Interstellar medium conditions in starburst galaxies

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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 (Larson & Tinsley 1978; Rieke et al. 1980; Weedman et al. 1981). 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 $L > 10^{11} L_{\odot}$ (Sanders & Mirabel 1996), and have star formation rates (SFR) up to 1000 times the SFR in our own galaxy (Neugebauer et al. 1984). In the local Universe, starburst galaxies are responsible for approximately a quarter of all the massive star formation (Heckman 1997), 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 (Tinsley & Larson 1978). 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 (Blitz & Shu 1980). 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.

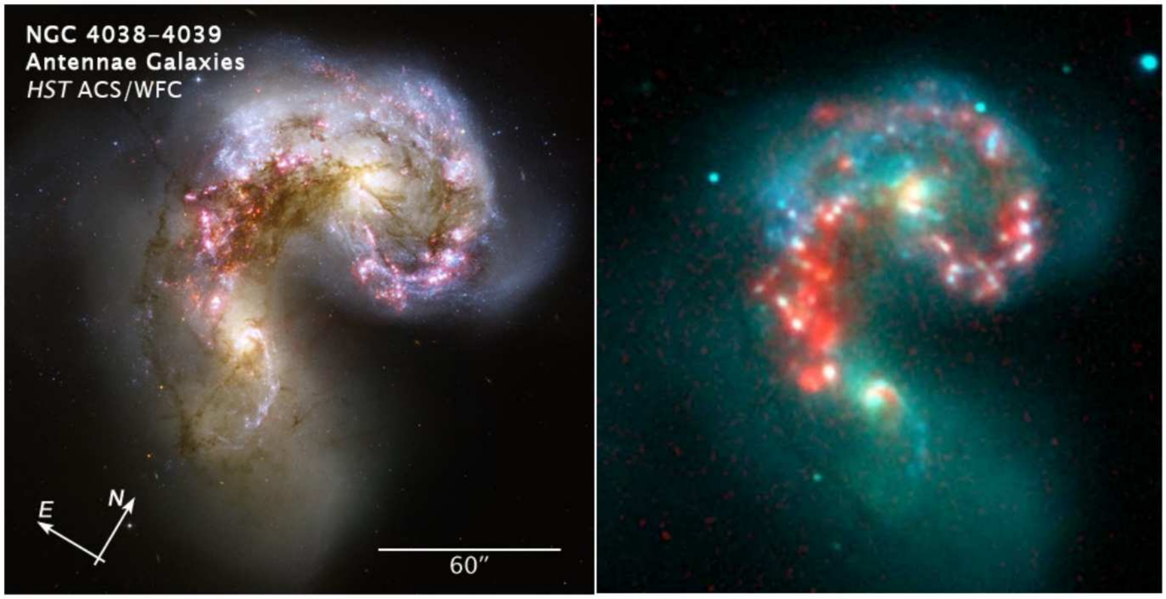

Figure 1.1 — Left: composite image of the Antennae galaxies (NGC 4038/4039), made using the ACS instrument on the Hubble Space Telescope using several different filters: F435W (B) in blue, F550M (y) in green, F658N (Hα=[NII]) in pink, and F814W (I) in red (Credit: NASA, ESA, and the Hubble Heritage Team (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.

A starburst region can contain up to hundreds of super star clusters (SSCs), each 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. 1.1 (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. 1.1 (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 (Whittet et al. 2003). 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 (Weingartner & Draine 2001; Draine 2003). 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 (Draine & Anderson 1985).

