A study of extreme IRAS galaxies
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Chapter 5

Summary and interpretation of the observations


Summary

A far-infrared complete sample in the southern hemisphere, consisting of so-called extreme IRAS galaxies with \( L_{\text{FIR}}/L_B \geq 3 \), for which optical, radio continuum and CO(1→0) line observations are available, is discussed. The far-infrared luminosities range from \( 10^9 \) to \( 10^{12} \) L_\odot. These galaxies show on average more active star formation than the galaxies in the IRAS Bright Galaxy Survey and the optical Revised Shapley-Ames Catalog.

It appears that the space density of far-infrared selected sources derived from this sample is comparable with an earlier determination from the Bright Galaxy Survey and that about 1% of the optical light in the nearby universe originates in this kind of galaxies.

Dust masses derived from the IRAS data only give gas-to-dust mass ratios close to the canonical Galactic value of 150 found in our galaxy if a two-component dust model is used with warm dust (60 K) associated with star forming regions and cool dust (18 K) associated with the interstellar medium. However, if a single dust temperature is used we find a dust-to-gas ratio, which is higher by a factor of about 40.

An estimate of \( 1-5 \times 10^9 \) M_\odot is made for the total HI and H_2 gas masses in the galaxies using nuclear NaID spectral absorption lines and CO(1→0) line measurements, respectively, which implies that enough gas is available to sustain the estimated initial star formation rates for at least \( 10^8 \) yr.

The sample can almost completely be divided into three distinct subgroups: dwarf galaxies (\( M_B \leq -19 \) mag), barred spirals and interacting systems, in order of increasing \( L_{\text{FIR}}/L_B \) ratios. The dwarf galaxies show extended star forming regions, which can cover as much as half of the optical disk, while in the barred spirals and the interacting systems the star forming regions are confined to the centres, with typical diameters of \( \sim 1 \) and \( \sim 3 \) kpc, respectively. The striking absence of non-barred spiral galaxies in our sample implies that star formation in spiral arms is not an efficient way to power the far-infrared emission.

About a quarter (12) of the galaxies in our sample show spectra typical for active
galactic nuclei. These galaxies are all barred spirals or interacting systems with far-infrared luminosities $\log(L_{\text{FIR}}/L_\odot) \geq 10.3$. It is argued that only one third (4) of these AGN-type galaxies are (real) 'classical' Seyferts, while the rest of these galaxies have spectra probably generated by an intense nuclear starburst.

The optical colours of the galaxies are completely dominated by the emission from the older population of stars already existing before the starburst. The large spread in the optical colours is due to extinction by dust in the disk, which, however, is not correlated with the extinction found towards the starforming regions determined from the H$\alpha$/H$\beta$ line ratios.

### 5.1 Introduction

This paper is the fourth in a series of papers presenting results of a study of IRAS galaxies with high $L_{\text{FIR}}/L_B$ ratios. In this paper we will summarize and interpret the observations.

In Paper I (van den Broek et al., 1990, Chapter 2) the optical observations are presented, which consist of broad-band B, V, R, and narrow-band H$\alpha$ CCD images, and optical long-slit spectra in the range 4800-7300 Å. In Paper II (van Driel et al., van den Broek, 1990, Chapter 3) low-resolution (10") and high-resolution (1") VLA 6 cm radio continuum observations are discussed, while in Paper III (van Driel and van den Broek, 1990, Chapter 4) CO(J=1→0) line observations for a distance-limited (V<6000 km s$^{-1}$) subsample are given. In Paper V (van den Broek, 1990, Chapter 6) the H$\alpha$/far-infrared correlation is discussed. We also obtained co-added IRAS flux densities for all sources, and near-infrared photoelectric photometry for a dozen sources in the extreme subsample form I.S. Glass. In a related paper (van den Broek and de Jong, 1990, Chapter 7) a correlation between near- and far-infrared luminosities found for the IRAS minisurvey galaxies is analysed with the aid of a simple starburst model.

