Chapter 7

Summary & Outlook

In this thesis, a near- and mid-infrared study of star-forming regions in starburst galaxies is presented. The general goal of the project was to gain a more detailed understanding of the nature of clusters formed in starburst events, their stellar populations and the surrounding gas and dust. To study these deeply embedded sources, mid-infrared imaging and near- and mid-infrared spectroscopic observations were obtained, both with ground-based instruments, ISAAC and VISIR at the VLT, and with the Spitzer Space Telescope. The objects put under the microscope were several super star clusters in the overlap and other regions in the major merger NGC 4038/4039, alias the Antennae, and the nuclear starburst in the barred spiral M83. With its unprecedented spatial resolution, VISIR resolves the H II/PDR complexes out to a distance of approximately 20 Mpc. The main results summarized below do not only show that the increased spatial resolution contributes significantly to our understanding of the embedded star clusters, but that a lot can learned from the comparison between ground- and space-based data as well.

In Section 7.1 the models used for the analysis of the observations are discussed. Some resulting highlights are presented in Section 7.2, and a brief glance into the future is given in Section 7.3.

7.1 Models

Our work focusses on the youngest star clusters, still embedded in their natal clouds. To increase our understanding of these objects, the SEDs of young embedded star clusters are modeled, the results of which are presented in Chapter **3** (Snijders et al 2007). Firstly, the SEDs of massive star clusters are created with the latest version of the stellar population synthesis code, *Starburst 99 v5.1* (Leitherer et al 1999). The effect of the surrounding gas and dust, reprocessing the cluster's radiation, is simulated with the photoionization code *Mappings IIIr* (Dopita et al 2000, 2002; Groves et al. 2004).

It is our aim to construct a comprehensive model grid, applicable not only to our own data, but of general use to astronomers working in this field. Therefore, the parameters are chosen to cover a wide range of observed properties, from diffuse to ultradense H II regions. The model grid thus explores a range of metallicities, ISM densities and ionization parameters for clusters of ages ranging from 0 to 6 Myr.

In more detail: the age evolution of a one million $M_\odot$ star cluster, formed in an instantaneous burst with a Salpeter IMF between 0.1 and 100 $M_\odot$, is modeled for various values of metallicity, ionized gas density and of the characteristic ionization parameter of the surrounding dusty nebula. The SEDs are evaluated from 0 – 6 Myr, for the metallicities Z = 0.4, 1 and $2Z_\odot$. The ionized gas density is varied from 10^2 to 10^6 cm^{-3}. The ionization parameter q is defined as $q = Q_{\mathrm{Lyc}}/4\pi \mathrm{R}^2 \mathrm{n}_{\mathrm{ion}}$, with Q_{Lyc} the hydrogen ionizing photon flux, R the distance between the radiating source and the inner boundary of the surrounding cloud, and n_{ion} the gas density. The ionization parameter ranges from $2 \cdot 10^7$ cm s^{-1} to $8 \cdot 10^8$ cm s^{-1}. It relates to the commonly used dimensionless ionization parameter U through $\mathrm{U} \equiv 1.1 \cdot q/c$, where the factor 1.1 takes the helium abundance into account.

The resulting model SEDs carry a wealth of information. In this thesis we focuss on the near- and mid-infrared emission lines, mainly addressing the parts of the spectrum accessible with ground-based telescopes. In the near-infrared J-, H-, and $\mathrm{K_s}$-band atmospheric windows (1.1 – 1.4, 1.5 – 1.8, and 2.0 – 2.3 μm, respectively), a large number of spectral emission lines are available for study; hydrogen and helium recombination lines originating from the H II region; iron lines, predominantly excited by shocks due to supernova remnants; $\mathrm{H_2}$ ro-vibrational lines, tracing the PDRs; and in somewhat older clusters CO-absorption bandheads from the photospheres of red super giants are observed. The mid-infrared N- and Q-band windows (8 – 13 μm and 16.5 – 24.5 μmrespectively) are less abundant in diagnostic emission lines; we are limited to a set of four fine-structure emission lines: [Ar III] at 8.99 μm, [S IV] at 10.51 μm, [Ne II] at 12.81 μm, and [S III] at 18.71 μm. The ratios between two of these fine-structure lines can, depending on the lines' excitation potential and critical density, be used to measure the $\mathrm{T_{eff}}$ of the radiation field and/or the gas density. Under the assumption of an instantaneous starburst, the line ratios sensitive to radiation hardness give constraints on the cluster age. These fine-structure lines are combined into a ratio sensitive to the hardness of the radiation field, [S IV]/[Ar III], and a density sensitive ratio, [S III]/[Ne II]. These two ratios are combined to form a diagnostic diagram, which is used to analyse the VISIR spectra.

