes for a galactic reddening of E(B-V)=0.051, using the extinction maps and laws of Schlegel et al. (56) and attenuation curve of Cardelli et al. (17), the latter exclusively for the UV fluxes. Along with a pure stellar synthetic spectrum, the output of Starburst99 includes a nebular emission component as well, which was added to the stellar spectrum for knots C, E, and F. A set of free parameters, such as age, extinction, and continuum flux were adjusted for each knot in order to minimize the χ^2 value. The results are listed in Table 4.6, as well as the range of parameters within a 95 % confidence level. Knot B was left out, as knot B has a foreground star that interferes with the measurements. Although the nucleus could be modeled using the above assumptions, the measured optical to UV flux ratio appears always larger than the modeled spectrum. The variation between subsolar metallicity $Z = 0.4Z_\odot$ and solar metallicity does not modify significantly the parameter values.

From the results of the SED fits in Table 4.6 we can divide the knots in two age groups: knots with ages from 2 - 4 Myr (A, C, E, and F), and knots with ages from 7 - 7.5 Myr (D, and G). Given that the interaction occurred 100 Myr ago Appleton et al. (5), this age difference is not very significant in terms of the interaction dynamics. Probably due to a clumpy ISM, some clouds collapsed earlier than others, forming stars a little ahead in time than others. The estimated ages come into agreement with Fig. 5.16 (left), which predicted the same range of temperatures for knots E, and F.

In Fig. 4.11 we show two examples of SED fittings on knots C (with nebular emission) and D (without nebular emission), being good representatives of the two age groups. We can see how the IRAC 5.8 μm and 8 μm fluxes, and the synthetic 24 μm flux, deviate from the pure stellar model for knot D, indicating the presence of PAH and thermal dust emission. We can also see that the SEDs are not easily fitted with a simple instantaneous starburst model, and an example is the excess of K-band emission in knot C, observed in Fig. 4.11 (left). A K-band flux excess was also reported in previous studies that fitted SEDs with Starburst99 (Surace & Sanders (64) for warm ULIGs; Mazzarella et al. (42) for the nuclei of Arp 220), which was compensated adding a hot dust (800 K) component contributing to 10-30% of the emission (64).

The nucleus of NGC 2445 was modeled using instantaneous (ISF) and continuous star formation (CSF). Continuous star formation is more a reasonable assumption, based on results from ring models, who predict a continuous fuelling of the nuclear starburst through gas inflow. In this case we used a Kroupa IMF with an upper-mass cutoff of 100 $M_\odot$ and a lower mass cutoff of 1 $M_\odot$. We found that the best fit is achieved for the age of 500 Myr. These ages are radically different than those obtained with

Figure 4.10 — *Left*: effect of the cluster age on the [NeIII]/[NeII] ratio. The model curves are computed for a cluster of $10^6 M_\odot$, assuming Salpeter IMF, $M_{up} = 100M_\odot$, and $M_{low} = 0.2M_\odot$. Each curve represents a different ionization parameter, and the solid curve is the one that approaches the value found in M82 by Förster Schreiber et al. (57), log$U = -2.3$. The horizontal lines indicate the [NeIII]/[NeII] for knots E and F, and the nucleus. The first dip in [NeIII]/[NeII] represents the ageing of the stellar population, after which WR stars are produced, increasing the [NeIII]/[NeII] ratio. The dip at 6 Myr occurs as most massive stars die through supernova explosions. *Right*: dependency of [SIII]18.7/[SIII]33.5 μm ratio on the electron density. The curve is for a single ionization parameter approaching log$U = -2.3$. The horizontal lines indicate [SIII]18.7/[SIII]33.5 for knots E, F, and G, and the nucleus. Knots E, and F have the same value for [SIII]18.7/[SIII]33.5, which is 0.5.

[NeIII]/[NeII] ratios (5 – 6 Myr), and this is due to the fact that both [NeII] and [NeIII] lines are produced from the gas excitation by the youngest and hottest massive stars, and that ISF was assumed in the modelling of the lines.

The age determination achieved here is a significant improvement in comparison with past efforts, e. g. Appleton et al. (4), as their color-based determinations did not include UV bands. The FUV and NUV, as demonstrated here, are essential to the breaking of the age-extinction-metallicity degeneracy.

4.4.5 Star rormation rates

With the H_α, FUV and mid-infrared continuum fluxes at 15 μm, 24 μm, and 30 μm we can derive star formation rates for each knot. Using the star formation rate calibration by Kennicutt et al. (3) we can derive the star formation rate from the H_α luminosity, which traces the very young and massive stars. However, the H_α flux is affected by internal extinction, and for the more dusty clusters, we should use the Calzetti calibration law (14), which includes the 24μm luminosity to compensate extinction that affects the H_α emission. Far ultraviolet is also a tracer of young massive stars, but even more affected by extinction than H_α. We use here the A_v values in Table 4.6 to correct the FUV fluxes and the calibration by Salim et al. (55), which uses GALEX FUV calibrations. Mid-infrared spectral diagnostics for the SFR were derived in Brandl et al. (40), based on the fluxes at 15 μm and 30 μm. For each spectrum of the knots, we measured the flux at 14.5-15.5 μm and 29.5-30.5 μm, and calculated the SFRs based on the Brandl et al. (40) calibrations. In Table 4.5 we list the corrected FUV, H_α, 24 μm luminosities, as well as the 15 μm and 30 μm fluxes. The SFRs derived using each one of these indicators are also listed.

Adding all the SFRs of the knots, we arrive to a total SFR of 2.16$\pm$0.17 $M_\odot yr^{-1}$ from H_α luminosities and 2.40$\pm$0.35 $M_\odot yr^{-1}$ using $H_\alpha + 24\mu$m luminosities. This is similar to the 2.5 $M_\odot yr^{-1}$ derived by (36) using the H_β fluxes but below the the far-infrared SFR of 6.21 $M_\odot yr^{-1}$ calculated from IRAS colors (44). It is also far below the SFR derived from the corrected FUV fluxes, which is in total 15.9 $M_\odot yr^{-1}$.

The SFRs calculated by the Brandl et al. (40) method are systematically below the SFR calculated using the (14) calibrations, which in turn are below the SFRs derived from FUV. This can be explained by the fact that most of the energy is detected in the optical and not absorbed by dust, which makes this system distinct from more archetypal starbursts like M82. Here, the UV and optical radiation from the clusters is heavily absorbed, making the A_v at least 10 times higher than in Arp 143 (see Chapter 3). This is mitigated in case of the nucleus, which accounts by $\sim 80\%$ of the total 24 μm flux, and thus the discrepancy is smaller. Notice that the star formation rate from UV is heavily dependent on the estimation of A_v, which values within a 95 % confidence can vary by a factor of two, as seen in Table 4.6.

4.5 The role of shocks in the propagation of star formation

In the past sections we discussed thoroughly the H_2 shocks occurring in NGC 2445 and the ages and densities of the knots that compose the star forming ring. The strong H_2 emission reported this paper exists in and around the density wave, as traced by HI emission shown in (4). This is expected from shocks created as the wave moves out through the disk. This is because the gas, unlike the stars in these models, cannot pass through each other and shocks should develop at caustics. In this section we will discuss the role of these shocks in the development of the knots, and its consequences on the morphology of Arp 143.

4.5.1 The evolution of PAH emission with cluster age

Figure 4.11 — Spectral energy distributions for knots C (left) and D (right), with Starburst99 synthetic spectra. The error bars represent photometric measurement errors.

The SED modeling in this paper provided a further refinement of the age dating of the knots, which is a main advantage over past attempts (4). It showed that not only the HII region nebulosity but also the clusters themselves are consistent with a recent very young burst.

The evolution of PAH excitation with starburst age has been speculated by other studies, like Roussel et al. (53) in their analysis of dust excitation in NGC 300. We can try to observe this behavior taking advantage of our detailed diagnostics of knot ages.

The improvement on the age dating of the knots allowed us to divide them into two groups: those with an age between 2-4 Myr old (knots A, C, E, and F), and those with an age of 7-8 Myr old (knots D and G). What is remarkable is that the younger group of knots corresponds exactly to the knots where PAH counterparts are observed, whereas the older knots are those "bare" of PAHs, as discussed in Section 4.4.1 and seen in Fig. 4.7. This is the first time this ageing effect in star forming galaxies is observed in such chronological detail.

The lack of PAH emission in older knots means that the PAHs have either "cleared out", ceased to be excited, or destroyed during a timescale of 4-5 Myr. The first possibility is that the PAH have been "swept" after ~ 6 Myr by winds from star formation regions. The 8μm shell in knot A, for example, has ~ 3 kpc in diameter. Assuming a wind velocity of 300 km/s, the shell has been expanding for 5 Myr, a timescale comparable to the age of the knot. Another possibility could be PAH destruction. Small molecules could become more exposed over time to the hard UV field and are subsequently destroyed, as the dust shell expands and the PDRs become exposed to the outer radiation field. However, both these processes also occur in other galaxies where

PAHs are observed at later ages, like the Antennae, so the cause for this behavior resides probably on the nature of the ring galaxy system.

Due to the shock wave traced by the H_2 emission, the knots in the ring were formed simultaneously, and therefore we assume an instantaneous burst for all the knots. This means that the UV radiation fades away after ~ 6 Myr, and no longer excites the dust surrounding the knot. This can be observed in Fig. 5.16, where the [NeIII]/[NeII] ratio, a measure of the hardness of the radiation field, decreases dramatically after 6 Myr. The slope of the continuum of knots D and G longwards 25 μm indicates the presence of cold dust, meaning that dust is present in these knots, but it is not heated by UV radiation. An older star-forming region with continuous burst like the nucleus of NGC 2445 keeps forming new massive stars which continue to excite PAHs and warm up dust. This could also be the origin of the SFR discrepancy seen in Sect. 4.4.5, where the SFRs in the knots calculated from the infrared continuum are systematically lower than the SFRs calculated from H_α+24 μm luminosities, but not the SFR in the nucleus.

4.5.2 The H_2 emission front and the simultaneity of knot formation

The strong H_2 emission reported this paper traces a density wave expanding outwards at a constant speed. In response to the density wave, the knots were formed simultaneously in situ, and that is confirmed by the narrow age range found in Table 6. The fact that the H_2 follows the shape of the HI overdensity is further confirmation that this is a coherent structure.

If we assume the shock velocity from (32), 118 ± 30 km s^{-1} and the distance of the clusters to the nucleus, we can calculate the propagation timescale of the shock from the nucleus outwards. Given that the knots are on an average distance of 10 kpc, the shock wave has been propagating from the nucleus since 85 Myr ago. However, star formation has been occurring in the nucleus way before then, at least since 300 Myr ago. This is consistent with the kinematic picture first advanced in Appleton et al. (4): a first interaction with NGC 2444, provoking the onset of star formation in the nucleus 300 Myr ago, and the HI plume observed in Appleton et al. (5); and a second interaction ~ 85 Myr ago, provoking the emergence of a shock wave which creates a gas overdensity visible in HI Appleton et al. (4); Higdon et al. (32), leading ultimately to a ring of young star forming knots. These knots were created almost simultaneously, and as we have seen, blows out surrounding PAHs in a very short timescale, $5 - 6$ Myr.

Models of ring galaxies have shown the emergence of simultaneous star formation due to an expanding shock wave as a consequence of a head-on collision Gerber et al. (25); Struck (61); Lamb & Hearn (37). However, the timescales and details such as gas distribution, frequency of starbursts, etc., are strongly dependent on the position and kinematics of the galaxies, and there are no models for the particular case of Arp 143.

The future of star formation in the ring of knots will depend on the gas reservoir. Given the mass of atomic and molecular gas, and the SFR for all the knots, we can calculate the duration of star formation in Arp 143 assuming constant SFR. Higdon et al. (32) found 1.25$\pm \times 10^9$ M$_\odot$ of atomic gas in Arp 143, and 2.2×10^9 M$_\odot$ of cold molecular gas. Taking the total gas content and an average SFR of 2.16 M$_\odot$, we calculate that the star formation in Arp 143 will last for ~ 2 Gyr. However, the evolution of Arp 143 as a ring galaxy is also likely to increase its SFR, meaning that this is an upper limit for the duration of star formation.

These estimates do not, however, take into account the dynamical evolution of the system. The intruder galaxy, NGC 2444, is likely to swing back, and disrupt once more NGC 2445. A dynamical model will be extremely useful to predict the future of star formation in this system, and therefore in similar systems at higher redshifts.

4.6 Conclusions

Mid-infrared observations of Arp 143 have been presented in this paper, along with ancillary data including GALEX UV images. Multiwavelength images from UV to mid-infrared show a bright dusty nucleus surrounded by young star forming knots. The four main conclusions of this study are the following:

- Spectral line maps of the H_2 rotational lines show a ridge of warm H_2 emission that curves between the nucleus and the western knots. The H_2 line flux related to PAH flux is nearly 10 times higher in the ridge than in the nucleus. The flux ratios between the sum of H_2 S(0) and S(2) lines over the sum of PAH 7.7 μm and 8.6 μm lines reveal that this H_2 ridge observed in Fig. 4.8 arises from shocked gas behind the wave that provoked the onset of the ring of star forming knots. This is one of the few cases were this kind of feature is seen.
- With the use of photometry and fitting the SEDs, we improved greatly the age determination of the knots. The knots in the ring are all very young, varying from 2-7.5 Myr old and the nucleus is about 500 Myr old. The ring of knots are a product of a shock wave that has been expanding from the nucleus since ~ 85 Myr ago, and were formed simultaneously in situ. Behind the shock the molecular gas condenses, and it is traced by the H_2 emission ridge. The improvement of age determination is achieved in this study especially due to the GALEX FUV and NUV bands, which are crucial to break the age-extinction-metallicity degeneracy.
- The distribution of ages of the knots correlate with the presence of PAH emission. Younger 2-4 Myr old knots are associated with PAH emission shells, whereas older 7-8 Myr knots contain little or no PAH emission. We considered PAH destruction and aging of the cluster as the most plausible explanations, but PAHs are observed in other systems like the Antennae at later age, so the cause for this behavior resides probably on the nature of the ring galaxy system.
- Given the current reservoir of molecular gas, and assuming that the current star formation rate maintains itself constant, the star formation in Arp 143 will last for about 2 Gyr. However, as it is very likely that the SFR will increase dramatically, this can only be an upper limit for the duration of the starburst.

Table 4.1 — Molecular Hydrogen Line Fluxes (Top Row), Equivalent Widths (Bottom Row) and Diagnostics of the Main Knots[a]

Knot	H_2 S(3)[a]	H_2 S(2)[a]	H_2 S(1)[a]	H_2 S(0)[a]	T (K)[b]	N_{H_2} [c]	M_{H_2} [d]	L(H_2)[e]
A	···	···	0.27	0.27	···	···	···	···
	···	···	···	···	···	···	···	···
B	0.22	0.31	0.39	0.18	···	···	···	···
	···	···	···	···	···	···	···	···
C	0.33	0.38	0.34	0.50±0.14	···	···	···	···
	···	···	···	0.604	···	···	···	···
D	0.39	0.38	0.27	0.20	···	···	···	···
	···	···	···	···	···	···	···	···
E	0.41	0.31	2.48±0.03	1.12±0.08	137	30.6	10.8	1.35
	···	···	0.335	0.340	···	···	···	···
F	1.85±0.10	1.17±0.21	4.24±0.32	0.88±0.12	280	5.8	0.92	3.11
	0.386	0.183	1.106	0.194	···	···	···	···
G	0.34	0.32	4.27±0.52	0.70±0.12	178	10.4	3.70	1.78
	0.355	···	1.285	0.233	···	···	···	···
Ring	3.37±0.34	1.57±0.18	14.5±0.6	5.70±0.69	236	3.1	4.45	7.46
	0.114	0.027	0.309	0.172	···	···	···	···
Nucleus	1.66±0.05	1.20	3.60±0.15	0.91	309	2.67	0.42	2.13
	0.022	···	0.030	···	···	···	···	···
Nucleus (high resolution)	···	2.72±0.28	5.94±0.36	0.87	330	1.58	0.60	3.98
	···	0.008	0.019	···	···	···	···	···

[a]Fluxes in units of 10^{-21} W cm^{-2}, and the equivalent widths, below the fluxes, are in μm. Fluxes without errors are upper limits.