The observed sample, which we call the extreme subsample, is derived from an infrared complete sample of about 250 galaxies, using $L_{\text{FIR}}/L_B \geq 3$ as a selection criterion, where $L_{\text{FIR}}$ is the far-infrared luminosity between 40 and 120 μm (see Lonsdale et al., 1985). The sources of the far-infrared complete sample are located in two southern fields: Field I with $10^4 \leq \alpha \leq 14^h$ and $-40^\circ \leq \delta \leq -20^\circ$ and Field II with $20^h \leq \alpha \leq 22^h$ and the same declination range. All sources in the far-infrared complete sample have far-infrared flux densities larger than 1 and 2.5 Jy at 60 and 100 μm, respectively. The extreme subsample consists of 42 sources in Field I and 16 sources in Field II. For a more detailed discussion of the definition of the sample we refer to Paper I.

The optical and radio observations are complete for the sources of the extreme subsample in Field I, but they are not complete for those in Field II. We will therefore only consider the sources of the extreme subsample in Field I throughout this paper, unless otherwise indicated, which can be used for statistical purposes. When sources in Field II are discussed in this paper, this will be noted explicitly.

Distances are calculated without applying relativistic corrections, using a Hubble constant $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and throughout this paper we will use the same galaxy identification numbers as in Paper I.
The paper is organized as follows. We will discuss the global properties of the extreme subsample in Sect. 5.2 and in Sect. 5.3 we will show that the extreme subsample can be divided into three subgroups. In Sect. 5.4 we will summarize the properties of the star forming regions observed in these galaxies. Nuclear activity, indicated by the optical spectra is reviewed in Sect. 5.5, and finally in Sect. 5.6 the optical colours and the reddening by dust are discussed.

5.2 Global discussion of the extreme subsample

In this section we will discuss and compare the properties of the observed extreme subsample with those of an infrared and an optical complete sample. Comparison with an infrared complete sample will show the influence of the $L_{FIR}/L_B$ selection criterion. We will show that galaxies with high $L_{FIR}/L_B$ ratios are almost absent in an optical complete sample, and comparison with the extreme subsample therefore gives a good idea of the differences between galaxies with high and low star formation rates.

The far-infrared complete comparison sample is the Bright Galaxy Survey sample (BGS, Soifer et al., 1987), since for this sample all distances are known. The BGS sample consists of all galaxies in about 25% of the sky with flux densities larger than 5.4 Jy at 60μm. The blue optical magnitudes given for this sample were derived from Zwicky magnitudes following Kirschner et al. (1978) and they have not been corrected for galactic reddening, unless the magnitudes for our sample. However, these corrections are smaller than the uncertainties in the Zwicky magnitudes, so they do not play an important role in the comparison.

The optical complete comparison sample consists of all galaxies with B-magnitudes ≤12.5 from the Revised Shapley-Ames Catalog (RSA, Sandage and Tammann, 1981). The far-infrared data of the RSA sample were compiled by K. Brink based on IRAS data from various sources (IRAS Point Source Catalog; IRAS Small Scale Structure Catalog; Rice et al., 1988).

In Sect 5.2.1 we will summarize basic properties as distances, luminosities and colours. In Sect. 5.2.2 we will discuss selection effects for the extreme subsample, while in Sect. 5.2.3, 5.2.4 and 5.2.5 the space density of our sources, far-infrared colours and dust masses are discussed. Finally in Sect. 5.2.6 we will relate the strength of the NaID absorption line to the HI gas mass.

5.2.1 Basic properties

In Fig. 5.1 we show histograms of various basic properties of the extreme subsample and the two comparison samples. Fig. 5.1a confirms that the extreme subsample has the highest $L_{FIR}/L_B$ ratios due to its selection criterion. Also the $L_{FIR}/L_B$ distributions of the RSA sample and the extreme subsample are almost completely disjunct illustrating that galaxies with high $L_{FIR}/L_B$ ratios can practically not be selected by means of optical selection criteria. The extreme subsample has also the largest average far-infrared luminosity (see Fig. 5.1b). Therefore it has also the largest average distance, since sources with higher luminosities have on average larger distances (see Fig. 5.1c). The B-band luminosities (Fig. 5.1d) of the three samples
5.2. Global discussion of the extreme subsample

Figure 5.1 Histograms of various properties (from top to bottom in each series of three histograms) of the extreme subsample, the Bright Galaxy Sample (BGS) and the Revised Shapley-Ames (RSA) sample. a. Far-infrared-to-blue luminosity ratio $L_{FIR}/L_B$. b. Far-infrared luminosity $L_{FIR}$. c. Distance. d. Blue luminosity $L_B$. e. $S_{100}/S_{60}$ flux density ratio. Definitions of the luminosities are given in Paper I.

are quite similar, but the far-infrared colours $S_{100}/S_{60}$ (Fig. 5.1e) are clearly smaller for the extreme subsample than for the RSA sample, while the BGS sample has intermediate colours.