7.2 Highlights

7.2.1 Properties of the stellar populations and the surrounding ISM

The star clusters in the overlap region between the two merging spirals NGC 4038 and NGC 4039, together forming the Antennae galaxies, are extensively studied in the near- and mid-infrared, both from ground with ISAAC and VISIR at the VLT as with Spitzer Space Telescope (Chapters 2 – 5). Here we will summarize the main results.

From the J-, H-, and $\mathrm{K_s}$-band ISAAC spectra the cluster ages and masses were derived (Chapter 4). From comparison of the observed EW(Brγ) with model predictions, cluster 1 was found to be very young, $\leq$ 2.5 Myr (see Fig.4.1 for the positions of the clusters). Clusters 2 and 3 are both age-dated at 0 – 3 Myr. The oldest of the four clusters in the overlap region is the highly reddened cluster 4. The EW(Brγ) indicates an age of 3 – 5 Myr, which is also apparent from the presence of (weak) CO bandheads in its $\mathrm{K_s}$-band spectrum, indicating the presence of a somewhat more evolved stellar population.

Cluster masses were determined both from near- and mid-infrared data. In Chapter 4 the cluster masses were estimated by fitting model SEDs to the extinction-corrected $\mathrm{K_s}$-band spectra of the clusters (see Section 4.4.4 for the details). The masses of clusters

3 and 4 could not very well be constrained, and must lie between 100,000 $M_\odot$ and almost 3 million $M_\odot$. The masses of cluster 1 and 2 can be estimated more accurately, when using the observational constraints known (the age range from EW(Brγ, and the gas density and ionization parameter derived from the analysis of the mid-infrared fine-structure lines, see below and Section 3.8.2). The resulting mass estimates are 1.1 – 1.2 million $M_\odot$ for cluster 1 and 1.2 – 1.7 million $M_\odot$ for cluster 2. In Chapter 5, the cluster luminosities were estimated from the continuum at 15 and 30 μm, resulting in higher ages, ranging from 2.6 – 6.7 million $M_\odot$ for the clusters in the overlap region(Section 5.4.5). Clusters 1 and 2 (peak 1 and 2 in Chapter 5) are calculated to be 6.7 and 6.3 million $M_\odot$. Although there is a factor of 4 – 6 difference, it is quite remarkable, given the large systematic uncertainties, that the various independent methods in this thesis and reported in the literature agree reasonably well. The star formation rate varies from 0.1 – 0.8 $M_\odot yr^{-1}$, with cluster 1 having the highest rate.

These mass and star formation rate estimates are totally dependent of the assumed IMF (which is Salpeter between 0.1 – 100 $M_\odot$ here), since the cluster mass is dominated by the low mass stars. Dynamical masses would give a much more robust result. However, due to the lack of absorption lines in the spectra of these very young star clusters, velocity dispersions are impossible to obtain. Our analysis indicates cluster masses in the same range as the masses determined for globular clusters, but it is unclear whether these systems are gravitationally bound and if they will survive the phase of infant mortality observed to take place on a timescale of $\sim$10 Myr in the Antennae (Fall et al. 2005; Mengel et al 2005; Gilbert & Graham 2007). To answer this question better constraints on the cluster masses and sizes are required. The sizes can be obtained using adaptive optics systems, but measuring accurate velocity dispersions will remain very difficult.

Narrow-band mid-infrared imaging of the overlap region, reveals a second H II region close to cluster 1 (source 1b; Chapter 2). In the optical, and even at near-infrared wavelengths no possible counterpart is identified, which indicates that this source is heavily embedded in a molecular cloud of gas and dust. The extinction is estimated to exceed 70 visual magnitudes. The detection of an obscured cluster in itself is not remarkable, since stellar populations are thought to spend the first stages of their life hidden from view in ultradense regions. However, it is interesting that our data reveal just one single highly embedded cluster, and not a handful or more in the overlap region. In combination with a large scale statistical study on the age distribution, this could be used to determine the duration of the heavily embedded phase of a young cluster, before it clears its surroundings and becomes visible at shorter wavelength ranges.