[b]Temperatures based on the following slopes: S(0)-S(1) for knot E, S(0)-S(3) for knot F, S(0)-S(1) for knot G, and S(1)-S(3) for the nucleus

[c]Column densities in units of 10^{19} cm^{-2}

[d]Warm molecular gas mass in units of 10^7 $M_\odot$

[e]Luminosities in units of 10^{40} erg s^{-1}

Table 4.2 — PAH Fluxes[a](top row) and Equivalent Widths (bottom row) in the Main Knots

Knot	6.2 μm	7.7 μm	8.6 μm	11.3 μm	17 μm complex	11.3/7.7
B	1.186±0.395	1.717±0.466	0.574±0.396	0.567±0.256	0.146±0.103	0.33±0.33
	1.14	2.49	0.949	1.20	0.045	
C	0.878±0.229	1.952±0.641	0.371±0.236	0.627±0.128	···	0.32±0.26
	1.38	3.02	0.652	1.73	···	
D	0.640±0.359	1.397±0.819	···	0.446±0.392	···	0.32±0.32
	6.49	11.1		2.93		
E	2.083±0.814	5.824±2.675	1.256±0.805	1.503±0.455	0.665±0.632	0.26±0.26
	4.42	9.03	1.72	1.74	0.756	
F	0.922±0.304	4.369±0.724	0.734±0.334	0.972±0.184	0.635±0.228	0.22±0.10
	2.93	9.08	1.26	1.51	1.17	
G	0.683±0.580	3.98±1.449	0.724±0.416	0.697±0.631	···	0.18±0.18
	7.89	20.7	1.46	1.25		
Nucleus	22.65±0.441	89.52±0.865	13.39±0.406	15.93±0.312	7.346±0.353	0.18±0.00
	3.04	14.8	2.12	1.87	0.595	
Ring	1.14±0.36	4.23±1.62	0.74±0.34	1.04±0.18	0.89±0.31	
	1.87	7.97	1.38	1.60	0.94	

[a]Fluxes in units of 10^{-20} W cm^{-2}

Table 4.3 — Ionic Line Fluxes[a] and Ratios of the Main Knots

Knot	[SIV]	[NeII]	[NeIII]	[SIII]18μm	[SIII]33μm	[SiII]	[NeIII]/[NeII]	[SIII]18.7μm/[SIII]33.5μm	[SiII]/[SIII]
A	⋯	⋯	0.53	⋯	0.99±0.09	0.87±0.05	⋯	⋯	0.87±0.15
B	0.24	⋯	0.29	0.43	0.59±0.10	1.16±0.06	⋯	⋯	1.97±0.51
C	0.36	⋯	0.33	0.36	0.43±0.12	0.87±0.11	⋯	⋯	1.14±0.90
E	0.90±0.04	2.25±0.09	1.16±0.04	1.24±0.27	2.48±0.29	2.88±0.16	0.52±0.04	0.50±0.19	1.16±0.23
F	0.34±0.02	0.92±0.05	0.62±0.06	0.85±0.19	1.70±0.22	1.64±0.08	0.67±0.11	0.50±0.20	0.96±0.20
G	0.84	0.84	0.90	1.85±0.35	1.38±0.21	2.05±0.25	⋯	1.34±0.63	1.49±0.48
Nucleus	0.06	30.8±1.36	2.54±0.08	8.71±0.25	14.2±1.2	14.56±1.60	0.08±0.01	0.61±0.08	0.82±0.22
Nucleus (high resolution)	⋯	63.6±1.6	5.17±0.60	20.7±0.8	28.4±5.3	31.9±1.6	0.08±0.01	0.73±0.20	1.12±0.21
Ring	1.12±0.14	3.29±0.38	0.99	5.21±0.89	10.0±1.12	8.10±0.68	⋯	0.64±0.15	0.81±0.14

[a] Fluxes in units of 10^{-21} Wcm^{-2}. Fluxes without uncertainties are upper limits.

Table 4.4 — Broadband Fluxes of the Main Knots[a]

Knot	R.A. (7 46)	Decl. (+39)	FUV	NUV	B	V	R	K	3.6 μm	4.5 μm	5.8 μm	8.0 μm	24 μm[b]
A	58.21s	$00'51''.24$	0.257±0.005	0.311±0.019	0.504±0.032	0.544±0.035	0.587±0.031	0.761±0.03	0.400±0.172	0.257±0.186	0.878±0.447	1.97±0.74	4.87±1.41
B	55.38s	$00'25''.75$	0.171±0.003	0.231±0.012	3.17±0.07	3.62±0.08	4.00±0.08	6.18±0.06	2.74±0.32	1.73±0.29	2.03±0.43	2.69±0.65	2.62±0.81
C	54.22s	$00'21''.25$	0.093±0.002	0.113±0.008	0.323±0.026	0.360±0.029	0.444±0.028	0.644±0.02	0.501±0.274	0.308±0.139	1.14±0.32	2.71±0.54	2.06±0.65
D	53.32s	$00'18''.25$	0.197±0.003	0.208±0.013	0.632±0.040	0.755±0.041	0.916±0.043	1.25±0.03	0.587±0.200	0.276±0.173	0.604±0.368	0.645±0.597	1.62±0.68
E	52.94s	$00'51''.25$	0.348±0.005	0.409±0.019	0.754±0.050	0.895±0.042	1.08±0.04	1.39±0.04	0.998±0.246	0.647±0.337	2.78±0.51	6.51±0.84	10.1±1.4
F	53.97s	$01'06''.25$	0.069±0.002	0.077±0.007	0.120±0.010	0.143±0.012	0.173±0.020	0.309±0.02	0.318±0.142	0.193±0.122	1.10±0.32	2.91±0.55	7.50±0.75
G	54.22s	$01'18''.25$	0.167±0.004	0.224±0.018	0.636±0.047	0.808±0.040	0.908±0.037	1.25±0.03	0.560±0.245	0.335±0.129	0.484±0.279	0.841±0.719	5.47±1.42
Nucleus	55.12s	$00'55''.75$	0.049±0.005	0.132±0.025	1.41±0.053	2.48±0.064	3.85±0.073	16.5±0.1	10.7±0.6	7.69±0.52	29.5±1.0	87.6±1.8	173±7.14

[a] Fluxes in units of mJy

[b] Errors represent 1σ deviations from the median flux between 22-28 μm.

Table 4.5 — Properties of Knots Derived from Starburst99 with Best Fit (Upper Row) and 95 % Confidence Level (Bottom Row)

Knot	Age (Myr)	A_V	Mass (10^6 $M_\odot$)
A	3.5	1.0	12.6
	2-4	0.8-1.2	10-15.8
C	3.5	1.5	12.6
	1-5.5	1.1-1.9	7.9-15.8
D	7.5	0.5	12.6
	6.5-8.5	0.4-0.6	10-15.8
E	3.5	1.2	25.1
	3.5-5	1.1-1.4	20-25.1
F	2.5	1.3	6.3
	0.5-6.5	0.8-1.8	4.0-10
G	7.5	0.8	20.0
	6.5-8.5	0.5-1.0	10-15.8
Nucleus (ISF)	16	3.0	1122
	15-16	2.6-3.4	1120-1260
Nucleus (CSF)	500	2.7	6.3
	400-800	2.2-3.1	5-7.9

Table 4.6 — Star Formation Rates of the Main Knots

Knot	L(FUV)[a]	L(H_α)[a]	L(24μm)[a]	F(15μm)[b]	F(30μm)[b]	SFR(FUV)[d]	SFR(H_α)[c]	SFR(H_α+24μm)[c]	SFR(F(15)+F(30))[c]
A	1.63±0.10	14.3±0.2	237±11	2.8±1.3	6.7±1.0	1.76±0.06	0.11±0.02	0.11±0.01	0.05
B	···	8.97±1.83	127±6	1.9±0.7	4.0±0.7		0.07±0.02	0.07±0.01	0.03
C	1.87±0.04	16.7±2.5	107±5	1.5±0.4	2.7±0.7	2.02±0.04	0.13±0.02	0.11±0.01	0.02
D	0.390±0.006	···	···	1.1±0.1	1.6±0.1	0.419±0.06	···	···	0.012
E	3.49±0.05	45.2±4.1	491±10	4.4±1.1	15.0±1.6	3.77±0.05	0.36±0.03	0.32±0.02	0.10
F	0.880±0.025	27.6±3.2	365±9	3.5±0.9	15.0±0.8	0.951±0.027	0.22±0.02	0.21±0.01	0.10
G	0.421±0.010	12.8±2.2	267±10	2.6±1.9	5.6±1.2	0.463±0.011	0.10±0.02	0.11±0.01	0.04
Nucleus	6.04±0.62	67.9±4.96	8420±363	62.9±1.8	274.9±4.8	6.53±0.67	0.54±0.04	1.46±0.27	1.63

[a] Luminosities in units of 10^{28} erg s^{-1}Hz

[b] Luminosities in units of 10^{39} erg s^{-1}

[c] Fluxes in mJy

[d] Star formation rates in $M_\odot$ yr^{-1}

Chapter 5

Simple models for the SEDs of Star Forming Galaxies

We model the infrared SEDs of a sample of 126 star forming galaxies with modified blackbody (MBB) models in order to explore the possibilities of reducing the necessary fitting parameter space in the models. We also investigate how this parameter space can be used to characterize dust in star forming galaxies. By comparing the parameter space of a single MBB to the galaxy color-color plots we find that the infrared SED is too broad to be modeled by a single MBB for 50% of the sample. This indicates that at least one additional dust component is required to model the infrared peak. Modeling each galaxy with a two MBB components, we conclude that the SEDs can be adequately described with fixed emissivities for both components ($\beta = 2$), leaving free the temperatures of the cold and warm components, T_c and T_w, and the scaling parameters of the cold and warm components N_c and N_w. Six galaxies were found exhibiting a submillimeter flux excess which require a very cold second MBB, with $T_c < 14$ K, and two of these, NGC 1614 and NGC 3310, have $T_c < 10$ K. Four of the excess galaxies are merger systems. We argue that the excess emission is a possible consequence of the merging process, of which NGC 1614 can be seen as an extreme example. We estimate the mass fraction between the cold dust and warm dust components as $M_c/M_w \sim 50$, which is very similar to the ratio derived from the two MBB model for NGC 1614, $N_c/N_w = 55$. However, the excess emission in NGC 3310 is better explained by the emission of Very Small Grains in the submillimeter. However, despite the excess galaxies having a high mass fraction of very Small Grains (VSGs) on average, a high VSG mass fraction is not a sufficient explanation for submillimeter excess.

5.1 Introduction

Active star-forming galaxies are usually rich in gas and dust. This means that a large fraction of the ultraviolet and optical light emitted by the massive stars is absorbed by the surrounding dust grains, and re-emitted in the mid- to far-infrared wavelength range. The intensity of the re-emitted radiation and its distribution over the infrared wavelength range, the infrared spectral energy distribution (SED), is a good tool to study the magnitude of a starburst and the properties of the dust population in a galaxy quantitatively. Model infrared SEDs can be constructed either from first principles and then adjusted to fit the observations, or derived more empirically, or from a combination of these two methods.

Until the mid 1990s, almost all relevant work was based on observations with the *Infrared Astronomical Satellite (IRAS)*. The limited IRAS measurements (four bands only and no wavelength coverage beyond $\lambda = 100\mu$m) made the application of models more complicated than a single-component isothermal model difficult, as all data points lie on the Wien side of a blackbody. The IRAS 12μm, 25μm, 60μm, and 100μm fluxes were extrapolated to provide total (3-1100μm) infrared fluxes (**?**), and the IRAS 60μm/100μm flux density ratio - the [60-100] infrared color - was used to quantify the dust temperatures. However, the advent of the *Infrared Space Observatory (ISO)* and the *Spitzer Space Telescope* MIPS and IRAC instruments, in addition to those provided by IRAS, increased the wavelength range covered, and made clear that modeling the dust SEDs of galaxies requires at least a two-temperature model. With the advent of long-wavelength bolometer arrays, such as the Submillimetre Common-User Bolometer Array SCUBA (**?**) on the James Clerk Maxwell Telescope it became feasible to extend the wavelength coverage even further, up to $\lambda \approx 1$ mm, even though the crucial wavelength range of 200μm-400μm is often poorly sampled.

The large majority of the SEDs of distant ULIRGs and sub-millimeter galaxies, which are responsible for most of the star formation history in the Universe (**?**), include only the four IRAS bands and the 850μm SCUBA band. This creates a need to model the SEDs of these galaxies with as few free parameters as possible. Many recent studies employ a simple superposition of modified blackbody (MBB) curves at different temperatures to model the different dust populations in the interstellar medium (see Section **??** for a description). This method has its limitations, as it is only applicable at wavelengths $\lambda > 25\mu$m. Although full dust modeling would be preferable, fitting SEDs with MBBs has the advantage of requiring only a few parameters and still providing good general insight in the properties of star forming galaxies. This is well-illustrated by the work of Dunne et al. (9) and James et al. (17) who took this approach in their study of the FIR/submillimeter SEDs of galaxies that were included in the SCUBA Local Universe Galaxy Survey (SLUGS). However, although each MBB has only three free parameters, fitting two MBBs simultaneously already requires determination of six free parameters. On SEDs with only IRAS+SCUBA observations at $\lambda > 25\mu$m, this makes any two-MBB fit uncertain and degenerate. One needs to formulate a simple model with as few parameters as possible in order to fit the SEDs of these galaxies.

Our goal for this work is to explore the possibilities of reducing the necessary fitting parameter space in order to find a simple description of the SEDs of these galaxies. We will also explore how the parameter space can be used to characterize dust in star forming galaxies. In the following, we will use the measured flux densities of star forming spiral galaxies and merger systems at wavelengths between $12 - 1300\mu$m obtained from the literature.

5.2 Galaxy Sample and SEDs

We have collected a sample of 126 relatively nearby (< 150 Mpc) star-forming galaxies which have publicly available 850 μm measurements from SCUBA. We consider only galaxies completely covered spatially. These are either smaller than the $2.3'$ SCUBA field-of-view (FOV), or were observed in mapping mode. We did not include galax-

Table 5.1. Distribution of the sample among the groups

Groups	Data points	Number
A	> 15	8
B	9-15	42
C	< 9	76

ies for which only upper limits could be estimated, or those interacting systems in which the emission is not dominated by a single member. Fully mapped large galaxies such as NGC 253, M82, M51, M83, and NGC 6946, exceed the SCUBA FOV and are useful to study aperture effects. The galaxies obeying these criteria were selected from the SCUBA Local Universe Galaxy Survey (SLUGS) (8; 9; 17; 10; 18), the Spitzer Near Infrared Nearby Galaxies Survey (SINGS) (**?**) and other MIPS samples (96**?**), the interacting galaxy sample by **?**), and we added a number of individually studied galaxies (7; 35**? ? ?**). All galaxies have IRAS measurements, so that each SED has at least 5 data points between $12 - 1300\mu$m. Wherever possible, we added to these data other available flux densities (notably from the Kuiper Airborne Observatory (KAO), Spitzer-MIPS, ISOPHOT, ISO-LWS and various bolometer arrays) in the 12μm–1300μm wavelength range. Table 5.2 summarizes the literature used, along with the instruments and collecting areas used for measuring flux-densities.

The data collected from the literature were taken with various aperture sizes and footprints. IRAS and MIPS data very often cover the whole galaxy, i.e. with an aperture or field-of-view larger than the major axis of the galaxy. However, ISO and single-pixel millimeter observations often covered substantially smaller fields of view. As a consequence, some data points may fall significantly below fitted curves defined by the other data points. For example, the ISO-LWS 170 μm and ISOPHOT 170 μm flux densities can be much lower than the Spitzer-MIPS 160 μm flux density. In these cases we chose the MIPS result, and ignore the ISO data, especially if the optical size of the galaxy appears to exceed the ISO-LWS or ISOCAM apertures.

We also determined area-integrated flux-densities from unpublished MIPS data of several bright galaxies (NGC 660, NGC 891, NGC 4388, NGC 4402, NGC 4501, NGC 5104, NGC 5907, NGC 6052, NGC 7591, and UGC 2369). The post-BCD data were retrieved from the Spitzer Science Center database, and aperture photometry was performed using the IDL tool *aper*. We chose circular apertures wide enough to include extended emission from the galaxies, defined as the emission with flux at least 3σ above the background level. The background was measured using an aperture of equal diameter in a position at least 2 arcmin off the galaxy for the 24μm band, $6'$ for the 70μm band, and $7'$ for the 160μm band. The circular apertures were sufficiently wide not to need aperture corrections. In Table **??** we list most of the flux densities considered in this study for each galaxy.

We divided the sample galaxies into three groups, A, B, and C, according to the number of independent datapoints between $12 - 1300\mu$m, (see Table **??**). We first concentrated mainly on the relatively well-sampled groups A and B. One has to note that all the SEDs containing previously unpublished MIPS data are in group B. Table 5.3 lists the names and properties of all the galaxies included in groups A and B.

Table 5.2. Instruments, wavelengths, and references for SED data

Instrument	Wavelength (μm)	FOV	References
IRAS	12, 25, 60, 100		Sanders et al. (11)
ISOCAM	15, 25	52″	Klaas et al. (12)
MIPS	24, 70, 160		? ?),this work
ISOPHOT	60, 80	46″ × 46″	Spinoglio et al. (13)
	100, 105	84″ × 84″	Spinoglio et al. (13)
	120, 150, 170, 180, 200	184″ × 184″	Spinoglio et al. (13)
ISO-LWS	52, 58, 63, 88, 122, 145, 158, 170	75″ × 75″	?)
KAO	160, 360	50″	Stark et al. (14)
CSO/SHARCII	350	···	Yan et al. (15)
SCUBA	450	138″	Dale et al. (16); Dunne et al. (8), Dunne et al. (9); James et al. (17), Stevens et al. (10); Vlahakis et al. (18?), ? ?)
	850	138″	Dale et al. (16); Dunne et al. (8), Dunne et al. (9); James et al. (17), ? Stevens et al. (10), Vlahakis et al. (18?)
LABOCA	870		Weiss et al. (20)
JCMT	850, 1100	18.5″	Chini et al. (25)
NRAO	1300	33″	Thronson et al. (22)
CSO	1250	30″	Carico et al. (23)
SEST	1300	70″	Chini et al. (25)
IRAM	1200	44″	?)
	1300	18″	Krugel et al. (27)
IRTF	1300	90″	Chini et al. (28)

The SCUBA images for the galaxies NGC 660, NGC 2903, NGC 3310, NGC 3628, NGC 4414, NGC 4631 (10) are composed of many "jiggle maps" of 138″FOV each slightly offset from each other.

In constructing the SEDs, we took care to eliminate as much as possible systematic effects caused by different aperture sizes. However, other systematic effects seem to affect the SED fitting. For instance, there are MIPS 70μm flux densities systematically below IRAS 60μm flux densities, for all galaxies in group A (NGC 1482, NGC 1614, NGC 4418, NGC 7714) where it was measured by **? ?**). The 160μm flux does not appear to be systematically low, nor do the MIPS flux densities of group B galaxies.