Not all properties shown in Fig. 5.1 are independent. Both $S_{100}/S_{60}$ and $L_{FIR}$ correlate with $L_{FIR}/L_B$ (cf. de Jong et al., 1984; Soifer et al., 1987) as shown in Fig. 5.2a and 5.2b where we plot $\log(S_{100}/S_{60})$ and $L_{FIR}$ versus $L_{FIR}/L_B$ for the three
samples. The \( S_{100}/S_{60} \) ratio decreases with increasing \( L_{\text{FIR}}/L_B^0 \). De Jong and Brink (1987) offered an explanation for this correlation by assuming two dust components: a cool \((\sim 16K)\) dust component associated with the interstellar radiation field and a warm \((\sim 60K)\) dust component associated with star forming regions. If \( \log(L_{\text{FIR}}/L_B^0) \) is a measure of the star formation rate, then an increase in the star formation rate will imply a smaller far-infrared colour, since the contribution of the warm component increases relative to the contribution of the cool component. The slope of the correlation between \( \log(L_{\text{FIR}}) \) and \( \log(L_{\text{FIR}}/L_B^0) \) in Fig. 5.2b is about unity, implying that the variation in \( L_{\text{FIR}}/L_B^0 \) is due to increasing far-infrared emission, rather than due to extinction of the blue radiation. The blue luminosity is therefore independent of the far-infrared luminosity.

Summarizing, we find that the galaxies in the extreme subsample on average show the most extreme far-infrared properties and thus the most active star formation in comparison with the two other samples, so that this sample is indeed well suited for the study of galaxies with enhanced star formation.

5.2.2 Selection effects

The selection criterion \( \log(L_{\text{FIR}}/L_B^0) \geq 3 \) for the extreme subsample will introduce biases for both \( L_{\text{FIR}} \) and \( S_{100}/S_{60} \), since these quantities are correlated with \( L_{\text{FIR}}/L_B^0 \) (see Sect. 5.2.1), as can be clearly seen in the comparison of the \( L_{\text{FIR}} \) and \( S_{100}/S_{60} \) distributions (Fig. 5.1b and 5.1e, respectively) of the extreme subsample and the BGS sample. The average \( \log(L_{\text{FIR}}/L_\odot) \) luminosity and \( S_{100}/S_{60} \) flux density ratio are 10.63 and 0.19, respectively, for the extreme subsample, compared to 10.18 and 0.27 for the BGS sample.

To investigate these selection effects in \( L_{\text{FIR}} \) and \( S_{100}/S_{60} \) further we estimate which fraction of our far-infrared complete sample is included in the extreme subsample, as a function of \( \log(L_{\text{FIR}}) \) and \( \log(S_{100}/S_{60}) \). Since we do not know distances for most of the sources in our far-infrared complete sample, we will do this by determining the equivalent fraction of galaxies with \( L_{\text{FIR}}/L_B \geq 3 \) in the BGS sample. We present the results in Fig. 5.3a and 5.3b, which show that the fraction of galaxies with \( L_{\text{FIR}}/L_B^0 \geq 3 \) in the BGS sample increases with \( \log(L_{\text{FIR}}) \) and decreases with \( \log(S_{100}/S_{60}) \). We also show fits representing an error function based on a Gaussian distribution around an average value of \( \log(L_{\text{FIR}}/L_\odot) = 10.5 \pm 0.45 \) with dispersion \( \sigma_1 = 0.45 \) and similarly for \( \log(S_{100}/S_{60}) = 0.18 \pm 0.15 \) with dispersion \( \sigma_1 = 0.15 \). The \( L_{\text{FIR}}/L_B^0 \) selection criterion may also be represented by an error function based on a Gaussian distribution around an average value of \( \log(L_{\text{FIR}}/L_B^0) = 0.5 \pm 0.25 \) with dispersion \( \sigma_2 = 0.25 \) (see Paper I). We estimate the total dispersion from \( (\sigma_1^2 + \sigma_2^2)^{\frac{1}{2}} \), so that we finally get \( \log(L_{\text{FIR}}/L_\odot) = 10.5 \pm 0.5 \) and \( \log(S_{100}/S_{60}) = 0.2 \pm 0.3 \). This means that at \( \log(L_{\text{FIR}}/L_\odot) = 10.5 \) and \( \log(S_{100}/S_{60}) = 0.2 \) half of the sources, and at \( \log(L_{\text{FIR}}/L_\odot) = 11.0 \) and \( \log(S_{100}/S_{60}) = -0.1 \) already 84\% (one \( \sigma \)) of the sources in our far-infrared complete sample are selected for the extreme subsample.