Analysis of the mid-infrared fine-structure lines measured in N- and Q-band spectra results in constraints on the properties of the ISM surrounding the clusters (Chapter 3). The observed values for the [S IV]/[Ar III] ratio, which is sensitive to the hardness of the radiation field, and the density-sensitive [S III]/[Ne II] ratio, were compared to the values predicted by the models. From the line ratios observed at clusters 1 and 2 evidence is found for clumpy, high density, ionized gas. The interstellar matter around the star clusters has a density $\geq 10^4$ cm^{-3} and can be characterized by a high ionization parameter, $\log U \geq -1.53$. Similar densities are locally observed only on very small scales in UCH II regions. Typically these star-forming clouds have a molecular gas density $\geq 10^5$ cm^{-3} within a radius ≤ 0.5 pc (Churchwell 2002). With comparable average gas densities, but radii almost two orders of magnitude larger (the radius of the clusters in the overlap regions as measured in the mid-infrared is approximately 40 pc, Chapter 2), the star-forming regions in the Antennae bear more resemblance to extreme star-forming regions in ultra luminous infrared galaxies (ULIGs). A large fraction of the molecular gas in these sources is found to have densities larger than 10^4 cm^{-3} (Solomon et al. 1992). Furthermore, detailed analysis of the mid-infrared spectral features shows that a (near-)homogeneous medium cannot account for the observations, and that complex structure on scales below the resolution limit, containing several young stellar clusters embedded in clumpy gas, is more likely.

In the near-infrared spectra presented in Chapter 4, several high vibrational level (v = 3,4,5,6,7) H_2 emission lines were observed. These lines have such high upper level temperatures ($\geq$ 15,000K) that they cannot be excited thermally, and thus reveal the presence of fluorescent UV-pumped H_2 emission in the PDRs around all four clusters in the overlap region. The v = 1 emission lines follow a thermal distribution (see Fig. 4.7)), while the higher v lines clearly deviate from it. The critical densities for the H_2 1-0 S(0), S(1), S(2), and S(3) lines range from $0.9 - 1.2 \cdot 10^5$ cm^3, so the density of the emitting gas has to be around or even above these values to be able to produce the observed line flux ratios. To explain the observed H_2 line ratios, the molecular gas densities have to fall in the range of several 10^4 to 1.5 times 10^5 cm^{-3}.

From the rotational H_2 emission lines in the mid-infrared, the temperature of the H_2 gas is found to anti-correlate with the hardness of the radiation field, which is possibly due to the evolution of the geometry of the ISM surrounding the clusters. The average H_2 temperature is 295 K, and the mass of the warm H_2 makes up $\leq 1\%$ of the total mass in molecular hydrogen.

7.2.2 Diffuse PAH emission

The most remarkable result of the work presented in this thesis, is the detection of large scale diffuse 11.25 μm PAH emission which can not directly be associated with the most recent star formation (Chapters 2 and 6). Ever since ISO became operational, broad PAH features at 3.3, 6.2, 7.7, 8.6, 11.3, 12.7 μm were observed to be strong in star-forming regions (plus numerous other, weaker features in the 3 – 17 μm range). However, although qualitatively connected to the process of star formation, the exact source responsible for the excitation of these molecules was never firmly established. Usually, the PAH molecules are thought to be excited by UV photons from young, massive stars, but the detection of significant PAH emission from UV-poor nebulae (Uchida et al 1998; Li & Draine 2002) indicates that lower energy optical photons can excite the PAH molecules as well.

With our high spatial resolution ground-based mid-infrared data we were able to study the distribution of PAH emission in the nucleus of M83 in detail. Two different components of PAH emission were distinguished, one directly related to the star-forming regions, plus another more diffuse component. From a comparison of the latter with mid-infrared continuum emission, near-infrared ro-vibrational H_2 line emission, and optical HST images, we conclude that this diffuse PAH emission is related to low-excitation PDRs.

This result is consistent with our findings that three-quarters of the 11.25 μm PAH emission around the super star clusters in the Antennae overlap region is of low surface brightness and originates from a region more extended than 200 pc in radius. For these objects in the Antennae, which are 4.5 times more distant than the clusters in M83, the spatial scales that can be resolved are of the order of 35 pc. A detailed mapping of the PAH emission and emission from the H II regions as in M83 is thus not possible. Still, from the differences between our ground-based VISIR and published space-based ISO spectra, we conclude that most of the PAH emission cannot directly be associated with the super star clusters.

Space-based observations with the Spitzer Space Telescope (Chapter 5) of six super star clusters in the Antennae, confirm that the observed characteristics of the PAH emission depend sensitively on the spatial resolution of the instrument. At these larger scales of a few hundreds pc, it is found that regions with stronger radiation fields show clearly reduced PAH emission. The PAH spectra show no evidence for PAH ionization effects or grain size variations, nor did we find a correlation between the H_2 line fluxes and PAH fluxes. However, the PAH fluxes scale with the temperature of the H_2 gas – warmer PDRs are more efficient PAH emitters.