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 (Leger & Puget 1984; Puget et al. 1985; Allamandola et al. 1987). 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

All these phases of gas and dust exist in starburst regions, and are revealed by studying infrared spectral features. Fig. 1.2 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. 1.3, a "template spectrum" of a starburst is presented, built averaging the mid-infrared spectra of 13 starburst galaxies (Brandl et al. 2006). The figure illustrates the richness of the $5 - 35\mu$m wavelength range. Important features include PAH emission bands, silicate

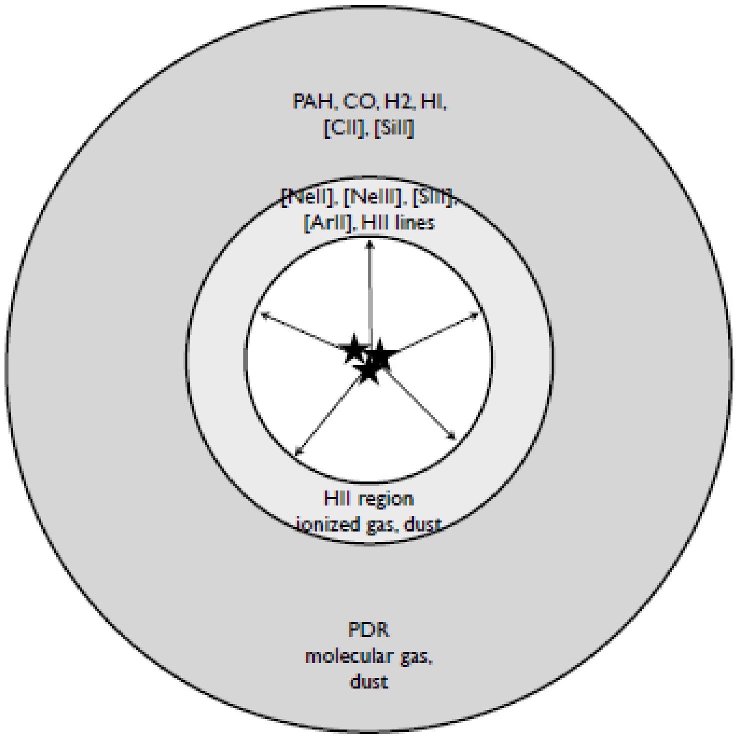

Figure 1.2 — Schematic of one of the geometries considered in PDR models. The stars represent the central cluster.

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 (Förster Schreiber et al. 2001), dwarf galaxies have typically much lower metallicities (Kunth & Östlin 2000), 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 (Houck et al. 2004). 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.