The far-infrared flux \( \text{FIR (Wm}^{-2}) \) is a function of both \( S_{100} \) and \( S_{60} \) (see eq. (2) in Paper I), implying that the flux density limits we imposed (1 and 2.5 Jy at 60 and 100 \( \mu \)m, respectively), create a far-infrared flux limit, which depends on the \( S_{100}/S_{60} \) ratio. This far-infrared flux limit increases for flux density ratios going from
Figure 5.2 (bottom) The $S_{100}/S_{60}$ flux density ratio and (top) the $L_{FIR}$ luminosity against the $L_{FIR}/L_B^0$ luminosity ratio for the extreme subsample (stars), the Bright Galaxy Sample (small circles) and the Revised Shapley-Ames sample (small crosses).
Summary and interpretation of the observations

Figure 5.3 Fraction of all sources in the Bright Galaxy Sample with $L_{FIR}/L_B^0 \geq 3$ as a function of a. (left) $L_{FIR}$ and b. (right) $S_{100}/S_{60}$. The smooth curves represent a Gaussian fit to the data.

log($S_{100}/S_{60}$) = 0.4 to -0.1, the interval for the sources in the extreme subsample (see Fig. 5.1e). This means that there will be a deficiency of sources in the extreme subsample near log($S_{100}/S_{60}$) = -0.1 (see also Paper I). To investigate the influence of this selection effect we have divided the extreme subsample in two parts: part A contains 10 sources with log($FIR$) ≤ -12.95 [Wm$^{-2}$] and part B contains 32 sources with log($FIR$) > -12.95 [Wm$^{-2}$]. We have chosen this particular division of the extreme subsample in order to remove the deficiency of the hot sources in part B, as explained by Fig. 2 in Paper I. In Fig. 5.4a we compare the distribution of $S_{100}/S_{60}$ of part A with that of part B. Due to the correlations discussed in Sect. 5.2.1, $L_{FIR}$ and $L_{FIR}/L_B^0$ are also affected by this selection effect (see Figs. 5.4b and 5.4c). The average value of log($S_{100}/S_{60}$) for parts A and B differs by three $\sigma$, while the average values of log($L_{FIR}$) and log($L_{FIR}/L_B^0$) differ by only one $\sigma$. Since these differences are marginally significant and because part A contains three times less sources than part B, we conclude that the deficiency of hot sources does not significantly influence the statistical analysis of the extreme subsample.

5.2.3 The far-infrared luminosity function

In this section we will determine the space density of galaxies in the extreme subsample. To derive the space density $\rho$ and the uncertainty $\sigma_\rho$ we use the following expressions (Schmidt, 1968)

$$\rho = \left(\frac{4\pi}{\Omega}\right) \left(\frac{1}{V_m}\right); \quad \sigma_\rho = \left(\frac{4\pi}{\Omega}\right) \left(\frac{1}{V_m^2}\right)$$

(5.1)

where $\Omega$ is the solid angle of Field I and $V_m = \frac{1}{6\sqrt{\pi}} \left(\frac{L_{FIR}}{L_{FIR}}\right)^{3/2}$ is the maximum volume to which a source in Field I could have been detected, where $L_{FIR}$ is the far-infrared luminosity.
5.2. Global discussion of the extreme subsample

Figure 5.4 Histograms comparing various properties of the sources in two parts of the extreme subsample: one with a far-infrared flux log(FIR)≤-12.95 Wm⁻² (top) and the other with log(FIR)>-12.95 Wm⁻² (bottom). a. The S₁₀₀/S₆₀ flux density ratio. b. The L_FIR luminosity. c. The L_FIR/L_B luminosity ratio. d. The S₆₀/S₂₅ flux density ratio.