These results imply that PAH emission as a SFR indicator behaves differently than for instance hydrogen recombination lines, which trace only O and B stars. Measured in small apertures around somewhat evolved clusters, the PAH emission is approximately proportional to the ionizing photon flux. However, integrated over large apertures or even whole galaxies PAH emission is not only sensitive to recent star formation, but has significant contribution from excitation by B, A and probably even later type stars. Attempts at a quantitative interpretation of the global PAH emission has to take this into account.

7.3 Outlook

In this thesis some of the first results of VISIR at the VLT were presented. With a growing number of observational setups available for this instrument each semester, the possibilities of VISIR (and of other ground-based mid-infrared instruments mounted on 8 m class telescopes) will be explored further in the near-future. Progress on the understanding of the dynamics of super star clusters and their surroundings are expected as a result of the analysis of the very rich SINFONI integral field data sets in the near-infrared.

Improvements in the codes and the method used here to model young, embedded clusters, will lead to progress in this field of research as well. Our assumptions on the properties of the star-forming region are clearly an oversimplification. From observations in our own galaxy, where we can study numerous star-forming regions up close, it is clear that the morphology of these regions is generally very complex, and spherical distributions are hardly ever seen. Furthermore, a delta-function starburst may not be a realistic approximation for all stellar populations, since significant age spreads are observed in the stellar populations of several local star-forming regions. A more sophisticated treatment of the morphology of the ISM and the star formation history of the stellar populations will probably improve the diagnostic power of model results. Both at Leiden Observatory and at the Institute for Astronomy in Honolulu groups are working on the implementation of these next steps, for example including dynamical evolution of the star-forming regions, taking the expansion of the H II regions due to stellar winds, outflows and supernovae into account. Extended burst times will also be considered, as well as creating mixed populations of diffuse and ultracompact components. All these developments will result in more realistic models of the objects under study (Groves et al, in preparation; Kewley et al, in preparation). Note however, that implementation of these effects will increase the number of free model parameters even further. Although the resulting models will be more realistic, the increasing number of input parameters will complicate the interpretation of observations. Apart from efforts to create more realistic representations of the observed systems using the current versions of the stellar population synthesis code *Starburst 99* and the photoionization code *Mappings*, these codes will also evolve themselves with progressing insights. An important update for *Starburst 99* is the inclusion of rotation of the atmospheres of massive stars, of which the results will be released soon. More accurate treatment of the behaviour of PAH molecules can greatly improve the predicted *Mappings* model SEDs in the mid-infrared. However, the current knowledge on the exact physical processes and compositions of the molecules involved is not sufficient, so before this aspect of the *Mappings* code can be improved, constraints have to be determined from observations and/or astrochemical laboratory work.

On the longer run results of various instrumentation projects planned on new observational facilities will have a great impact on the research of star-forming regions in starbursts and in galaxies of all other types. With the launch planned in 2013, the Mid-InfraRed Instrument (MIRI) for the James Webb Space Telescope (JWST) will offer imaging and spectroscopy (both longslit and IFU; R up to $\sim$ 3000) in the range of 5 – 27 μm. This instrument will be significantly more sensitive than current ground- and even space-based mid-infrared instruments, which will benefit our understanding of for example the diffuse component of PAH emission. Half a decade later the European Extremely Large Telescope (E-ELT) is foreseen to become operational. One of the instruments planned for this 42 m telescope, is the thermal/Mid-InfraRed InstRument for the E-ELT (MIDIR). This instrument will cover the L-, M-, N-, and Q-band (all atmospheric windows between 3.5 – 20 μm) in several imaging and spectroscopic modes (longslit and IFU; R up to 50,000). Not only will the sensitivity of MIDIR be orders of magnitude higher than that of current ground-based mid-infrared instruments, the key advantage of the E-ELT will be the revolutionary high spatial resolution. With diffraction limited performance, the resolution will be 50 mas at 10 μm, corresponding to $\sim$ 5 pc at the distance of the Antennae galaxies.

Other exciting prospects are offered by Atacama Large Millimeter/submillimeter Array (ALMA), which is currently under construction in the Atacama dessert and is scheduled to be fully operational in 2012 . The longest baseline of this submillimeter interferometer provides sub-arcsec spatial resolution between 350 μm and 10 mm. With ALMA data detailed spatial comparisons of the PAHs, warm and cold dust can be made. These data will provide the possibility to study dynamics, temperature, and density of neutral gas at a spatial resolution comparable to the JWST or the ELT, again contributing to our understanding of the starburst phenomenon.