5.3 Analysis

5.3.1 Colors

Color-color plots using infrared fluxes are useful as a first study of the SED shapes in our sample. They have been commonly used to diagnose the properties of galaxies such as morphological types and the main source of dust heating (AGN or HII regions). The most widely used infrared color-color diagrams use IRAS flux ratios such as $F_\nu(60)/F_\nu(100)$, which is thought to measure the overall thermal dust temperature and the star formation rate density. In Fig. **??** we plot several flux ratios as functions of $F_\nu(60)/F_\nu(100)$: $F_\nu(100)/F_\nu(850)$ (upper), $F_\nu(100)/F_\nu(160)$ (middle), and $F_\nu(450)/F_\nu(850)$ (lower). In the upper plot, the range of IRAS fluxes is $0.2 < F_\nu(60)/F_\nu(100) < 1.2$ and $20 < F_\nu(100)/F_\nu(850) < 300$. Although there is a wide dispersion, both flux ratios clearly correlate with each other. This can be associated with the shift of the SED peak to shorter wavelengths as the average temperature increases, as the luminosity increases (**?**). Group A galaxies also appear to be distributed differently from the rest of the sample. Group A galaxies have $F_\nu(60)/F_\nu(100) > 0.6$, indicating

Table 5.3 — Group A and B galaxy samples

Galaxies	Type	D	12+log([O/H])	M(H_2)	M_{HI}	L(1.49 GHz)	L(IR)	Area
		Mpc		10^9 $M_\odot$	10^9 $M_\odot$	10^{22}W Hz^{-1}	$10^{10}L_\odot$	kpc^2
				Group A				
Arp220	Merger/HII	79.9	· · ·	62.3	4.6	25.6	162	972.3
NGC 520	Merger/HII	27.8	8.69	8.73	4.53	1.66	6.89	1040.0
NGC 1482	SA0/HII	19.6	· · ·	3.19	0.52	1.02	3.85	160.6
NGC 1614	Sbc/Sy2 HII	62.6	8.69	10.4	2.80	5.62	39.8	474.1
NGC 3690	Merger/HII	42.0	8.8	23.9	5.89	14.7	58.8	1255.2
NGC 4418	SABa/Sy2	31.9	· · ·	2.19	0.676	0.51	12.0	76.9
NGC 6240	I0/LINER Sy2	95	· · ·	32.2	8.19	66.1	59.2	1763.9
NGC 7714	SBb/HII	36.9	8.26	3.87	10.7	0.14	4.90	326.7
				Group B				
IC 1623	Merger	78.6	· · ·	34.5	4.79	1.46	44.7	1176.1
M51	Sabc	7.6	8.63	9.55	5.25	1.55	2.63	310.9
Mrk 231	Sac/Sy1	171.8	· · ·	11.5	1.6	128.8	224	3246.5
Mrk 273	Merger/Sy2	154.7	· · ·	36	57.5	0.95	138.0	583.2
Mrk 331	S?/HII/LINER/Sy2	70.5	8.76	17	9.12	4.37	25.7	117.8
NGC 253	Sabc/HII/Sy2	3.3	· · ·	2.51	4.57	7.32	2.75	547.3
NGC 660	SBa/HII/LINER	11.8	· · ·	3.57	7.39	0.65	2.83	637.4
NGC 695	S0?/HII	126.7	· · ·	21.0	21.9	15.1	42.7	682.7
NGC 891	Sab/HII	9.9	· · ·	8.13	3.91	0.82	2.46	1187.0
NGC 1222	S0/HII	31.0	8.57	1.02	1.55	0.64	3.69	77.3
NGC 1667	SABc/Sy2	60.5	· · ·	4.17	5.62	2.13	9.12	788.1
NGC 2903	SBd/HII	8.9	8.68	1.98	4.38	0.37	1.80	835.7
NGC 2976	SAc/HII	3.6	· · ·	0.083	0.182	0.009	0.063	30.0
NGC 3079	SBc/LINER	17.6	8.57	6.45	7.99	5.01	5.02	1328.9
NGC 3310	SABbc/HII	17.5	8.18	0.41	4.26	1.91	3.18	195.6
NGC3583	SBb	31.6	· · ·	3.83	2.78	1.0	2.81	613.3
NGC3627	SAB(s)b/LINER	10.1	9.25	4.45	1.52	0.27	5.21	1036.3
NGC3628	SAb/HII/LINER	7.7	8.57	1.07	2.80	5.50	1.05	863.0
NGC4254	SAc	16.8	· · ·	9.3	5.14	0.95	4.18	546.9
NGC4388	SAb Sy2	16.8	· · ·	2.85	1.41	0.90	1.21	439.4
NGC4402	SB	15.3	· · ·	6.32	1.55	0.06	0.452	236.6
NGC4414	SAc/HII/LINER	17.7	9.2	2.70	1.32	0.69	3.63	269.8
NGC4501	SAb/HII/Sy2	10.5	· · ·	2.69	2.71	0.63	1.01	348.8
NGC4532	IBm/HII	15.5	· · ·	0.13	2.47	0.28	0.617	55.5
NGC4631	SBd	7.6	· · ·	0.99	6.98	2.88	1.66	922.2
NGC4736	SAab/LINER Sy2	4.7	· · ·	2.0	1.49	0.078	0.560	184.1
NGC4826	SAab/HII/Sy2	7.5	· · ·	1.35	0.550	0.019	0.707	373.8
NGC4922	I0/LINER/Sy2	147.0	· · ·	0.245	1.40	5.75	20.9	2802.0
NGC5104	Sa/LIRG/LINER	82.4	· · ·	· · ·	3.56	3.89	15.8	859.3
NGC5433	Sdm/HII	65.3	· · ·	0.18	3.32	3.80	6.76	725.4
NGC5713	SABbc/HII	18.3	· · ·	3.0	3.37	1.86	2.46	174.5
NGC5907	SAc/HII	14.9	· · ·	3.02	11.5	0.25	0.959	2405.8
NGC5953	SAa/LINER/Sy2	33.0	8.73	1.58	1.07	1.07	5.25	185.3
NGC5962	SAc/HII	31.8	· · ·	0.11	5.0	1.17	3.55	471.4
NGC6052	Merger	70.4	8.65	0.21	4.90	5.50	10.5	339.7
NGC6090	Sd/HII	122.6	· · ·	14.1	· · ·	8.71	32.4	3675.4
NGC6946	SABcd/Sy2	6.8	9.06	6.26	9.47	0.54	2.37	406.4
NGC7331	SAb/LINER	14.4	9.1	7.81	8.66	0.89	3.64	1519.2
NGC7469	SABa/Sy1.2	65.2	8.80	9.12	8.18	11.0	38.9	635.6
NGC7591	SBbc/Sy	62.3	· · ·	17.0	21.4	31.6	10.1	931.1
NGC7674	SAbc/HII/Sy2	113.6	8.31	11.2	10.7	42.7	31.6	1037.7
NGC7679	SB0/HII/Sy1	67.7	· · ·	21.4	31.6	3.63	11.2	514.7
NGC7771	Sba/HII	57.1	· · ·	8.46	2.18	6.31	21.9	1354.2
UGC2369	Merger	121.9	· · ·	42.2	3.08	9.55	39.8	1257.2

Distances from the following methods: Tip of RGB (**? ? ? ? ? ?**), Sosies (**?**), planetary nebula luminosity function (**?**), Cepheids (**? ? ?**), Tully-Fisher. M(H_2) and M(HI) from S(CO) and S(HI) measurements in Young et al. (29); Sanders et al. (30**? ?**); Kasparova & Zasov (31**?**), assuming $X_{CO} = 2.8 \times 10^{20}$ K km/s/cm^2; radio luminosities (1.49 GHz) calculated from **? ? ?**); metallicities from James et al. (17**?**); infrared luminosities from IRAS broadband fluxes in Sanders et al. (11) following $L_{IR} = 312,700D^2 1.8(13.48S12\mu m + 5.16S25\mu m + 2.58S60\mu m + S100\mu m)$ where S_λ is in Jy; Areas calculated from the angular lengths of the major and minor diameters from NED. Metallicities, M(H_2), M(HI), radio luminosities and areas are listed for reference only.

that these are galaxies with higher average dust temperature. This could be a selection effect, as the galaxies with more datapoints, and therefore better observed, tend to be the most luminous and heat the dust at higher temperatures. Outlying is NGC 5371 ($F_\nu(100)/F_\nu(850)$ ~130), a normal spiral galaxy, and NGC 4418 ($F_\nu(60)/F_\nu(100)$ ~1.25), a spiral galaxy with very obscured star formation.

In order to investigate how the 60/100 and 100/850 ratios vary with the SED shape, a grid from a single MBB model is overlayed on Fig. **??**. The parameters vary between $1.0 \leq \beta \leq 2$ and $25 < T < 50$, which is the range of parameters encountered on the single MBB fits on the SLUGS sample (8). About 50% of all galaxies in the sample are between $30 < T < 35$. The fit to the data follows the temperature gradient with only a small deviation, which means that the ratio between the 100/850 colors and the 60/100 colors depend strongly on dust temperature. However, β accounts for the wide dispersion seen on $F_\nu(100)/F_\nu(850) \sim$. Special cases are the galaxies with $F_\nu(100)/F_\nu(850) < 30$, M51, NGC 4631, and NGC 5907. These are located below the grid including error bars. Such low values of $F_\nu(100)/F_\nu(850)$ indicate that the 100μm datapoint is located far from the infrared SED peak in these galaxies. The main problem with this diagram is that the 60/100 colors describe only the Wien side of the MBB, and therefore other datapoint between 100μm and 350μm is needed to describe the infrared peak. It is also clear that $\beta = 2$ is too high to model adequately the SEDs with only one component, as the MBB needs to be shallow enough to fit both the infrared peak and the SCUBA band fluxes.

Color-color plots involving $F_\nu(160)$ provide a better description of the SED shape because, for many galaxies, the infrared peak is between $100 - 200\mu$m. In Fig. **??** (middle) we show the flux ratio $F_\nu(100)/F_\nu(160)$ as a function of the $F_\nu(60)/F_\nu(100)$ ratio, only for groups A and B. When the MIPS 160μm is not available, the 160μm datapoint is an average of the ISOPHOT band flux between the $150 - 170\mu$m. As expected, the $F_\nu(100)/F_\nu(160) \sim$ ratio increases with increasing $F_\nu(60)/F_\nu(100)$ ratio, but a wide dispersion is observed, not all accounted by errors in $F_\nu(100)/F_\nu(160)$. We also overplot the same grid of parameters as in the upper plot, but now $F_\nu(100)/F_\nu(160)$ has only a weak dependence on β.

Although the error bars account for most of the dispersion, 90% of the galaxies in Fig. **??** lie below the modeled F(100)/F(160) values. The SEDs that are modeled with a single MBB can only only be located in narrow range of F(100)/F(160) values. The galaxies that have a low F(100)/F(160) indicate that Fν(160) is too high for a given F(60)/F(100), which means that the infrared peak is too broad to be modeled by a single MBB. This would suggest that at least an additional dust component is required to model the infrared peak. This was not revealed in the upper plot, as the 850μm data points can be well fitted by a single MBB, whereas the same model cannot fit $F_\nu(160)$. Some of these galaxies (M51, NGC 253, NGC 6946, NGC 7331) exhibit 160μm MIPS flux excess, probably due to flux non-linearities in the MIPS detectors (**?**). These non-linearities are caused by objects brighter than 40 Jy, and represent the differences in the flux conversion as a function of source flux, provoking an overestimation of the photometric measurements. A non-linearity correction recipe currently exists only for the 70μm band (**?**) but a procedure for correction for the 160μm MIPS band is still in development. We include the 160μm MIPS fluxes for these galaxies in the color-color plots.

Figure 5.1 — Flux ratios $F_\nu(100)/F_\nu(850) \sim$ (upper), $F_\nu(100)/F_\nu(160)$ (middle), $F_\nu(450)/F_\nu(850)$ (lower) as a function of $F_\nu(60)/F_\nu(100)$ for all the relevant galaxies in the sample. Overlayed are single MBB model grids for $25 < T < 50$ K and $1.0 \leq \beta \leq 2.0$. Triangles are group A galaxies, diamonds are group B galaxies, and asterisks are group C galaxies.

The two SCUBA bands, 450μm, and 850μm are emitted by the coldest dust existing in the ISM of the galaxies in the sample. By studying their ratio one can study the temperature of this cold dust. In Fig. **??** (lower) we show a color-color plot of $F_\nu(450)/F_\nu(850)$ as a function of $F_\nu(60)/F_\nu(100)$. Overlayed is the grid of model parameters now applied to $F_\nu(450)/F_\nu(850)$. No correlation is seen with $F_\nu(60)/F_\nu(100)$. Most galaxies ($\sim 75\%$) are between $5 < F_\nu(450)/F_\nu(850) < 8$, which accounting for the error bars, is predicted by the range of single MBB parameters. One needs to bear in mind that 450μm SCUBA calibration have often been reported as unreliable. Therefore some of the $F_\nu(450)/F_\nu(850)$ ratios could be underestimated.

Although with clear limitations on fitting the infrared peak, a simple model of the dust emission will help to relate the flux ratios with physical properties such as dust temperatures. However, to explain the wide dispersion in the correlations, and the conditions of dust emission in the outlying galaxies, the single MBB model is not sufficient.

5.3.2 Dust SED Model Fits

Modified blackbody functions, as already referred to above, are useful to describe an SED using a minimum of parameters. Each function is a simple description of a particular homogeneous dust grain component characterized by a single temperature T, an emissivity parameter β, and a scaling factor N.

As reviewed by (36), large ('classical') dust grains of radius $\approx 0.1\,\mu$m will quickly reach an equilibrium temperature T when immersed in an interstellar radiation field. Under such circumstances, heating due to the absorption of short-wavelength (optical, ultraviolet) photons is balanced by cooling at long (mid- and far-infrared) wavelengths. The efficiency with which grains emit at any wavelength, including those in the (sub)millimeter region, depends on their composition and structure and is expressed by the emissivity Q (also called extinction efficiency), a dimensionless quantity which indicates how the flux density (F) recorded at wavelength λ compares with that emitted by a true blackbody:

$$F(\lambda) = n\sigma D^2 Q(\lambda) B(T_d, \lambda) \quad (5.1)$$

where D is the distance to a dust cloud containing n dust grains of geometrical cross section σ. B is the Planck function for a blackbody of temperature T_d.

In the infrared regime, the extinction efficiency of dust particles is often approximated by a simple power law:

$$Q_{FIR}(\lambda) \propto \lambda^{-\beta} \quad (5.2)$$

Table 5.4. Parameters derived from the single MBB model

Groups	β	Temperature (K)
A	1.25±0.20	42.1±4.9
B	1.35±0.35	34.5±6.1
C	1.34±0.32	33.2±4.8

for some index β that depends on the nature of the material. Theoretically, we expect β=2 for metals and crystalline dielectric substances such as big silicate grains and $\beta = 1$ for amorphous, carbonaceous grains (**?**).

With the advent of ISO and SCUBA data it appeared that the infrared SEDs of galaxies, even ultraluminous galaxies such as Arp 220 (9), are best fitted with at least two large dust grain components at different temperatures. Such models have the form:

$$F_\lambda = N_w \times \lambda^{-\beta_w} \times B(\lambda, T_w) + N_c \times \lambda^{-\beta_c} \times B(\lambda, T_c) \tag{5.3}$$

in which β_w and β_c are the emissivity indexes of the dust grains, $B(\lambda, T_w)$ and $B(\lambda, T_c)$ are the Planck functions of the two components, and N_w and N_c are scaling factors that represent the relative masses of the two components with temperatures T_w and T_c. The value of β_c determines the slope at the long-wavelength tail of the curve, and if $\beta_c = \beta_w$, N_c/N_w will represent the ratio between the mass of the cold component and the mass of the warm component.

5.3.3 Single dust-component fits

First, we attempted to fit the observed galaxy SEDs in the simplest way possible. For this purpose we investigated whether the long-wavelength emission can be modeled by a single MBB. Given that a single MBB model has 3 free parameters, we excluded all galaxies for which only three data points (60, 100, and 850μm) were left, leaving 80 galaxies. We fitted single MBB curves to all SEDs of groups A, B, and C, assuming that all emission from 25μm to 1300μm originates from a single population of dust grains in thermal equilibrium. All the parameters (N, β, T) are let free. We use the reduced χ^2 minimization method to determine the best fit to the data, and the fits to 50% (59 galaxies) resulted in reduced $\chi^2 > 2$. We also note that many of the ISOPHOT 180μm and 200μm flux densities published by Spinoglio et al. (13) fall below the modeled flux density curve, and therefore we excluded these datapoints as well. The results of the single MBB fits are illustrated by Fig. **??**.

Figure 5.2 — Distributions of temperatures and β values for a single MBB model of all galaxies in the sample.

In the histograms shown in Fig. **??**, the distributions of β values and temperatures follow a gaussian shape for all groups, and the mean values and σ dispersion are tabulated in Table **??**. The outlier in the temperature distribution is the galaxy NGC 4418 which was excluded from the calculation of the mean temperature for group A. There is little distinction in β values between the groups, indicating that the division between groups A, B, and C is not biased against physical characteristics of the grains. However, it is noticeable that the mean dust temperature of group A, 42.1±4.9 K, is quite higher than the mean dust temperatures derived for groups B and C, 34.3±6.1 K, and 33.2 ± 4.8 K respectively, which are quite similar. Only two galaxies in group A have dust temperatures below 40 K. This means that it can only be explained by an observational selection in favor of the brightest galaxies in group A. The plot in Fig. **??** shows this, with the dust temperature increasing with the infrared luminosity surface density. Because infrared luminosity is a tracer of star formation rate (3), this shows how the dust temperature increases with star formation rate density. The mean infrared luminosity density of group A is higher than groups B and C and this causes a higher mean temperature. There is an outlier from this relation, NGC 4418 (T=64 K), which corresponds to a $F_\nu(60)/F_\nu(100) = 1.25$, the highest of the sample. No correlation of the parameter β with luminosity was found.

In order to confirm if group A galaxies are part of a different distribution than groups B and C, we performed a simple two-sample Komolgorov-Smirnov test on the infrared luminosity distributions of groups A and B. The suspicions were confirmed, as the maximum deviation between the two distributions is $D = 0.54$. This means that only the parameters derived from group B should be applied to group C.