luminosity and l_FIR the far-infrared flux limit, which depends on the S₁₀₀/S₆₀ flux density ratio (see Sect. 5.2.2). Summation is over all sources in a given luminosity bin. In Table 5.1 we give the space density and its uncertainty as a function of the far-infrared luminosity (see also Fig. 5.5), as well as the number of galaxies in each luminosity bin. Also shown in Table 5.1 is the average and the uncertainty of the V/V_m parameter in each bin, where V is the volume corresponding to the actual distance at which a galaxy is observed. When the sources are uniformly distributed in space, we expect an average value V/V_m=0.5. Only for log(L_FIR/L_☉)=9.6 the average of V/V_m differs significantly from 0.5, but this bin contains only three sources so that the statistical uncertainty is large. We conclude therefore that the sources in the extreme subsample are in general homogeneously distributed in space.

The total far-infrared luminosity density for the extreme subsample is given by \( \sum_i \rho_i L^i_{FIR} \) where \( \rho_i \) and \( L^i_{FIR} \) are the space density and the far-infrared luminosity of the \( i^{th} \) bin, respectively. The result is \( 8.7 \times 10^6 L_☉ \) Mpc⁻³ corresponding to \( 1.5 \times 10^6 L_☉ \) Mpc⁻³ in the blue for the average log(L_FIR/L_B) ratio of 0.77 (see Fig. 5.1a) for the extreme subsample. Felten (1977) gave a total blue luminosity density of \( 1.8 \times 10^8 \)
Summary and interpretation of the observations

Table 5.1 The far-infrared luminosity function

<table>
<thead>
<tr>
<th>$L_{FIR}$ ($L_\odot$)</th>
<th>$N$</th>
<th>$\rho$ (Mpc$^{-3}$mag$^{-1}$)</th>
<th>$V/V_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.8</td>
<td>1</td>
<td>1.6</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>9.2</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>9.6</td>
<td>3</td>
<td>$4.4\pm2.8$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>10.0</td>
<td>5</td>
<td>$2.4\pm1.1$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>10.4</td>
<td>7</td>
<td>$7.0\pm2.8$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>10.8</td>
<td>14</td>
<td>$3.9\pm1.1$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>11.2</td>
<td>11</td>
<td>$8.8\pm2.8$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>11.6</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.0</td>
<td>1</td>
<td>$4.8$</td>
<td>$10^{-8}$</td>
</tr>
</tbody>
</table>

$L_\odot$ Mpc$^{-3}$ for all galaxies in the nearby universe, so that about 1% of the optical emission from galaxies in the nearby universe originates from galaxies with $L_{FIR}/L_B^0$ ratios larger than 3, a value close to the 2% estimated by van den Broek and de Jong (1990) from the $L_{FIR}/L_B^0$ distribution of a volume-complete sample of galaxies.

The space density of sources with low luminosities ($\log(L_{FIR}/L_\odot)\leq10.5$) in the extreme subsample is lower than that of the BGS sample (see Fig. 5.5), since due to the $\log(L_{FIR}/L_B^0)$ selection criterion we selected predominantly sources with higher luminosities (see Sect. 5.2.2). The missing fraction of galaxies is described as a function of $L_{FIR}$ by the error function based on a Gaussian distribution around an average value of $\log(L_{FIR}/L_\odot)=10.5\pm0.5$ with dispersion $\sigma=0.5$ derived in Sect. 5.2.2. If we add this missing fraction our data can very well be fitted by a single power-law in the range $\log(L_{FIR}/L_\odot)=9.4$ to 11.4: $\log(\rho)=2.0 \log(L_{FIR})+17.3$. This result differs from the two power-law fit for the BGS sample made by Soifer et al. (1987), which is also shown in Fig. 5.5. The fit to the corrected extreme subsample implies that there are more galaxies with low far-infrared luminosities in our far-infrared complete sample than in the BGS sample. However, it is questionable whether this difference is real, in view of the large corrections and uncertainties in the space density.