In galaxies with higher mass there is enough gas to form dense starburst regions

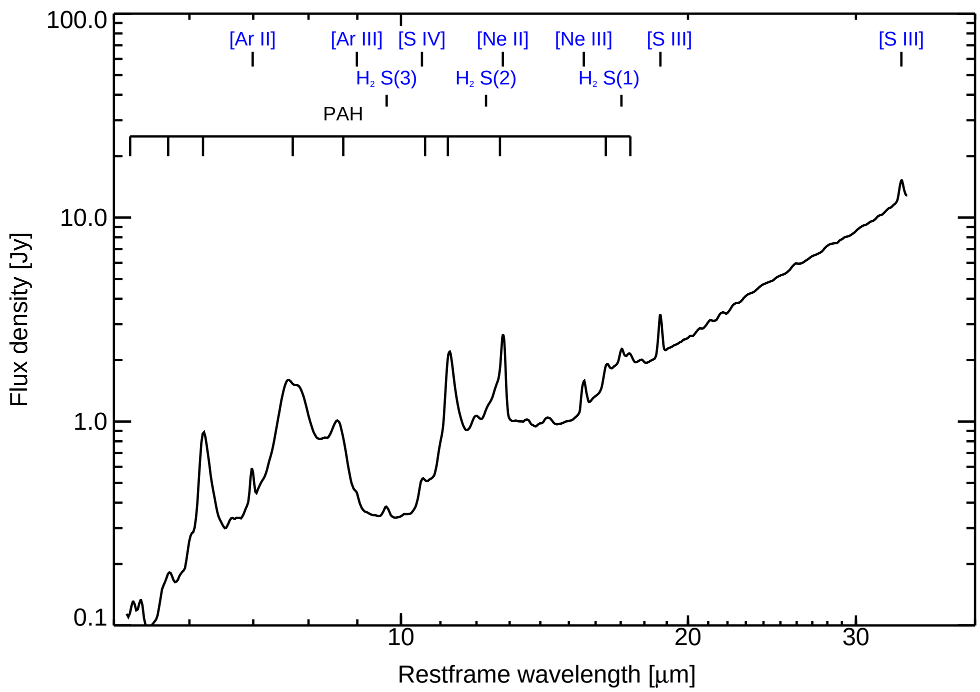

Figure 1.3 — Average IRS spectrum from 13 galaxies (IC342, NGC 660, NGC 1097, NGC 1222, NGC 2146, NGC 3310, NGC 3556, NGC 4088, NGC 4194, NGC 4676, NGC 4818, NGC 7252, NGC 7714). All spectra have been normalized to a flux density of 1 at 15μm before co-addition (Brandl et al. 2006).

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 (Schwarz 1984; Noguchi 1988), interactions, or mergers (Negroponte & White 1983; Mihos & Hernquist 1994). 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 (Charmandaris et al. 1999). 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 (van der Hulst 1946; Disney et al. 1989).

1.3 This thesis

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?

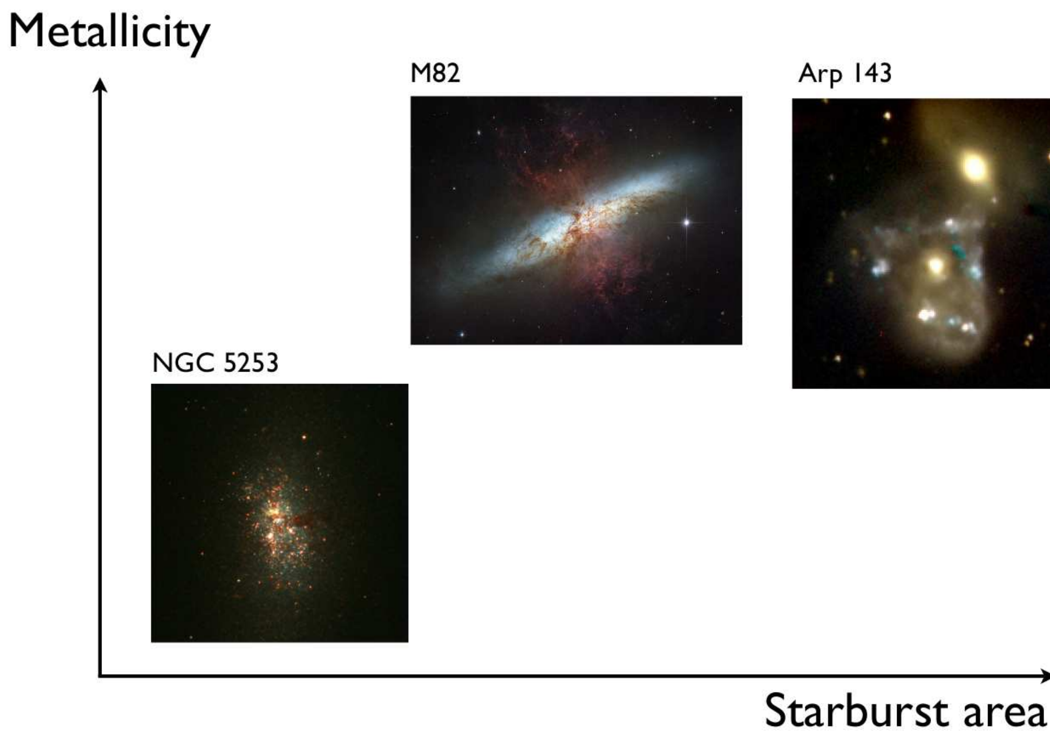

Figure 1.4 — Distribution of NGC 5253, M82, and Arp 143 according to metallicity and starburst area.

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. 1.4 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 (e.g. Wu et al. 2006; O'Halloran et al. 2005) 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 (Madden et al. 2006). 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 ~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.