Figure 5.3 — Plot of temperatures as a function of surface luminosity density of all galaxies in the sample, using a single MBB model. The dashed line is a linear fit Triangles are group A galaxies, asterisks are group B galaxies, and squares are group C galaxies.

Notwithstanding the fact that some galaxies are well-fitted by a single MBB curve, the poor overall fit of $\sim 50\%$ of the sample and the unsatisfactory fit of the peak emission of many of the remaining galaxies renders the use of single MBB fits in general questionable. **?**) reported that the SEDs of the more luminous galaxies are well-modeled with just one MBB, whereas the SEDs of more quiescent galaxies require the use of a two-component MBB fit. We do not reproduce this trend in our sample, which means that many galaxies with higher star formation activity must also have a second component of diffuse cold dust.

5.3.4 Two dust components with free β

The advent of ISO and SCUBA data strengthened the notion that galaxy infrared SEDs should be fitted with at least two dust components with different temperatures (9). The models are described by Eqn. **??**, which includes six free parameters. This number could be diminished if one or more parameters are distributed according to a single gaussian centered on a mean value and with a width σ. If a parameter varies around its mean value with minimal dispersion, the mean can be used a fixed value with a minimum loss of accuracy of the fit.

We fit the individual SEDs in groups A and B with a function composed of the sum of two MBB curves, each with three free parameters, N, β, and T. We did not include any data points at wavelengths longer than 1000μm, as they might be contaminated by synchrotron emission, or free-free thermal emission from ionized gas. The 25μm data point is considered as an upper limit, and it was fitted only in the cases where the

Table 5.5. Parameters for the mean SEDs

Groups	β_w	β_c	T_w	T_c	N_c/N_w
A	1.52±0.19	1.55±0.21	51.5±9.7	26.3±9.4	10.2±10.0
B	1.58±0.60	2.16±0.94	51.0±18.4	23.4±8.2	30300±132155

warm component flux at 25μm exceeded the measured value. The model could not be run for 8 galaxies of group B, as they have fewer datapoints between $60 - 850\mu$m than the number of free parameters.

In Fig. **??** we plot the distributions of the warm and cold temperatures, T_w and T_c. The warm component temperature T_w distribution for group B spans from 20 K to 80 K for group B, with a peak at ~ 60 K. This is a consequence of the fact that 26 galaxies ($\sim 55\%$) in group B need the 25μm data point to constrain the warm component. The temperatures that result from fitting the warm component to the 25μm flux are upper limits. For group A, T_w is almost evenly distributed between 35 K and 65 K. The cold temperature T_c for group B, follows an broad gaussian-like symmetric distribution, whereas for group A, 50% of the galaxies have T_c between $25 - 30$ K. The mean temperature values are, for group A, $T_w = 51.5$ K and $T_c = 26.3$ K, and for group B, $T_w = 51.0$ K and $T_c = 23.4$ K.

Figure 5.4 — Distributions of T_w and T_c for groups A (solid) and B (dashed). The distributions are normalized to the number of galaxies in each group.

The resulting parameters are summarized in Table **??**. The average values of β_w and β_c for both groups are of the order of the range of values $1 < \beta < 2$ suggested by laboratory studies (**? ? ?**). For group A, both β values could be constrained to a mean value β 1.5 with σ deviations of the order of 13%. However, there is a large σ uncertainty in the order of 40% for the mean β value for group B, making them essentially unconstrained. The average temperature T_w is about the same for both groups, but with large uncertainties, reaching 30% in group B, whereas the average T_c is only 3 K higher for group A. The most noticeable difference between the groups exists in the N_c/N_w. Given the high dispersion, one cannot take any conclusions although the difference in the N_c/N_w ratio is consistent with the difference in IRAS 60/100 ratios: 0.83 for group A and 0.58 for group B.

Figure 5.5 — Distributions of β_w and β_c for groups A (solid) and B (dashed), with the 25μm included in the fits. The distributions are normalized to the number of galaxies in each group.

The distribution of β parameters is shown in Fig. **??**. Only about 50% of the β values for both groups lie between $1 < \beta < 2$, and the mean parameter values from the distributions are listed in Table **??**). The outlier with $\beta_c = 4.09$ is NGC 1482. The high mean value for β_c in group B is a consequence of the 10% of the galaxies with $\beta_c > 3$. Comparing with the single MBB models, there is an improvement on the reduced χ^2 for both groups, with 84% having reduced $\chi^2 < 2$ and a mean reduced $\chi^2 = 1.18$ for group A and $\chi^2 = 1.64$ for group B. However, the dispersion of reduced χ^2 values is as wide as in the single MBB models.

Figure 5.6 — Distribution of the reduced χ^2 using $\beta = 2$ (full line) and β free (dashed line).

The parameter values derived from the free parameter fits, with the given data quality, are insufficiently constrained by the observations for group B. In order to make progress, we must therefore make additional assumptions reducing the number of free parameters in the fits. The most promising appears to be a constraint on the emissivity β, as it was constrained for group A, because it is the parameter most directly associated with the emission properties of the dust, and physical studies of the grains might be used to derive the desired additional constraints.

5.3.5 Two dust components with fixed β

The first approach in reducing the parameter space would be to limit β into a range of physically meaningful values. COBE/FIRAS studies (**? ? ?**) find $\beta = 1.5 - 2$, with $\beta = 2$ giving the best fit for 2 MBB models. **?**) found $\beta = 2$ for several molecular clouds with dust temperatures ranging from 30-80 K. Estimates of β come from various sources: laboratory experiments, theoretical models, observations within the Milky Way, and observations of external galaxies. The standard theoretical study of dust properties is **?**). Calculating optical constants of a mixture of silicates and graphite, they found $\beta \sim 2$ between $40 - 1000\mu$m. Much smaller values of β were derived for amorphous carbon grains, but these grains are very small ($< 0.01\mu$m). The structure of the grains also influences β, and studies of fluffy or fractal grains found $0.6 < \beta < 1.5$ (**? ?**). However, **?**) found $\beta = 2$ for fluffy composites, with exception of very large grains ($> 30\mu$m) that are not representative of the dust population. Almost all observations of external galaxies find $1.5 < \beta < 2$, favouring $\beta = 2$ (**? ? ? 7? ?** ; 9**?**).

The grains that produce the warm and cold components are assumed to be of the same type, i. e. large silicate grains with size $> 0.01\mu$m. Therefore they should have similar infrared emission properties. For that reason we expect that β_c and β_w to be very similar, and it is perfectly reasonable to assume that $\beta_c = \beta_w$ throughout the sample. This is a further constrain on the parameters that could help us to determine the temperatures T_w and T_c. The favored value among galactic and extragalactic studies is $\beta = 2$, but β distributions revealed that $\beta = 1.5$ is adequate for both components of group A. We will therefore use either value and compare the resulting temperatures and reduced χ^2 in order to determine which is the most adequate.

5.3.5.1 T and N parameters

As in previous sections, we modeled the $60 - 1000\mu$m SED of each galaxy, assuming $1/\sigma^2$ weighting, σ^2 being the total uncertainty of the flux at each λ. We used two values for β: $\beta = 1.5$, and $\beta = 2$. As for the free parameter models, we left out the 180μm and 200μm measurements of (13) in all SEDs.

The reliability of the fits with $\beta = 1.5$ and $\beta = 2$ is quite similar, as 68% and 65% have reduced $\chi^2 < 2$ respectively. These are lower than the proportion for free β (84%), which is expected as there are now four free parameters instead of six. The χ^2 comparison favors slightly $\beta = 1.5$, but given the dispersion in χ^2 values, this difference is not significant. In Fig. **??** we compare the distribution of the reduced χ^2 between

Table 5.6. Parameters for SED models using $\beta = 1.5$ and $\beta = 2$

Groups	β	T_w	T_c	N_c/N_w
A	2	43.8±5.2	18.3±6	31.4±31.8
	1.5	52.5±17.5	30.8±7.63	25.7±32.8
B	2	42.5±11.2	19.0±5.5	162±227
	1.5	57.6±20.6	27.7±5.51	107.5±1360

$\beta = 2$ models and free β models. The reduced χ^2 values for $\beta = 2$ are comparable to the values for free β. We did not observe any correlations between the reduced χ^2 and the infrared luminosity, which means that there are no systematic errors arising from the model. Five galaxies have reduced $\chi^2 << 0.2$: two spiral galaxies (M51, NGC 891), and three mergers (IC 1623, NGC 6052, and UGC 2369).

The mean parameters calculated from the distributions are listed in Table **??**. The most noticeable difference between $\beta = 1.5$ and $\beta = 2$ is the shift of both T_w and T_c. For $\beta = 1.5$, T_w and T_c are on average 10 K and 12 K higher respectively than the values of the same parameters for $\beta = 2$. This is expected, as the shallower slope at the Rayleigh-Jeans side of the curves makes the warm component move to shorter wavelengths, fitting the 25μm datapoint. This is physically unrealistic, as dust in thermal equilibrium is not responsible for most of the flux at this wavelength. For this reason, and because $\beta = 2$ is the favored result by the literature, we will adopt this value for the rest of this study.

Figure 5.7 — Normalized distribution of T_w (upper plot) and T_c (lower plot) for groups A (dashed line) and B (solid line), assuming $\beta = 2$ for both components.

In Fig. **??** we present the distributions of the warm and cold component temperatures. There is a broad distribution of T_w values for group B, possibly a bimodal distribution. About 70 % of the group B SED have T_w distributed between $25 - 45$ K, whereas the remaining 30 % of the SEDs are distributed between $45 - 65$ K. From these plots, we can see that the cold component temperature is well constrained, the distribution has a defined peak and variation. The mean T_c is the same for groups A and B, showing that the cold dust has on average the same temperature for the galaxies in both groups, despite the differences in luminosity. The warm temperature component distribution is harder to interpret. There is a small percentage (30%) that required a fit to the 25μm flux, otherwise the modeled flux at 25μm would be far above the measured value. This means that many of the T_w values resulting from these fits could be in fact upper limits, as implies that the whole 25μm flux is emitted by grains in thermal equlibrium, which is not true in many cases. The warm component temperatures for group A are all from galaxies that do not need to be constrained by the 25μm flux. Therefore, they are to be compared to the T_w of the galaxies in group B that are not fitted to the 25μm datapoint, which is $T_w = 36.2 \pm 6.2$ K. This is more than 7 K below the mean T_w for group A, which indicates a warmer diffuse dust component in group A galaxies, as suggested earlier.

We can now fix one of the parameters in order to fit group C galaxies as well. As it was shown in § **??**, group C galaxies and group B galaxies have the same flux ratio distribution and likely represent the same range of properties. Therefore, we will use $T_c = 19$ K, determined from group B galaxies for all the fits to group C, with three free parameters remaining, T_w, N_w, and N_c. This allows us to model the 34 galaxies in group C that have more than three datapoints between $60 - 850\mu$m, which corresponds to 40% of group C galaxies. This results in mean reduced $\chi^2 = 1.87$, which in the same order of the reduced χ^2 achieved for the fits to groups A and B.

5.3.5.2 Model parameters and infrared colors

We investigated how the parameters derived from the two-MBB fits relate to the IRAS colors. We excluded group C galaxies from these studies. In the upper plot in Fig. **??** we plot T_w and T_w/T_c as a function of $F_\nu(60)/F_\nu(100)$, where we divide the sample between galaxies without the fit to the 25μm datapoint, and galaxies where the 25μm datapoint was fitted to constrain the warm component. There is a noticeable division between them, as it is clear that for the galaxies without the fit to the 25μm datapoint, T_w increases proportionally to $F_\nu(60)/F_\nu(100)$, which is expected. As for galaxies with fit to 25μm is an upper limit, the determined T_w is only an upper limit, so we expected these galaxies to be separated from the rest of the sample in this plot.

The tracks overlaying the plot were done using two MBB models, varying $0 < N_c/N_w < 1000$. We assumed $T_c = 19$ K, the mean T_w of group B. The tracks for $T_c = 15$ K and $T_w = 25$ K when $N_c/N_w = 0$ and $N_c/N_w = 1000$ are plotted for comparison. One sees how $F_\nu(60)/F_\nu(100)$ depends on the temperature of the warm component changes with the relative mass contributions of the cold and warm components. For $T_c = 19$ K, an increase in N_c/N_w by a factor of 100 create an increase in T_w by 15 K in galaxies without the 25μm fit. When $N_c/N_w = 0$ the SEDs are modeled with a single MBB, independently of T_c. It is important to note that N_c/N_w is higher for the galaxies with the fit to the 25μm datapoint due to the higher derived T_w, but because this is an upper limit, N_c/N_w is an upper limit for these galaxies as well.

Figure 5.8 — Plot of the parameters T_w (upper) and ratio T_w/T_c (lower) as a function of $F_\nu(60)/F_\nu(100)$ from the fits to the SEDs using $\beta = 2$. In the upper and lower plots, asterisks represent galaxies without the 25μ datapoint, and triangles represent galaxies with unconstrained warm component where the 25μm datapoint was fitted. Overplotted are parameter grids from a two MBB model, varying $0 \leq N_c/N_w \leq 1000$. For both plots, the different lines represent $T_c = 19$ K (full line), and $T_c = 25$ K (dot-dashed line). In the upper plot, dashed lines represent $T_c = 15$ K whereas in the lower plot, dashed lines represent $T_c = 5$ K and $T_c = 4$ K.

The parameter ratio T_w/T_c has an interesting interplay with the $F_\nu(60)/F_\nu(100)$ flux ratio, as seen in the upper plot in Fig. **??**. This is to be expected as this is the most sensitive ratio to the shift of the SED peak. There is a slight correlation between F(60)/F(100) the T_w/T_c ratio whereas the two galaxies with $T_w < 10$ K, NGC 1614 and NGC 3310, are outliers. The overplotted model tracks are from the same model used in the upper plot, where $0 < N_c/N_w < 1000$. This variation in the N_c/N_w parameter explains the dispersion in the datapoints, as for the same N_c/N_w, $F_\nu(60)/F_\nu(100)$ depends essentially on T_w, as T_c remains fixed at 19 K. When $T_w = T_c = 19$ K, all the N_c/N_w tracks converge to $T_w/T_c = 0.0823$. The case of a single MBB is $N_c/N_w = 0$, and below the track corresponding to this value there are no datapoints, which is an indication of how $T_c = 19$ K is an adequate T_c value for the model tracks.

5.3.5.3 Correlations among model parameters

In order to investigate the range of properties of the galaxies included in the sample, we first describe the sample in terms of the model parameters and their correlations. Fig. 5.4 (upper) shows a plot of T_c as a function of T_w. There is a possible correlation between these two parameters, due to the galaxies for which the warm component was forced to fit the 25μm datapoint, which makes most (but not all) of the galaxies with $T_w > 50$ K. If they are not taken in consideration, the correlation is less evident. About 90% of group C galaxies have $T_w < 40$ K, as the 25μm datapoint was used only as an upper limit for these galaxies. Two galaxies between $30 < T_w < 40$ K (NGC 1614 and NGC 3310) have $T_c < 10$ K, meaning that the SED peak between $60 - 200\mu$m is close to be modeled by a single MBB, but at $\lambda > 200\mu$m the flux requires a second, very cold MBB. The other 5 galaxies offset from the correlation are Mrk 231, Mrk 273, NGC 4418, NGC 4922, and NGC 5907. All have $T_c < 14$ K, with the SED between $60 - 200\mu$m modeled by a single MBB, and a very cold component modeling a flux excess at 850μm. However, NGC 5907 also has a cool warm component, with $T_w < 30$ K.

Figure 5.9 — Upper: Plot of T_w as a function of T_c. Triangles are group A and asterisks are group B galaxies. Squares represent the galaxies with a fit to the 25μm datapoint. The dashed line represents a linear fit to the data. Lower: Plot of the parameter ratio N_c/N_w as a function of T_w/T_c, with an increase of 20% in the 850μm flux with the arrows representing the evolution of the ratios. Asterisks represent galaxies without an AGN, and triangles represent galaxies with an AGN. The dashed line represents a linear fit to the data using the least absolute deviation method. Arrows represent the evolution of the parameters when the 850μm is increased by 20% for all galaxies, and decreased by 20% for the outliers.

The lower plot of Fig. 5.4 shows the ratio between the temperatures T_w/T_c as a function of ratio between the scaling factors N_c/N_w. We only used group A and B galaxies for these plots as T_c is fixed for group C galaxies. The sample is divided between galaxies that have an active nucleus (AGN), and those with HII regions as the only source of dust heating. This presents an overall picture of how the four parameters vary together. Most galaxies have $1.5 < T_w/T_c < 2.5$ with N_c/N_w stretching through two orders of magnitude. The ratio T_w/T_c increases slightly with N_c/N_w which indicates that the correlation between T_w and T_c (upper plot) is not linear, but depends on N_c/N_w. There are 6 galaxies that are offset from the correlation in this plot. These galaxies are Mrk 231, Mrk 273, NGC 1614, NGC 3310, NGC 4418, and NGC 4922. The two galaxies with $T_w < 10$ K, NGC 1614, NGC 3310 have $T_w/T_c > 5$. We call these galaxies "excess galaxies", as their low T_c and high T_w/T_c arise from a flux excess at $\lambda > 350\mu$m, which is modeled by a very cold MBB. The galaxies NGC 5907 and NGC 7331 are both in the correlation along with the other galaxies and cannot be considered as part of this group. All galaxies with $T_w > 50$ K have $N_c/N_w > 100$, meaning that the fit to the 25μm datapoint confirms the correlation between T_w and T_c, but it is not the sole responsible factor.

One has to be sure of the robustness of the values determined from the MBB models. This means that T_w and T_c, for example, would not change significantly if the 850μm flux varies within the flux uncertainty. The arrows show how T_w and T_c evolve if the 850μm is increased by 20%, which is the uncertainty assumed for all the 850μm fluxes. Shown only for the outlying galaxies are the arrows corresponding to a decrease of the 850μm flux by 20%. When increasing the 850μm fluxes by 20%, T_w and T_c decrease on average by 2 K and 1.2 K, respectively. In the lower plot, for the galaxies that lie on the correlation, N_c/N_w decreases on average by 10%. Those with $T_c/T_w > 2.5$ will see T_w/T_c and N_c/N_w increasing by the same amount. When increasing the 850μm flux by 20%, T_c drops to $T_c = 8.5$ K for Mrk 231. Both NGC 1614 and NGC 3310 are well apart from the correlation, but the variation in the 850μm flux affects them differently. When the 850μm flux decreases by 20%, NGC 3310 joins the rest of the sample in the correlations. For this case in particular, this is due to a bad fit, as the 20% decrease in the 850μm flux makes the model not to fit properly the 450μm and the 850μm datapoints. By eliminating the 160μm datapoint, T_w/T_c only decreases by 30%. For this reason we decided to maintain NGC 3310 as an excess galaxy.

Cold dust emission is not the only possible explanation for the submillimeter excess. An alternative explanation is emission from very small grains (VSGs) (6). These grains are stochastically heated (instead of thermally heated) and are responsible for the emission of most flux $\lambda < 60\mu$m. For most of the galaxies in our sample, it is the main source of infrared emission at the IRAS 25μm band. These grains could also be the cause for the flux excess at $\lambda > 450\mu$m as the stochastic process in these grains means that they can spend a significant amount of time in a very cold state. Their temperature can vary from less than 10 K to more than 100 K, depending on the size of the grain, the distance to the heating source and its luminosity. These factors will change the width and the peak of the SED emitted by VSGs, which could explain both the 25μm emission and the $\lambda > 450\mu$m emission excess.

The model we have used here is clearly too limited for this task, as it only incorporates dust at thermal equilibrium with the surrounding gas, described by a single temperature. A more realistic model, which incorporates stochastically heated dust, is necessary to test which is the most plausible cause for the excess emission, as well as explain the emission at shorter ($\lambda < 25\mu$m) wavelengths.

5.3.6 The DBP90 model

Motivated by the results from IRAS, the Dsert et al. (46) (DBP90) model was one of the first models to provide a consistent picture of the interstellar dust. The model requires a minimal number of dust components, uses the same parameters to explain simultaneously both dust absorption and dust infrared emission, and has been applied successfully to extragalactic sources. We applied this model on all the diagnosed "excess galaxies", and on a subsample of SEDs in groups A and B which include at least one datapoint between 200μm and 850μm, to serve as a comparison. We will first describe the characteristics of the dust grains that are incorporated in the DBP90 model and in any model that describes the absorption of the ISRF by dust.

5.3.6.1 Big grains

Big silicate grains (BGs) of radius $a \sim 10 - 100$ nm are used to explain the near-infrared part of the extinction curve. They are grains in thermal equilibrium with the surrounding gas, and they emit in the far-infrared as a modified blackbody (MBB) characterized by a single grain temperature T, which determines the position of the MBB peak. Higher temperatures move the MBB peak to shorter wavelengths, and lower temperatures move the MBB peak to longer wavelengths. Thermal emission from BGs usually account for most of the far-infrared ($> 60\mu$m) SED emission in the Milky Way and nearby galaxies, and also the SED peak, as we have seen in the previous sections of this chapter.

5.3.6.2 Very small grains

Very small carbonaceous grains (VSGs) with $a < 50$. Unlike BGs, these grains are stochastically heated rather than thermally heated. When the grains are immersed in an ISRF, their temperatures fluctuate according to their size and the energy of the photons. Studies of the temperature spiking of very small grains of $5 - 50\mathring{A}$ have suggested that the temperature spike associated with absorption of a 10 eV photon may approach 10^3 K (**?**), but the timescale for cooling of a very small grain after the absorption of an energetic photon may typically be only 1 second (**?**). If this spike is responsible for the continuum dust emission at the IRAS 12μm band (**?**), then stochastically heated grains will spend most of their time (10^5 - 10^6 s) at very low temperatures, which can be even below 5 K (**?**). This means that they can provide a significant part of the SED flux at $\lambda > 500\mu$m.

5.3.6.3 Polycyclic Aromatic Hydrocarbons

Polycyclic aromatic hydrocarbon molecules (PAH) can produce the FUV part of the extinction curve. They are also thought to be responsible for the broad emission bands seen in the mid-infrared between $3.3 - 18\mu$m (**? ? ?** 96). They are the smallest of the dust grains considered here, with $a \sim 10$ nm. Due to their small size they also undergo stochastic heating in an ISRF, being excited by single photons with temperatures $T > 50 - 100$ K. There is wide variety of configurations of PAH molecules, with the main broad emission bands at 3.3, 6.2, 7.7, 8.6, and 11.3 μm being produced by C-C and C-H rotational, vibrational, and bending modes. The underlying continuum at these wavelengths is produced by amorphous carbon VSGs, and also weaker PAH emission bands.

5.3.6.4 Model input

The input parameters the DBP90 model requires are: (i) the number and type of dust components to be fit; (ii) the maximum and minimum grain sizes for each component, (iii) the shape of the spectrum of the interstellar radiation field (ISRF), (iv) the intensity of the ISRF relative to the ISRF in the solar neighborhood, and v) the mass abundance Y of the different dust components as a fraction of the hydrogen mass. These parameters determine the shape of the SED of each grain population. We had to convert the model output, the emitted power per H-atom expressed in units of W/H, and also the measured SED fluxes expressed in Jy, to luminosity units (erg s^{-1} Hz^{-1}). To do that, we took into account the total number of hydrogen atoms in each galaxy, which was calculated from the sum of the molecular gas and atomic gas masses listed in Table 5.3, and also the distance to the galaxies.

For each dust component the grain size distribution is modeled as a power law where the number density of grains of radius between a and $a + da$ is $n(a) \propto a^{-\alpha}$ between a_{min} and a_{max}. The values we use are those for which DBP90 achieved the the best-fit for the Solar Neighborhood. The sizes of the big grains range from $150 - 1100\AA$ and $\alpha = 2.9$. The VSGs have sizes between $12 - 150\AA$ with $\alpha = 2.6$. PAHs have sizes from $4 - 12\AA$ and $\alpha = 3$.

The extinction coefficient in the optical and UV has a wavelength dependence with an exponent of $\beta = 2$ for large grains and $\beta = 1$ for VSGs (46). The values of the size distribution exponents, as well as the minimum and maximum values were fixed to the Milky Way values as determined by Dsert et al. (46). Other input parameters set to the Milky Way dust properties are the maximum albedo (set to zero for PAHs and VSGs and 0.61 for BG) and density ρ (2.3 g/cm^3 for PAH and VSGs and 3.0 g/cm^3 for BG).

The DBP90 model needs an estimate of the interstellar radiation field (ISRF), the heating source of the dust. Its spectral shape and intensity have a direct effect on the SED emitted by the dust. The shape and intensity of the ISRF vary strongly from quiescent to star-forming regions. The main sources of the ISRF in the Solar Neighborhood are stars of spectral type A and F. Therefore, by definition, the ISRF intensity scales with the surface density of the bolometric luminosity.

The DBP90 model provides a choice between the ISRF within the Solar Neighborhood (LISRF), assumed constant at a galactocentric distance of 10 kpc, an ISRF produced by a theoretical O5 type star at a distance of 1 pc, and an ISRF produced by a theoretical B3 type star at a distance of 0.15 pc. The main differences between using the O5 type star ISRF and the LIRSF resides on the VSG component, which moves to shorter wavelengths. The PAH component is enhanced, but that is just a scaling for the best fit. We chose the ISRF of the Solar Neighborhood as the input ISRF heating the grains as it can represent the average integrated ISRF of whole galaxies.

5.3.6.5 SED fitting

Figure 5.10 — Variation of the fluxes of the DBP90 components fitting the SEDs of the galaxy Arp 220. The VSG component is the the dashed line, the BG component is the dotted line, and the PAH component is the dashed-dotted line. The solid line is the final total spectrum. Upper left: ISRF 50X, VSG/BG=0.98; lower left: ISRF=50X, VSG/BG=0.098; upper right: ISRF=20X, VSG/BG=0.98; lower right:ISRF=20X, VSG/BG=0.098

We ran the DBP90 model on the SEDs in groups A and B that include at least one datapoint between 200μm and 850μm, and also in all SEDs with $T_c < 13$ K. We used different intensities of the ISRF (ISRF+X(ISRF)) and mass abundance fractions $X(PAH) = M(PAH)/M(gas)$, $X(VSG) = M(VSG)/M(gas)$, and $X(BG) = M(BG)/M(gas)$ for the different dust components. These parameters are shown in Table 5.4. We allow the

Table 5.7 — Range of input parameters used on DBP90

Parameter	Values	Info
X(ISRF)	0.5, 0.7, 1.0, 2.0, 5.0, 10.0, 20.0, 50.0, 70.0, 100.0, 120, 150	intensity of the radiation field (Solar Neighborhood)
X(PAH)	0.04, 0.10, 0.20, 0.30, 0.43, 1.00, 2.00, 3.00, 4.30, 10.0	Relative mass of PAHs ($10^{-4} \times M_{gas}$)
X(VSG)	0.47, 1.00, 2.00, 3.00, 4.70, 10.0, 20.0, 30.0, 47.0	Relative mass of VSGs ($10^{-4} \times M_{gas}$)
X(BG)	0.64, 1.50, 3.00, 4.50, 6.40, 15.0, 30.0, 45.0, 64.0	Relative mass of BGs ($10^{-3} \times M_{gas}$)

X(ISRF) to vary between 0.5 and 150, X(PAH) to vary between $0.04 - 10 \times 10^{-4}$, X(VSG) between $0.47 - 47 \times 10^{-4}$, and X(BG) between $0.64 - 64 \times 10^{-3}$. This range of values of PAH, VSG, and BG components was chosen based on the known characteristics of the galaxies in the sample, and also to scale to the Milky Way values of these parameters [X(ISRF)=1, X(PAH)=4.30×10^{-4}, X(VSG)=4.7×10^{-4}, X(BG)=6.4×10^{-3}]. The output of the DBP90 model is a grid of modeled PAH, VSG, and BG SEDs for each X(ISRF).

Figure 5.11 — Spectral energy distributions of the 25 galaxies fitted with the DBP90 model with the three dust components, very small grains (VSGs - dashed line), big grains (BGs - dotted line), and PAHs (dashed/dotted line).

How the modeled components vary with different parameters is shown in Fig. 5.9, where we vary the ISRF and the relative abundances of each dust component and the resulting model SED is scaled to the measured SED of Arp 220. At low ISRF, the BG component peaks at $> 100\mu$m and the BG component contributes to most of the flux in this region. Therefore, VSG/BG ratios are low, and the VSG component is used to contribute to the short wavelength range. With increasing ISRF, the BG component peak moves to shorter wavelengths, and the contribution of the VSG component to the submillimeter flux increases. In galaxies with submillimeter excess at high ISRF, such as NGC 1614, it means that extra VSGs are required to contribute to the submillimeter flux, hence a high VSG/BG ratio. Because the VSG component dominates not only the submillimeter excess, but also the short-wavelength end of the SED, if we set the ISRF to a single factor, for example 20, and fit the SEDs for all the dust components, we still obtain different variations of VSG/BG. That is what we see in the lower plots in Fig. 5.9, where for the same ISRF, different VSG components can be used to fit the SED.

To obtain the best model for the dust emission in our galaxies, each output spectrum was scaled and fitted to the observations, using a χ^2 statistic. In Figs. **??**, 5.7,and **??** we present the best fits for the sample of galaxies with $T_c < 13$ K and the subsample of "normal" galaxies from groups A and B. There are wide differences in the contribution of VSGs and BGs to the SEDs. The narrower SEDs with more pronounced peaks have an enhanced BG contribution, whereas VSGs are enhanced in SEDs with shallower slopes both at mid-infrared and submillimeter. In 11 of the 26 modeled galaxies, the flux produced by the VSG component at 850μm is more than 50% the total flux. The PAH component has a minimal influence on the submillimeter tail of the fits, up to about 2%.

Figure 5.12 — Same as for Fig. **??**.

Figure 5.13 — Same as for Fig. **??**.

The 25μm flux is not well fitted in Mrk 231 and NGC 3690, as the VSG component seems to be too low for the 25μm flux. The SED of NGC 1614 has a similar shape, but with a better fit. The reason for this is that the submillimeter excess emission in NGC 1614, which makes the VSG component increase and fit the 25μm datapoint. It may seem that Mrk 231 should have a similar excess at 850μm, in order to fit the SED. NGC 5907 and NGC 7331 have also fitting difficulties, as the BG component in NGC 5907 does not seem to be wide enough to fit the SED at $\lambda > 60\mu$m, whereas for NGC 7331, the discrepancy between the fluxes at 160μm and 170μm affect the quality of the fit, although less than the MBB fit.

The results of our fitting procedure for the 26 galaxies are listed in Table 5.5, where each contribution is expressed in therms of fractions of the total gas mass. The total dust mass is listed in Table 5.5 was obtained from the mass fractions of each dust component that minimize the χ^2 fitting.

5.3.7 The variation of dust properties with the ISRF

Table 5.8 — DBP90 model parameters

Galaxy	X(ISRF)	$M(PAH)/M_H(10^{-4})$	$M(VSG)/M_H(10^{-4})$	$M(VSG)/M_H(10^{-4})$	Y(VSG)/Y(BG) $\times 10^5$ $M_\odot$	M_{dust}
Arp220	55±10	0.00385±0.00241	0.588±0.071	5.64±0.660	0.104±0.017	416.9
IC1623	85±44	0.173±0.0676	0.681±0.308	2.59±1.02	0.263±0.157	135.3
Mrk 231*	130±25	1.29±0.22	1.02±0.19	15.05±5.26	0.0675±0.0267	227.4
Mrk 273*	150±0	0.0106±0.00313	0.337±0.0858	1.56±0.045	0.216±0.055	178.4
NGC 520	60±11.5	0.0312±0.00705	0.165±0.0197	0.996±0.175	0.165±0.035	15.8
NGC 660	10±0	0.123±0.00750	0.296±0.319	1.85±0.0111	0.160±0.001	27.1
NGC 891	2.25±0.96	0.858±0.303	0.593±0.216	12.8±4.50	0.046±0.023	171.6
NGC 1614*	123±21	0.0795±0.0184	0.308±0.0309	0.810±0.169	0.380±0.088	15.8
NGC 1667	10±0	2.15±0.118	1.15±0.314	22.0±0.984	0.052±0.014	247.7
NGC 2903	7.5±2.9	0.652±0.228	1.17±0.389	4.67±1.54	0.250±0.117	41.3
NGC 3079	7.5±2.9	0.260±0.0731	0.168±0.0624	3.90±1.08	0.043±0.020	62.5
NGC 3310*	70±0	0.0801±0.00461	0.380±0.0156	1.10±0.132	0.345±0.044	7.29
NGC 3628	2.25±0.5	0.941±0.106	2.05±0.335	14.1±1.61	0.145±0.029	66.1
NGC 3690	150	0.0739±0.00914	0.166±0.0181	1.22±0.0990	0.136±0.018	43.4
NGC 4402	1.5±0.6	0.815±0.152	0.133±0.0480	8.36±1.65	0.016±0.007	73.3
NGC 4414	3.5±1.0	1.14±0.194	1.04±0.225	10.0±2.54	0.104±0.034	49.0
NGC 4418*	135±17.3	0.848±0.187	7.56±0.68	18.6±3.9	0.406±0.093	77.5
NGC 4501	4.5±1.0	0.701±0.138	0.290±0.327	8.60±1.34	0.034±0.005	116.1
NGC 4631	5±0	0.805±0.0416	0.671±0.113	12.0±0.608	0.056±0.010	107.4
NGC 4922*	130±25	2.45±0.696	13.4±1.13	25.5±7.50	0.525±0.160	68.0
NGC 5907	0.725±0.206	0.850±0.127	0.463±0.175	12.7±1.87	0.036±0.015	203.4
NGC 5962	5±0	3.07±0.182	2.62±0.505	31.4±1.70	0.083±0.017	189.5
NGC 6052	47.5±37.7	1.61±1.25	2.61±1.99	15.6±4.42	0.167±0.136	101.2
NGC 6240	125±50	0.059±0.059	0.316±0.0222	1.55±1.19	0.204±0.157	77.7
NGC 7331	4.5±1	0.340±0.057	0.183±0.068	5.10±0.86	0.036±0.015	92.6
UGC 2369	115±33.2	0.0424±0.0234	0.325±0.0285	1.58±0.574	0.206±0.077	88.1

* Excess galaxies.

As seen in Fig. **??**, the temperature of the warm MBB component is the main responsible for the variation of the infrared SED peak, measured by the flux ratio F(60)/F(100). However, the MBB model did not provide any information on the cause for the variation of the dust temperature. With the DBP90 model, we have now the opportunity to study the physical causes of dust heating. In Fig. **??** (upper), we show T_w as a function of the intensity of the ISRF. Despite the broad dispersion, there is a real correlation, which means that the ISRF intensity plays an important role in regulating the temperature of the warm dust. The excess galaxies are all associated with high T_w. The four galaxies outside the correlation (NGC 1667, NGC 2903, NGC 4402, and NGC 4501), with $T_w > 50$ K, are spiral galaxies where a MBB fit was forced to the 25μm datapoint, and therefore for these galaxies T_w is an upper limit.

From Table 5.5 one can calculate the ratio between VSGs and BGs, in order to study the variation of the size distribution. In Fig. **??** (lower) we show the variation of the ratio between VSG and BG abundances with the ISRF intensity. We can see that the $\log M(VSG)/M(BG)$ increase in a nearly linear fashion with the logarithm of the ISRF intensity. The error bars are the deviations from the average ratio calculated from the four best fits (as measured by χ^2 minimization). They cover most, but not all, of the dispersion. Also shown are the excess galaxies, which ar all grouped among the galaxies with the highest ISRF intensity, and therefore also tend to have high VSG mass fraction. There is a wide range of $M(VSG)/M(BG)$ among these galaxies, and there are other galaxies with similar VSG mass fractions and ISRF intensity that are not part of this group. Moreover, the most extreme of the excess galaxies, NGC 3310, is neither among those with the highest $M(VSG)/M(BG)$ ratio nor ISRF intensity and there is no correlation between T_c and $M(VSG)/M(BG)$ in these galaxies. Therefore, although VSGs are found to be associated with the existence of sub-millimeter excess emission, it is not a sufficient cause.

5.4 Discussion

5.4.1 Correlations

Figure 5.14 — Upper: variation of T_w with the ISRF intensity factor. The triangles represent excess galaxies. The dashed line is a linear fit to the data based on the least absolute deviation method. Lower: variation of the VSG/BG ratio with the intensity of the interstellar radiation field (ISRF), represented as an intensity factor above the galactic ISRF. The triangles are the values for excess galaxies, and the error bars represent the variations in the fit.

Our sample has a wide range of spiral galaxy types and merger systems, representing the full range of IRAS colors and luminosities. We fit the SEDs using MBB models with one component and later two components. One component fits are quite adequate for about 50% of the galaxies in the sample, and many of the SEDs are equally well fitted with 1 or 2 components. However the other half of the sample, the SED peak is too wide to be modeled by a single component, and an additional MBB component is required. In about 20% of the fits resulted in unconstrained warm component, and the 25μm had to be included to set an upper limit on the warm component temperature T_w.

The $F_\nu(60)/F_\nu(100)$ ratio is well established as a tracer of the warm dust temperature (**?**). A definite correlation was observed between the $F_\nu(60)/F_\nu(100)$ ratio and T_w, and the observed variation of the N_c/N_w ratio, fully accounts for the dispersion in the correlation meaning that it is created by the differences in the mass contribution between the warm and cold components. This indicates a degeneracy between T_w and N_c/N_w, as $F_\nu(60)/F_\nu(100)$ increases with the former, but decreases with the latter. For $\beta_w = \beta_c$, the ratio N_c/N_w is a measure of the relative mass fraction of the cold and warm components. More luminous galaxies not only have warmer dust, which exists around star forming regions, but also the mass fraction of the warm dust is increased relative to the cold dust.

Also interesting results arise from the ratio T_w/T_c and its correlation with the scale factor ratio N_c/N_w and the flux ratio $F_\nu(60)/F_\nu(100)$. The T_w/T_c ratio increases slightly with N_c/N_w, and that indicates that the correlation between T_c with T_w is not linear. It is an effect of compensating the decrease of the mass fraction of the warm component by increasing T_w over T_c. The ratio T_w/T_c does not vary with $F_\nu(60)/F_\nu(100)$ and is limited between 1.5 and 2.5 for 80% of the galaxies, which is expected given that the grains are assumed to be of the same type and heated thermally. This is because we are studying dust emission at galaxy-wide scales, an only a small fraction of the thermally heated dust is close enough to stars to be heated to $T > 100$ K, which is indicated by the large N_c/N_w required if T_c remains constant.

The ISRF is a measure of infrared luminosity density. This means that the $F_\nu(60)/F_\nu(100)$ ratio is also a measure of ISRF intensity. The influence of the ISRF on the dust temperature is seen in Fig. **??** where, as expected, the temperature of the warm dust component increases with the intensity of the ISRF, as was observed earlier with $F_\nu(60)/F_\nu(100)$. Other quantity that increases with the ISRF is the mass fraction of the VSGs over the BGs, as seen in Fig. **??**. However, the mass fraction of VSG over the total dust mass does not correlate with T_c. It seems that the VSGs are associated with regions with high star formation rate density and it possibly reflects processes of destruction of BGs in regions where very massive stars are formed. In low density regions, supernova shocks or shocks driven by stellar winds destroy the grains through sputtering or shattering (33**?**). Grain size variation could also be a partial explanation of the dispersion seen in the lower plot of Fig. **??**, as for the same ISRF intensity, a different size range could alter the M(VSG)/M(BG) value. However, as the grain types are defined basically by size range, one needs to fix it for consistency.

The merger systems in our sample could be distinguished from spiral galaxies due to their hotter colors, with $F_\nu(100)/F_\nu(160) > 1.4$ and $F_\nu(60)/F_\nu(100) > 0.9$. Mergers have typically a high infrared luminosity ($L_{IR} > 10^{11} L_\odot$), reflected in our determined ISRF intensity, whereas the spirals have typically low ISRF intensity and therefore low SFR density and M(VSG)/M(BG). We could not distinguish HII regions from AGNs as sources of dust heating using the MBB model alone, as it is limited to $60 - 850\mu$m. One of the advantages of the DBP90 over the MBB model is that allows the SED to be modeled at $\lambda < 60\mu$m, as it is not limited to grains that emit thermally. One of the most commonly accepted diagnostics of dust heating source (AGNs or starburst) is based on the $F_\nu(60)/F_\nu(12)$ ratio of IRAS bands (**?**), in which an increasing $F_\nu(60)/F_\nu(12)$ ratio corresponds to an increasing AGN contribution to the SED. The IRAS colors could therefore be used to derive an AGN/starburst diagnostic based on the mass contributions of PAHs and VSGs. However, more recent diagnostics based on mid-infrared spectral features (**? ?**) challenge this method. There are galaxies such as NGC 4418, in which mid-infrared spectral characteristics such as the depth of the silicate absorption at 9.8μ and the absence of PAH bands are indicators of the presence of an embedded AGN, which could not be diagnosed using IRAS colors.

5.4.2 Submillimeter excess

Six galaxies were found outlying from both N_c/N_w vs. T_w/T_c and T_w vs T_c correlations. These are Mrk 231, Mrk 273, NGC 1614, NGC 3310, NGC 4418, and NGC 4922. It was confirmed that these deviations are caused by a flux excess at $\lambda > 300\mu$m, modeled by a very cold component at $T_c < 13$ K, wich reaches 6.5 K for NGC 1614 and 3.7 K for NGC 3310. It is interesting to note that four of these galaxies are mergers. Very low dust temperatures detected in merger systems have been associated with tidally removed dust (**?**), whereas for spirals it is associated with the least luminous regions of the disk as observed in M51 (**?**), M81 (**?**), and NGC 4631 **?**).

Excess emission has been diagnosed in previous studies in NGC 1569, NGC 3310, and NGC 4631. As NGC 1569 is a dwarf galaxy, it was not included in our study. The emission excess diagnostic in Lisenfeld et al. (6) for this galaxy was based on the use of three MBB curves, with the third MBB curve having $\beta = 1$ and fitting both 12μm and the 25μm fluxes. We do not think this is realistic, as these bands are mostly influenced by stochastic grain emission. In NGC 3310, (**?**) derived a very cold dust temperature of 5.7 K based on a two-MBB model with $\beta = 2$, similar to our own. However, the MBB model was fitted to only four datapoints (IRAS 60μm, IRAS 100μm, SCUBA 450μm, SCUBA 850μm). Because we include also the MIPS 160μm, our results are more reliable.

On their modeling of the SED of NGC 4631, **? ?**) diagnosed submillimeter excess from a MBB model similar to the one employed by Lisenfeld et al. (6) and us. However, **?**) fitted the 25μm datapoint, which is not the best approach. Their claim for submillimeter excess arises from a deviation of the flux at 1100μm from the model. **?**) detected a 850μm excess on the faintest regions in the disk, but it was based on a single MBB model fiting only three datapoints. With our increased number of datapoints, we cannot confirm this excess in the 850μm flux of NGC 4631. Given that the SED is based on the flux of the entire galaxy, the existence of excess in the faintest regions is not to be ruled out, and requires a spatially detailed photometric study of these regions between $450 - 850\mu$m.

The most extreme submillimeter excess emission exists in NGC 1614 and NGC 3310, which was modeled by a cold dust component of $T_c = 6.2$ K and $T_c = 3.7$ K. NGC 3310 is a low-metallicity spiral galaxy, and for this system it is unlikely that cold dust is responsible for the 850μm excess. Using the **?**) recipe for the calculation of dust mass, such a low temperature implies a gas-to-dust mass ratio ~ 7, which is highly unrealistic for a low metallicity system. For this case, emission by cold VSGs is a better explanation for the emission excess. The gas-to-dust mass ratio found in NGC 1614 is 40. Although still low, it is a more realistic value, comparable to the values found in other mergers (9).

A possible explanation for the excess in NGC 1614 is that this is an extreme example of cold dust emission in a merger system. In order to estimate the relative fraction of cold and warm dust mass in a spiral galaxy, let us assume as a first approximation that the warm dust is concentrated in the inner 1 kpc, and the cold dust is distributed from a distance of 1 kpc to 20 kpc from the nucleus. Based on the model stellar surface density profiles for post-merger spirals by **?**) and assuming that dust follows the same profile, we arrived to a ratio between cold and warm dust masses $M_c/M_w \sim 50$, which corresponds to the expected value of N_c/N_w, as the grains of both components have the same β. For NGC 1614, $N_c/N_w \sim= 55$, which means that the tidal dust mass would be 55 times the dust mass in the star forming region, and that is remarkably close to the estimated value. This indicates that the associations of the cold component with the diffuse dust ("cirrus") and the warm component with dust surrounding the star forming regions ("starburst"). This two-stage dust scenario was already proposed by Klaas et al. (12), also based in two-MBB models with $\beta = 2$. High sensitivity submillimeter observations of the diffuse dust in mergers would be required for a better estimate of the dust density and temperature distributions in mergers and spiral galaxies.

As revealed by the DBP90 model, the excess galaxies have a high M(VSG)/M(BG) on average, but similar to other galaxies with high ISRF intensities. The excess galaxies have a broad dispersion of relative abundances of very small grains M(VSG)/M(BG), so VSGs are not a sufficient cause for the submillimeter emission in these particular galaxies. Dust heated at low temperatures is still an important cause for submillimeter excess emission, and NGC 3310 may be an exception.

5.5 Summary and conclusions

In this chapter we pursued two goals: to explore the possibility of reducing the necessary fitting parameter space in SED models of star forming galaxies and investigate how the parameter space can be used to characterize dust in star forming galaxies. One needs a simple model with as few parameters as possible to describe the infrared SEDs between $60 - 1000\mu$m that have only the IRAS bands 60μm and 100μm and at most the 850μm SCUBA band, of star forming galaxies For this purpose we have assembled a sample of 126 relatively nearby (< 150 Mpc) star-forming galaxies which have publicly available 850 μm measurements from SCUBA.

We first used a single MBB to model the SEDs, with three free parameters: the temperature T, the emissivity factor β, and a scaling factor N. We compare the parameters to color-color plots involving infrared and submillimeter fluxes at 60μm, 100μ, 160μm, and 850μm as a first study of the range of SED shapes in our sample. For 90% of the sample, the infrared peak is too broad to be modeled by a single MBB. This indicates that at least an additional colder dust component is required to model the infrared peak. We also used a model (DBP90) incorporating infrared emission by stochastically heated very small grains (VSGs) at wavelengths $< 60\mu$m and possibly at $> 350\mu$m, in order to test the possibility that these grains could be responsible for the excess emission. This model is especially employed to model the SEDs at $\lambda 60\mu$m, including the IRAS bands 12μm and 25μm.

In order to decrease the number of free parameters one or more parameters has to be well constrained so that it could be fixed to a constant and still describe the SEDs. For normalization, we divided each SED by the integral of the 1 MBB curves. Then we distributed our sample into three groups A, B, and C, according to the number of datapoints in their SEDs. Because the SEDs in A and B had at least 8 datapoints, we used them to reduce the parameter space.

Modeling each galaxy of groups A and B with two MBB components, we found β 1.5 for both components in group A galaxies, but they could not be determined for group B. However, setting $\beta_w = \beta_c = 2$ to match literature and laboratory evidence gives adequate fits. With that value of β, we concluded that the SEDs can be adequately described using four free parameters, the temperatures of each component T_c and T_w and the scaling factors N_c and N_w. By deriving the values of each parameter and studying their distributions, we found that the parameter T_c is distributed as a gaussian, with mean value $T_c = 19$ K for group B. Using this value, we were able to reduce the parameter space to three free parameters, enough to model SEDs with only four data points. The first goal was reached.

Studying the correlations between N_c/N_w and T_w/T_c and also between T_w and T_c, six galaxies were found as significant outliers, and five of them were identified as "excess galaxies", as the offsets from the correlations were attributed to a flux excess at $\lambda > 350\mu$m. All these galaxies have a cold dust component with $T_c < 14$ K, which is used to explain a possible emission excess at submillimeter wavelengths. The most significant flux excess emission at 450μm and 850μm was confirmed for two galaxies NGC 1614 and NGC 3310, for which the two-MBB model derives a cold dust temperature of $T_c = 6.5$ K and $T_c = 3.7$ K. It is a robust result within the total flux uncertainty of the 850μm SCUBA band (20%). NGC 1614 can be seen as an extreme example of cold dust emission in a merger system, with a single MBB describing the dust associated to star formation, and a very cold dust component associated with low-density diffuse ISM. The excess emission NGC 3310 is more likely to be associated with an enhanced sub-millimeter emission of Very Small Grains (VSGs).

The intensity of the interstellar radiation field (ISRF) that heats the grains is correlated with the temperature of the warm component of the MBB models (T_w), and mergers were found to have the highest ISRF intensity and VSG mass fraction. Although the excess galaxies have a high VSG mass fraction on average, a high VSG mass fraction is not a sufficient cause for the submillimeter excess. This study improves on previous studies of SED modeling using MBB components such as Dunne et al. (9); Stevens et al. (10); Vlahakis et al. (18) in the sense that we include more datapoints in the far-infrared, improving the determination of the SED peak and therefore the MBB parameters.

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Table 5.9 — Flux densities in Jy

Galaxies	12 μm	24 μm	25 μm	60 μm	70 μm	90 μm	100 μm	120 μm	150 μm	160 μm	170 μm	170 μm	180 μm	200 μm	350 μm	450 μm	850 μm	1300 μm
Arp 90	0.35	...	1.6	9.36	...	...	13.68	...	...	...	15.7	...	...	...	...	...	0.119	...
Arp 91	0.82	0.737	1.58	11.79	9.18	...	19.89	...	...	...	...	...	...	...	...	...	0.306	...
Arp 148	0.2	...	0.71	6.38	...	...	10.3	...	...	...	...	...	...	...	...	0.646	0.092	...
Arp 193	0.25	...	1.42	17	...	...	24.4	...	...	...	...	...	...	...	...	...	0.11	...
Arp 220	0.61	5.38	8	104.09	68.2	...	115.29	117.3	79.4	...	77.1	71.4	41.1	31.2	10.5	6.286	0.832	...
Arp 240	0.57	...	1.34	10.73	...	...	19.97	...	...	...	...	...	...	...	...	...	0.283	...
Arp 271	1.29	...	1.48	10.24	...	...	25.29	...	...	...	...	...	...	...	...	...	0.548	...
Arp 302	0.36	...	0.41	6.95	...	...	15.16	...	...	...	...	...	...	...	...	0.37	0.215	...
IC563	0.46	...	0.54	5.26	...	...	12.18	...	...	...	...	...	...	...	...	...	0.228	...
IC797	0.265	...	0.334	0.744	...	...	0.112	...	...	...	...	...	...	...	...	...	0.085	...
IC800	0.132	...	0.185	0.376	...	...	1.1	...	...	...	...	...	...	...	...	...	0.076	...
IC1623	1.03	0	3.65	22.93	0	0	31.55	36.5	26.7	0	23.5	0	12.8	9.69	0	2.43	0.273	...
M51	11	12.67	17.5	109	147.1	0	292	0	0	494.7	0	0	0	0	11.9	5.4	15	...
M82	79.4	...	333	1480	...	...	1370	...	...	...	...	...	...	...	...	...	21.2	...
M83	21.5	42.2	43.6	138	312	0	524	0	0	848	0	0	0	0	0	9.7	1.36	...
Mrk231	1.83	0	8.84	30.8	0	27.3	29.74	24.3	14.7	0	20.8	0	9.75	6.88	1.73	0	0.126	...
Mrk273	0.24	0	2.36	22.51	0	0	22.53	0	0	0	8.3	0	0	0	0	0	0.104	...
Mrk331	0.52	2.02	2.54	18	14.8	0	22.7	0	0	13.2	12.4	0	0	0	0	0	0.132	...
Mrk848	0.29	...	1.42	9.02	...	...	10	...	...	...	...	...	...	...	...	...	0.06	...
NGC23	0.66	...	1.29	9.03	...	...	15.66	...	...	...	...	...	...	...	...	...	0.144	...
NGC99	0.097	...	0.203	0.81	...	...	1.49	...	...	...	...	...	...	...	...	0.49	0.063	...
NGC157	1.61	...	2.17	17.93	...	...	42.43	...	...	...	...	79.6	...	...	...	4.73	0.91	...
NGC253	41	0	155	968	0	0	1290	0	0	0	0	...	1693	0	172	0	10.5	...
NGC337	0.24	0.68	0.76	9.07	...	...	20.1	...	...	20.1	...	...	...	...	...	...	0.35	...
NGC470	0.42	...	1.11	7.22	...	...	12.2	...	...	...	...	1.52	...	...	...	...	0.213	...
NGC520	0.9	...	3.22	31.52	...	...	47.37	...	...	...	29.6	25.4	...	...	3.01	...	0.325	...
NGC660	3.05	0	7.3	65.52	0	0	114.74	0	0	0	75.6	0	0	0	0	6.92	1.36	0.6
NGC695	0.5	0	0.83	7.59	0	0	13.56	0	0	0	15.5	0	0	0	0	0	0.136	...
NGC697	0.65	...	0.91	5.38	...	...	18.01	...	...	...	...	...	...	...	...	...	0.221	...
NGC772	1.1	...	0.92	6.73	...	...	24.15	...	...	...	...	...	...	...	...	...	0.288	...
NGC803	0.131	...	0.162	0.689	...	...	2.84	...	...	...	...	...	...	...	...	0.631	0.093	...
NGC877	0.84	...	1.41	11.82	...	...	25.56	...	...	...	...	...	...	...	...	...	0.332	0.105
NGC891	5.27	6.63	7	66.46	94.4	0	172.23	0	0	0	0	193	0	165	0	39	4.8	0.6
NGC958	0.62	...	0.94	5.85	...	...	15.08	...	...	...	...	...	...	...	...	...	0.262	...
NGC992	0.56	...	1.76	11.4	...	...	16.72	...	...	...	...	...	...	...	...	...	0.146	...
NGC1097	2.96	6.63	7.3	53.35	59.84	...	104.79	...	...	153.8	...	...	...	...	...	...	1.44	...
NGC1134	0.55	...	0.92	9.09	...	...	16.43	...	...	...	...	...	...	...	...	...	0.242	...
NGC1222	0.5	0	2.28	13.06	0	0	15.41	0	0	0	8	0	0	0	0	0	0.084	...
NGC1275	1.06	...	3.44	6.99	...	...	7.2	...	...	...	5.47	...	...	2.92	...	1.2	1.6	...
NGC1482	1.55	3.64	4.68	33.36	32.45	...	46.73	...	...	38.74	55.7	...	...	...	...	...	0.33	0.072
NGC1614	1.38	5.89	7.5	32.12	24.8	...	34.32	...	...	17.1	12.5	16.3	...	...	...	0.981	0.219	...
NGC1667	0.63	0	0.71	6.27	0	0	14.92	29.6	16.3	0	0	17	9.03	6.33	0	1.183	0.163	...
NGC1808	5.4	12.9	17	105.55	67.1	...	141.76	...	...	...	...	...	...	...	...	7.14	1.3	...

Galaxies	12 μm	24 μm	25 μm	60 μm	70 μm	90 μm	100 μm	120 μm	150 μm	160 μm	170 μm	170 μm	180 μm	200 μm	350 μm	450 μm	850 μm	1300 μm	
NGC2623	0.21	…	1.81	23.74	…	…	25.8	…	…	…	…	…	…	…	1.43	…	0.091	…
NGC2782	0.64	1.17	1.51	9.17	10.3	…	13.76	…	…	11.5	…	…	…	…	…	…	0.237	…
NGC2785	0.49	…	1.09	8.4	…	…	15.79	…	…	…	…	…	…	…	…	…	0.201	…
NGC2798	0.789	2.62	3.08	20.6	21.7	…	29.7	…	…	20.7	…	…	…	…	…	…	0.19	…
NGC2856	0.35	…	0.94	5.73	…	…	10.15	…	…	…	…	…	…	…	…	0.993	0.089	…
NGC2903	5.29	9.69	8.64	60.54	76.4	…	130.43	…	…	156	…	…	…	…	…	7.94	1.8	1.5
NGC2966	0.46	…	0.8	5.36	…	…	8.24	…	…	…	…	…	…	…	…	…	0.136	…
NGC2976	0.92	1.37	1.71	13.1	…	…	33.4	…	…	52.56	…	…	…	…	…	2.41	0.793	…
NGC2990	0.227	…	0.466	5.2	…	…	9.44	…	…	…	…	…	…	…	…	1.275	0.11	…
NGC3079	2.54	3	3.61	50.67	63.7	…	104.69	…	…	91.3	…	…	…	…	10.7	7.86	1.26	0.5
NGC3094	0.82	…	2.89	10.88	…	…	13.89	…	…	…	…	…	…	…	…	…	0.152	…
NGC3110	0.59	0.97	1.13	11.28	10.4	…	22.27	…	…	…	…	…	…	…	…	…	0.188	…
NGC3190	0.315	0.27	0.351	3.19	5.66	…	10.1	…	…	15	13.4	…	…	…	…	…	0.19	…
NGC3221	0.52	0.8	0.93	7.72	10.6	…	18.76	…	…	…	…	…	…	…	…	…	0.253	…
NGC3270	0.09	…	0.38	0.71	…	…	2.51	…	…	…	…	…	…	…	…	…	0.059	…
NGC3310	1.54	4.99	5.32	34.56	32.3	…	44.19	…	…	29.8	…	…	…	…	…	1.29	0.358	…
NGC3367	0.51	…	1.98	6.44	…	…	13.48	…	…	…	…	…	…	…	…	…	0.132	…
NGC3368	0.98	…	0.51	10.51	…	…	31.63	…	…	…	…	…	…	…	…	3.44	0.513	…
NGC3432	0.25	…	0.43	8.42	…	…	16	…	…	…	…	…	…	…	…	…	0.45	…
NGC3521	5.04	5.51	5.46	49.2	63.1	…	122	…	…	222	…	…	…	…	…	…	2.11	…
NGC3583	0.6	…	0.77	7.43	…	…	17.92	…	…	…	19.6	…	…	…	…	…	0.185	…
NGC3597	0.67	…	2.18	12.84	…	…	16.21	…	…	…	…	…	…	…	…	…	0.061	…
NGC3627	4.82	7.42	8.55	66.3	92.6	…	137	…	…	230	…	…	…	…	9.3	…	1.86	0.7
NGC3628	3.13	7	4.85	54.8	77.1	…	105.76	…	…	147	…	…	…	…	…	16.9	2.82	0.5
NGC3690	3.97	…	24.51	113.05	…	…	111.42	…	…	…	60.7	…	…	…	7.5	1.5	0.486	…
NGC3994	0.5	0.35	0.9	8.53	5.21	…	16.88	…	…	4.6	…	…	…	…	…	…	0.232	…
NGC4045	0.27	…	1.02	6.75	…	…	13.69	…	…	…	…	…	…	…	…	…	0.142	…
NGC4088	2.06	…	3.45	26.8	…	…	61.7	…	…	…	…	…	…	…	…	…	0.98	1
NGC4254	3.67	4.19	4.38	37.5	50.3	…	91.9	…	…	143	…	…	…	…	7.8	3.8	1.01	1.3
NGC4273	0.77	…	1.65	9.38	…	…	21.76	…	…	…	…	…	…	…	…	…	0.324	…
NGC4303	3.28	3.52	4.9	37.27	…	…	78.74	…	…	…	…	…	…	…	…	4.6	0.705	…
NGC4321	2.52	3.34	3.1	26	40.6	…	68.4	…	…	140	…	…	…	…	…	…	0.88	1
NGC4374	0.22	…	0.19	0.5	…	1	1.16	…	…	…	…	…	…	…	…	0.12	0.147	…
NGC4388	1.01	2.4	3.57	10.27	9.78	…	17.15	…	…	12.04	…	19.5	…	…	…	…	0.234	…
NGC4402	0.74	0.6	0.66	5.54	6.94	…	17.53	…	…	…	15.69	…	…	…	…	2.31	0.357	…
NGC4414	2.78	…	3.61	29.55	…	…	70.7	…	…	…	…	55.9	…	…	…	7.54	1.16	…
NGC4418	0.99	5.61	9.67	43.89	26.3	…	31.94	…	…	…	…	14.2	…	…	2.03	…	0.255	…
NGC4433	0.63	…	1.52	13.35	…	…	23.83	…	…	…	…	…	…	…	…	…	0.22	…
NGC4501	2.29	1.93	2.98	19.68	25.21	35	62.97	116	94.1	…	…	…	52.3	47	…	6.39	0.962	1
NGC4490	1.82	…	4.92	46.9	…	…	88.6	…	…	…	190	…	…	…	…	…	0.223	1.6
NGC4536	1.55	3.46	4.04	30.3	32	…	44.5	…	…	58.1	…	…	…	…	…	…	0.42	…
NGC4569	1.27	1.44	2.06	9.8	12.4	…	26.6	…	…	41.2	25.4	29.2	…	…	…	…	0.47	…
NGC4594	1	0.71	0.497	3.11	8.02	…	14.1	…	…	42.1	…	…	…	…	…	…	0.25	…
NGC4631	5.16	8.15	8.97	85.4	130.2	…	160.08	…	…	289.5	…	…	…	…	…	30.7	5.73	3.1
NGC4712	0.119	…	0.869	0.478	…	…	2.02	…	…	…	0.792	…	…	…	…	…	0.102	…
NGC4736	5.07	5.65	6.11	71.5	93.9	…	121	…	…	177	…	…	…	…	…	…	1.54	2.4

Galaxies	12 μm	24 μm	25 μm	60 μm	70 μm	90 μm	100 μm	120 μm	150 μm	160 μm	170 μm	170 μm	180 μm	200 μm	350 μm	450 μm	850 μm	1300 μm
NGC4793	1.08	···	1.57	12.42	···	···	28.11	···	···	···	···	···	···	···	···	···	0.258	···
NGC4826	2.36	2.72	2.86	36.7	55.2	···	81.7	···	···	···	98.82	···	···	···	···	···	1.01	···
NGC4922	0.27	···	1.48	6.21	···	···	7.33	6.8	7.1	···	···	···	···	1.83	···	···	0.053	···
NGC5020	0.36	···	0.72	5.58	···	···	11.7	···	···	···	···	···	···	···	···	···	0.206	···
NGC5104	0.39	0.53	0.74	6.78	6.66	···	13.37	···	···	7.9	···	7.87	···	···	···	···	0.091	···
NGC5135	0.63	···	2.38	16.86	···	···	30.97	···	···	···	···	···	···	···	3.8	···	0.182	···
NGC5195	0.35	1.4	1.02	15.2	···	···	31.3	···	···	14.9	···	···	···	···	···	···	0.26	···
NGC5256	0.32	···	1.07	7.25	···	···	10.11	···	···	···	···	8.73	···	···	···	···	0.082	···
NGC5257	0.57	···	1.34	10.73	···	···	19.97	···	···	···	···	···	···	···	···	···	0.283	···
NGC5371	0.86	···	0.97	5.27	···	···	18.66	···	···	···	···	···	···	···	···	···	0.136	···
NGC5353	0.174	···	0.102	0.32	···	···	1.45	···	···	···	···	···	0.6	···	···	···	0.017	···
NGC5394	0.52	···	1.19	5.62	···	···	10.4	···	···	···	···	···	···	···	···	···	0.071	···
NGC5433	0.27	···	0.85	6.31	···	···	11.67	···	···	···	9.7	···	···	···	···	···	0.163	···
NGC5600	0.35	···	0.72	5.44	···	···	11.68	···	···	···	···	···	···	···	···	···	0.112	···
NGC5653	0.64	···	1.37	10.57	···	···	23.03	···	···	···	···	···	···	···	···	···	0.205	···
NGC5665	0.47	···	0.82	6.25	···	···	12.41	···	···	···	···	···	···	···	···	···	0.157	···
NGC5676	1.13	···	1.7	12.04	···	···	29.91	···	···	···	···	···	···	···	···	···	0.481	···
NGC5713	1.47	···	2.84	22.1	···	···	37.28	···	29.9	···	41.3	···	···	···	···	0	0.57	···
NGC5792	0.97	···	1	9.08	···	···	20.32	···	···	···	···	···	···	···	···	···	0.383	···
NGC5866	0.35	···	0.34	5.26	···	16.9	16.98	···	14.1	···	4.4	···	···	···	···	0.8	0.14	···
NGC5900	0.4	···	0.7	7.51	···	···	16.95	···	···	···	···	···	···	···	···	···	0.179	···
NGC5907	1.29	1.68	1.44	9.14	···	···	37.43	···	···	···	35.8	···	···	···	···	3.12	1.96	···
NGC5929	0.43	1.31	1.62	9.14	···	···	13.7	···	···	7.68	···	···	···	···	···	···	0.024	···
NGC5936	0.48	···	1.47	8.73	···	···	17.66	···	···	11	···	···	···	···	···	···	0.152	···
NGC5937	0.68	1.03	1.47	10.41	···	···	21.47	···	···	···	···	···	···	···	···	···	0.247	···
NGC5953	0.82	···	1.58	11.79	···	21.2	19.89	···	17.2	···	15.5	···	···	···	···	···	0.184	···
NGC5962	0.73	···	1.04	8.93	···	···	21.82	···	17.7	···	21.5	···	···	···	···	1.959	0.317	···
NGC5990	0.6	···	1.6	9.59	···	···	17.14	···	···	···	···	···	···	···	···	···	0.11	···
NGC6052	0.28	0.67	0.83	6.79	5.91	···	10.57	···	···	6.56	···	6.89	···	···	···	0.721	0.095	···
NGC6090	0.26	···	1.24	6.48	···	···	9.41	9.98	6.87	···	···	···	3.47	2.55	···	···	0.103	···
NGC6181	0.63	···	1.41	8.94	···	···	20.83	···	···	···	···	···	···	···	···	1.47	0.228	···
NGC6240	0.59	···	3.55	22.94	···	26.7	26.49	18.2	16.7	···	11.5	9.5	7.1	···	1.1	1	0.15	···
NGC6946	12.11	20.37	20.7	129.78	207.2	···	290.69	···	···	502.8	···	673	···	366	···	18.5	2.98	···
NGC7047	0.0831	···	0.148	0.43	···	···	1.65	···	···	···	···	···	···	···	···	···	0.055	···
NGC7081	0.131	···	0.204	1.79	···	···	3.87	···	···	···	···	···	···	···	···	0.241	0.044	···
NGC7331	3.94	4.36	5.92	45	75	···	110.2	···	···	189.5	···	66.5	···	···	···	20.6	2.11	···
NGC7448	0.45	···	0.77	8.88	···	···	17.9	···	···	···	···	···	···	···	···	···	0.193	0.09
NGC7465	0.26	···	0.67	5.47	···	···	8.14	···	···	···	···	···	···	···	···	···	0.225	···
NGC7469	1.59	···	5.96	27.3	···	···	35.2	···	···	···	28.9	···	···	···	2.23	···	0.192	···
NGC7541	1.52	···	2.09	20.08	···	···	41.87	···	···	···	···	43.2	···	···	···	2.639	0.427	···
NGC7591	0.28	0.62	1.27	7.87	7.91	···	14.87	···	···	10.3	···	4.2	···	···	···	···	0.135	···
NGC7592	0.26	···	0.97	8.05	···	···	10.58	···	···	···	···	···	···	···	···	···	0.108	···
NGC7653	0.144	···	0.339	1.31	···	···	4.46	···	···	···	···	···	···	···	···	···	0.112	···
NGC7674	0.68	···	1.92	5.36	···	2.99	8.33	9.38	7.65	···	···	6.02	3.67	2.78	···	···	0.108	···
NGC7678	0.63	···	1.16	6.98	···	···	14.84	···	···	···	···	···	···	···	···	···	0.195	···
NGC7679	0.5	···	1.12	7.4	···	11.6	10.71	8.9	8.9	···	···	···	6.7	6.3	···	···	0.093	0.072

Galaxies	12 μm	24 μm	25 μm	60 μm	70 μm	90 μm	100 μm	120 μm	150 μm	160 μm	170 μm	170 μm	180 μm	200 μm	350 μm	450 μm	850 μm	1300 μm
NGC7714	0.47	2.36	2.88	11.2	9.73	14.6	12.26	8.5	8	7.5	8.4	...	5.3	...	...	...	0.072	0.011
NGC7722	0.17	...	0.21	0.8	...	...	3.19	...	...	...	...	...	...	0.8	...	0.595	0.061	...
NGC7771	0.99	...	2.17	19.7	...	...	40.1	...	...	...	39	10.1	...	...	...	...	0.377	
PGC035952	0.924	...	0.166	0.469	...	...	1.32	...	...	...	...	...	...	...	...	0.421	0.051	
UGC148	0.159	...	0.259	2.21	...	...	5.04	...	...	...	5.3	...	...	...	...	0.944	0.055	
UGC 2369	0.23	...	1.88	8.07	...	...	11.18	...	...	...	6.97	...	4.27	3.22	...	0.52	0.072	
UGC 2982	0.57	0.62	0.83	8.39	...	...	16.8	12.4	...	...	...	...	...	...	...	...	0.176	0.055
UGC 4881	0.14	0.42	0.61	6.07	...	...	10.33	6.03	...	...	...	...	...	...	...	...	0.065	
UGC 5376	0.29	...	0.62	5.36	...	...	10.41	...	...	...	...	...	...	...	...	...	0.148	
UGC 8739	0.35	...	0.42	5.79	...	...	15.89	...	...	...	16.4	...	...	...	...	...	0.187	
UGC10205	0.0891	...	0.0841	0.394	...	...	1.54	...	...	...	...	...	...	...	...	...	0.058	
UGC12519	0.172	...	0.208	0.763	...	...	2.59	...	...	...	...	...	...	...	...	0.408	0.074	

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Color figures

Figure 6.1 — Left: composite image of the Antennae galaxies (NGC 4038/4039), made using the ACS instrument on the Hubble Space Telescope using several different filters: F435W (B) in blue, F550M (y) in green, F658N (Hα=[NII]) in pink, and F814W (I) in red (Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)). Right: composite image of the Antennae galaxies, made from 3.6 μm (in blue), 4.5μm (in green) and 8.0 μm (in red) images from the Infrared Array Camera on board Spitzer Space Telescope (Credit: NASA/JPL-Caltech/Z. Wang (Harvard-Smithsonian CfA)).

Figure 6.2 — *IRAC* color composite image of NGC 5253 at 3.6μm (blue), 4.5μm (green) and 8.0μm (red). The image is 4 arcmin aside. North is up and East to the left.

Figure 6.3 — Left: Overlay of SL (red) and SH (blue) coverages and selected low-res extraction regions on an IRAC 8μm image. Regions A and B, represented in yellow, are regions where LL (14 - 35 μm) spectra were extracted. Right: Zoom-in of the IRAC 8μm image with an overlay of the SH map area in blue and the selected regions (in green) from where the SH+SL spectra were extracted. The ISO-SWS aperture used in the $12 - 27\mu$m range by Förster Schreiber et al. (57) is also overlayed in yellow on the image. Both figures are in logarithmic scaling.

Figure 6.4 — Decomposition of SL+SH spectrum of Region 2. Red solid lines represent the thermal dust continuum components, the thick gray line the total continuum, blue lines are dust features, while the violet peaks are atomic and molecular spectral lines. The dotted black line indicates the fully mixed extinction which affects all components, with axis at right. The solid green line is the full fitted model, plotted on the observed flux intensities and uncertainties.

Figure 6.5 — Overlay of the SL (sparse) and LL (complete) maps on a V-band image of Arp 143. North is up.

Figure 6.6 — Composite of FUV (blue), V-band (green), and 8 μm (red) images of Arp 143.

Figure 6.7 — Contour maps of the H_2 S(0) (left) and H_2 S(1) (right) emission in Arp 143, overlayed on an IRAC 8μm image. Contour levels are at 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.5 , 2, and 3 MJy/sr for H_2 S(0) and 1, 1.4, 1.8, 2, 2.5, 3, 4, 6, and 8 MJy/sr for H_2 S(1).

Nederlandse samenvatting

De Omstandigheden in het Interstellaire Medium van Starburststelsels

pplr7tToen de eerste sterrenstelsels ongeveer 10 miljard jaar geleden werden gevormd, was het Heelal veel kleiner en dichter dan nu. De interacties tussen deze eerste sterrenstelsels waren waarschijnlijk zeer frequent. Met behulp van diepe waarnemingen van de hemel kunnen we zien hoe de sterrenstelsels zich lijken te groeperen in dichte gebieden, waar interacties zijn gemeenschappelijk. Deze interacties zorgen voor de opeenhoping van gas en stof, wat leidt tot de vorming van grote hoeveelheden massieve sterren. In een aantal van deze voorwerpen is de stervormingssnelheid zo hoog dat, indien gehandhaafd, al het gas in het sterrenstelsel zou worden verbruikt in een tijdsbestek veel korter dan de levensduur van het sterrenstelsel. Deze sterrenstelsels worden “starburststelsels” genoemd (van het Engels “Starburst”).

Door de succesvolle Infrarood Astronomische Sateliet (IRAS), gelanceerd in 1983, werd duidelijk dat starburst een belangrijk en veel voorkomend proces is in de evolutie van sterrenstelsels. Starbursts zenden krachtig licht uit in het infrarood en ze produceren tot meer dan 1000 keer sneller sterren dan ons eigen Melkweg. In het lokale heelal, zijn starburststelsels verantwoordelijk voor ongeveer een kwart van alle stervorming. Kleinere versies van starbursts zijn te vinden in de Lokale Groep van sterrenstelsels, bijvoorbeeld 30 Doradus in de LMC, en verschillende prototypische starburststelsels liggen in het lokale heelal, op afstanden van minder dan 100 Megaparsec. Deze sterrenstelsels kunnen gezien worden als de lokale/recente tegenhangers van de eerste sterrenstelsels in het Heelal.

Een starburstregio kan honderden supersterclusters (SSCs) bevatten, die ieder weer bestaan uit honderden sterren, omgeven door gas en stof. In het interactiesysteem van de Antennae (NGC 4038/NGC 4039), zie Fig. **??** (links), kan men de supersterclusterevolutie in de verschillende fasen waarnemen. Aan de randen van het systeem, in roze, kan men emissie rond de centrale zware clusters zien ten gevolge van geïoniseerd gas. In het gebied waar de twee sterrenstelsels elkaar raken, verduisteren grote hoeveelheden stof (in bruin) echter volledig het licht van de sterren. In Fig. **??** (rechts), dit gebied licht op bij 8μm, in het midden-infrarood. De zeer jonge (< 5 Myr) SSCs, die ontstaan tijdens een starburst, zijn meestal gehuld in stof. Dit stof absorbeert het UV en zichtbare licht dat zware sterren uitzenden, waardoor deze sterren moeilijk te bestuderen zijn op deze golflengtes. De eigenschappen van lichtkrachtige starbursts kunnen daarom het beste worden onderzocht met behulp van infraroodwaarnemingen.

Figuur 6.8 — Links: composiet beeld van de Antennae sterrenstelsels (NGC 4038/4039), gemaakt door het ACS-instrument op de Hubble Space Telescope met behulp van verschillende filters: F435W (B) in blauw, F550M (y) in groen, F658N (H α = [NII]) in roze, en F814W (I) in rood (Credit: NASA, ESA, en het Hubble Heritage Team (STScI / AURA)). Rechts: composiet beeld van de Antennae sterrenstelsels, bestaande uit 3,6 μ m (in blauw), 4,5 μ m (in groen) en 8,0 μ m (in rood) beelden van de Infrared Array Camera aan boord van de Spitzer Space Telescope (Credit: NASA / JPL-Caltech / Z. Wang (Harvard-Smithsonian CFA))

Starburststelsels in het infrarood

Het grootste deel van het infrarode lichtkracht van starburststelsels komt uit drie bronnen: sterren, interstellair gas en stof. De variatie in de flux van deze drie componenten met de golflengte heet een spectrale energiedistributie (SED). De emissie door sterren piekt in het nabije infrarood ($1 - 3\mu$m). De primaire bron van infrarode straling bij 3μm is thermische emissie van stofdeeltjes verwarmd door sterrenlicht. Emissie door atomen en moleculen in het interstellaire gas resulteert in smalle banden op het breedbandige continuüm ten gevolge van de thermische stofemissie.

Deze emissielijnen zijn een belangrijke indicator voor de omstandigheden van stervorming. Een starburst moet een grote hoeveelheid gas beschikbaar hebben om sterren te vormen. De starburst zelf kan worden veroorzaakt door interacties met een naburig sterrenstelsel (zoals M81/M82), een botsing met een ander sterrenstelsel, of door een ander proces dat materiaal naar het centrum van het sterrenstelsel stuwt (zoals een sterrenbalk). De starburstregio heeft een hoge dichtheid met grote hoeveelheden gas waaruit zeer zware sterren ontstaan. Jonge, hete sterren ioniseren het gas, dat voornamelijk uit waterstof bestaat, rondom hen en creëren zo HII gebieden. Dit gïoniseerde gas veroorzaakt sterke emissielijnen.

Hoewel slechts een kleine fractie van de massa van een sterrenstelsel uit stof bestaat (tussen 0,1 % en 0,01 % voor de Melkweg), bepalen stofdeeltjes voor een belangrijk deel hoe het sterrenstelsel er uitziet. Hun straal is meestal kleiner dan een paar tienden van een micrometer en ze absorberen en verstrooien de straling van sterren in het ultraviolette, zichtbare en nabij-infrarode golflengtegebied en zenden dit opnieuw uit in de vorm van ver-infrarode (FIR) en sub-millimeter (submm) straling. De stofdeeltjes die verantwoordelijk zijn voor de continuümemissie bij $\lambda > 3\mu$m kunnen worden onderverdeeld in drie categoriën, afhankelijk van hun grootte en samenstelling: grote deeltjes (GDs), zeer kleine deeltjes (ZKDs) en polycyclische aromatische koolwaterstoffen (PAKs).

Het bestuderen van infrarode spectrale kenmerken kan al deze fasen van gas en stof in starburstregio's blootleggen. In Fig. **??** is een schematische voorstelling van de structuur van het interstellaire medium (ISM) rond een zware cluster. Stellaire winden uit het cluster stuwen het nabijgelegen gas en stof tot een straal R, waar het gas wordt geïoniseerd en zo een HII gebied vormt in een dunne schil rond het cluster. Buiten een HII regio is een fotodissociatieregio (PDR - Photodissociation Region, in het Engels). PDRs omvatten alle regio's waar het interstellaire gas overwegend neutraal is, maar waar ver-ultraviolette (FUV) fotonen een belangrijke rol spelen in de chemie en/of de opwarming. Het is in deze gebieden waar we moleculen, zoals moleculair waterstof, kunnen waarnemen. PDRs zijn daarom verantwoordelijk voor een groot gedeelte van de IR-straling (lijnen en continuüm) in sterrenstelsel. Het grootste gedeelte van de massa van het gas en stof in de Melkweg bevindt zich in PDRs.

Figuur 6.9 — Schematische voorstelling van een van de geometrieën die worden aangenomen in PDR modellen. De sterren vertegenwoordigen de centrale cluster.

Dit proefschrift

In dit proefschrift behandel ik de ISM-eigenschappen van drie starburststelsels in detail. Deze stelsels varieren in metaalabundanties en stervormingsgebieden zoals is weergegeven in Fig. **??**. Deze sterrenstelsels zijn NGC 5253 (een dwergstelsel met lage metaalabundantie), M82 (een prototypische centrale starburststelsel) en Arp 143 (twee botsende starburststelsels). Ik zal ingaan op de volgende vragen:

- Hoe worden starbursts geïnitieerd op verschillende schalen?
- Hoe beïnvloeden SSCs de ISM-omstandigheden op verschillende schalen?

In bf Hoofdstuk 2 bediscusieer ik eerst het effect van een cluster op het ISM, met behulp van lijnverhoudingen van geïonseerd gas. De abundantie van PAKs wordt vooral beïnvloed door twee factoren: de hardheid van het stralingsveld en de metaalabundantie. Uit studies in het midden-infrarood van Blue Compact Dwarf (BCD) sterrenstelsels bleek dat de abundantie van PAKs sterk is gecorreleerd aan de metaalabundantie. M82 is een voorbeeld van een centraal starburststelsel met meerdere SSCs. In (bf Hoofdstuk 3) analyseer ik de variatie van de ISM-omstandigheden in de centrale regio met behulp van 5-38 mu m spectra met een grote ruimtelijke resolutie. In (bf Hoofdstuk 4) zal ik ingaan hoe zware SSCs die verspreid liggen over een gebied van maarliefst tientallen kpc^2, kunnen worden geactiveerd in slechts enkele miljoenen jaren. Ik presenteer nieuwe mid-infrarood data ($5 - 35\mu$ m) en ultraviolet waarnemingen (1539-2316Å) van het interactie-sterrenstelselsysteem Arp 143 (NGC 2444/2445). De centrale kern van NGC 2445 is omringd door knopen van zware stervorming in een ringachtige structuur.

Figuur 6.10 — Verdeling van NGC 5253, M82 en Arp 143 volgens metaalabundantie en starburst gebied.

Warme stof is geassocieerd met een hoge dichtheid van starbursts. Het grootste deel van de stofmassa in stervormende sterrenstelsels bestaat uit grote silicate deeltjes, die in het golflengtegebied van $\lambda > 60\mu$ m uitzenden. Dit deel van het spectrum wordt meestal gesimuleerd met een model dat weinig vrije parameters vereist. Echter een minimum van zeven datapunten is vereist voor een betrouwbaar SED model. Veel infrarood SEDs van stervormende sterrenstelsels, met inbegrip van starbursts, hebben slechts drie datapunten. Dit betekent dat de stofeigenschappen zoals temperatuur en massa verkregen uit deze modelen grotendeels onzeker zijn. In (bf Hoofdstuk 5) heb ik de mogelijkheid onderzocht om het minimum aantal benodigde punten te verminderen. Dit heb ik gedaan door infrarode SEDs van 126 stervormende sterrenstelsels te modeleren met de som van twee aangepaste zwarte stralermodellen (MBB). De meeste infrarode SEDs zijn namelijk te breed om door een enkel MBB model te worden benaderd en kunnen alleen met de toevoeging van een koud-stofcomponent worden beschreven.

De belangrijkste conclusies van mijn proefschrift zijn:

- De lage PAK abundanties die zijn waargenomen in blauwe compacte dwergstelsels worden veroorzaakt door de vernietiging van de PAKs door het sterkte UV-stralingsveld. In dit proefschrift heb ik aangetoond dat in het blauwe compacte dwergsterrenstelsel NGC 5253 met een lage metaalabundantie, de relatieve sterkte (equivalente breedte) van de PAKsemissie afneemt met de afstand tot het centrale, ioniserende stellaire cluster. Omdat geen significante verschillen in de metaalabundantie worden veracht binnen een paar honderd parsec in een sterrenstelsel, wordt deze bevinding gezien als een krachtig argument voor een anticorrelatie tussen de sterkte van de PAK-emissie en het UV-stralingsveld.
- In de nucleaire gebied van de klassieke starburststelsel M82 de UV stralingveld over de centrale paar honderd parsec is, op ruimtelijke schaalen van ongeveer 30 parsec, ongeveer 40 keer zachter dan in NGC 5253 met verschillen weinig ruimtelijke variaties. Vandaar dat voor elke locatie te geven, moet er een samenstelling van oudere en jongere clusters, waarbij de eerste zich de dominante bevolking. Uit de grote hoeveelheid van dichte moleculair gas nog aanwezig in het centrum van M82 zou men een zeer actieve fase van stervorming verwachten. Dit is echter niet waargenomen in M82, met stervorming sterk onderdrukt in de laatste 5 Myr, dus mechanismen die de omzetting van gas in sterren onderdrukken moet op spelen. Supernovae schokken en stellaire winden waarschijnlijk efficinte maar gelokaliseerd, negatieve feedback te geven.
- Op schalen groter dan een paar kiloparsecs, kan supernova feedback niet langer een dominante factor in die de stervorming efficintie op de korte termijnen en grootschalige evenementen zoals sterrenstelsel interacties relevant worden. Anders dan in M82, de zware clusters in Arp 143 liggen op een afstand van elkaar dat verbieden hun wederzijdse invloed en zorgen voor een gedetailleerde studie. Ik vond dat hun leeftijden verschillen, maar de leeftijd spreiding is zeer klein in vergelijking met de dynamische tijd in de ring van clusters. Dit is een sterke ondersteuning voor het scenario waarin een radiaal uitbreiden, grote schokgolf van een frontale botsing tussen twee sterrenstelsels heeft geteisterd van het ISM en leverde ook de vorming van deze clusters.
- De ver-infrarood (60μm -1 mm) SED van de meeste starburststelsels redelijkerwijs kan worden gereproduceerd door aangepaste zwarte stralers met constante emissiviteit. Echter, een kleine fractie van sterrenstelsels een zeer koude component met $T < 14$ K. De meeste van deze "koude"sterrenstelsels zijn fusies en vertonen een grote fractie van stochastisch verwarmde zeer kleine deeltjes (ZKDs). Deze bevinding opent twee plausibele verklaringen voor de koude stof: ofwel een grote hoeveelheid grote, zeer koud silicaat deeltjes (GDs) in de diffuse ISM, of een significant hogere fractie van ZKDs. Voor de meeste "koude"sterrenstelsels de gegevens niet voldoende zijn om onderscheid te maken tussen deze twee mogelijkheden, maar in een geval, de spiraal NGC 3310, een hogere fractie van VSGs is duidelijk de voorkeur.

De nabije toekomst van starburststelselonderzoek gaat meestal geassocieerd worden met de ver-infrarood en submillimeter. De *Herschel Space Telescope*, gelanceerd mei 2009 zal een studie van starburststelsels met superieure gevoeligheid, ruimtelijke en spectrale resolutie in het ver-infrarood. De James Webb Space Telescope, gepland voor lancering in 2014, zal de volgende instrument moet worden gewijd aan het naabij- en midden-infrarood golflengten. In de sub-millimeter bereik, gedetailleerde observaties van starbursts op hoge roodverschuiving in zal mogelijk zijn met ALMA (Atacama Large Array milimeter). Dit wordt een array van radiotelescopen waarvan het belangrijkste doel is om een inzicht te vorming ster in het vroege heelal geven. Op $z > 5$, de ver-infrarood piek verhuist naar sub-millimeter golflengten, waar ALMA wordt ~ 1000 keer gevoeliger dan de huidige apparatuur. Dit alles toont een mooie toekomst voor het onderzoek van starburststelsels.

Curriculum vitae

pplr7tI was born in September 29th 1977 in Lisbon, Portugal. When I was six, I moved to! the beautiful town of Évora, where I stayed till I was 14. It was there where I first became fascinated with Astronomy, not by looking at the sky, but by looking at the beautiful pictures in the books (I was a big bookworm). Back in Lisbon, I enrolled in the Faculty of Science as a Physics student, determined to become an Astronomer. After I graduated in 2002 I enrolled immediatly in the Masters programme in Astreonomy and Astrophysics the same University, where I worked in stellar spectroscopy under the supervision of Dr. Nuno C. Santos. The theme of my masters research was "Abundances of Mg, Na, & Al in Stars with Planets", which I defended successfully in September 2004. The excitement of scientific research got me, and so I felt motivated to apply for a PhD position at Leiden University, where I started working in October 2004.

My experience as a PhD student in Leiden has been full of excitement. Under the supervision of Dr. Bernhard Brandl, and with Prof. Dr. Frank Israel as promotor, I started analyzing mid-infrared spectra of starburst galaxies from the then new Spitzer Space Telescope. In my first year I visited Dr. Daniel Devost in Cornell University who assisted me in reducing and analyzing the Spitzer/IRS spectra of NGC 5253. In 2006, I spent 6 months in the Spitzer Science Center under the supervision of Dr. Phil Appleton, working on building spectral maps with mid-infrared spectra, and on the analysis of GALEX, Palomar, and Spitzer/IRAC data on M82 and Arp 143. I presented my research in the Spitzer Conferences in 2005 and 2007, in Pasadena, and also in a conference on Studying Galaxy Formation with Spitzer and Herschel, which took place in May 2006 in Crete, Greece.

In November 2009 I will move to Pasadena to start working with Dr. Lee Armus and Dr. Phil Appleton on Herschel Space Telescope data of nearby starburst galaxies.

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