On the other hand, at high far-infrared luminosities the space density of the corrected extreme subsample is about a factor of two lower than that of the BGS sample. Such differences with the BGS sample can be expected due to local space density variations, since Field I of the extreme subsample covers only 3% of the total sky at southern latitudes, while the BGS survey covers more than 25% of the total sky mainly at northern latitudes. Furthermore, Rowan-Robinson et al. (1986) demonstrated the existence of a large-scale anisotropy, showing a 20% lower space density at southern galactic latitudes ($<-60^\circ$) than at northern galactic latitudes ($>60^\circ$). Because the extreme subsample and the BGS sample cover remote parts of the sky such a large-scale anisotropy may also help to explain the difference in space density at high far-infrared luminosities.

Summarizing, we find that the space density for infrared selected galaxies is consistent with the earlier estimate found for the BGS sample and that small apparent
5.2. Global discussion of the extreme subsample

5.2.4 Infrared colours

Co-added flux-densities are available for about 70% of the sources in the extreme subsample at 12 μm and for 95% at 25 μm, while only 45% and 55% of the sources of the RSA sample are detected at 12 μm and at 25 μm, respectively. No. 12 and 25 μm flux densities have been published for the BGS sample (Soifer et al., 1987). In Fig. 5.6 we have plotted a log(S_{25}/S_{12}) versus log(S_{100}/S_{60}) two-colour diagram for the extreme subsample and the RSA sample, which shows that for both samples the two colours are anti-correlated. This was already found by Helou et al. (1986) for normal galaxies like those in the RSA sample.

The anti-correlation seems to indicate that the 25 and 60 μm flux densities vary together with respect to the 12 and 100 μm flux densities. This is probably due to

Figure 5.5 The space density as a function of the far-infrared luminosity $L_{FIR}$ for various samples of galaxies (see text). The small diamond with error bars give the space density for the extreme subsample, while the small circles give the space density for the extreme subsample corrected for the missing fraction of galaxies. The straight dashed line is the single power-law fit to the small circles. The other dashed line is the two power-law fit for the Bright Galaxy Sample from Soifer et al. (1987), while the full line with points gives the space density of Seyfert galaxies (Meurs et al, 1984).
Figure 5.6 The S_{25}/S_{12} versus the S_{100}/S_{60} flux density ratio for the extreme subsample (stars) and the Revised Shapley-Ames sample (small crosses).

...warm dust of ~ 60 K associated with the star forming regions which radiates mainly at 25 and 60 μm, while the 12 and 100 μm flux densities are much less influenced by the warm dust.

The extreme subsample has larger S_{25}/S_{12} and smaller S_{100}/S_{60} ratios and the correlation is somewhat tighter than for the RSA sample, which can be explained by a two-component dust model discussed by Helou et al. (1986).

5.2.5 Dust masses

In Fig. 5.7 we have plotted the S_{100}/S_{60} ratio against L_{FIR} for the extreme subsample, the BGS, and the RSA sample. Furthermore, lines of equal dust mass are shown, assuming a single dust temperature T_d derived from the S_{100}/S_{60} ratio. The radiating dust masses are calculated adopting $\kappa_\lambda=2.3 \times 10^4 \lambda^{-1} \text{cm}^2\text{gr}^{-1}\mu\text{m}$ (Gillett et al., 1988) using

$$M_{\text{dust}} = 0.5D^2S_{100}(e^{144/T_d} - 1) \, [M_\odot]$$

(5.2)

where D is the distance in Mpc, S_{100} is in Jy, and T_d is in K (see Paper III). The radiating dust masses in the extreme subsample vary from $10^5$ to $10^7$ M_\odot, except for the dwarf galaxy No. 2 which has only $5 \times 10^4$ M_\odot. As already noticed by Young (1990) and in Paper III, dust masses derived using a single dust temperature give dust-to-gas...
5.2. Global discussion of the extreme subsample

Figure 5.7 The $S_{100}/S_{60}$ flux density ratio versus the $L_{FIR}$ luminosity for the extreme subsample (stars), the Bright Galaxy Sample (small circles) and the Revised Shapley-Ames sample (small crosses). Also shown are contours of equal dust mass for a single dust component (dashed lines) and for two dust components (full lines); see text.

ratios, which are an order of magnitude smaller than those observed in our Galaxy. Various authors (de Jong and Brink, 1987; Helou et al, 1986; Rowan-Robinson and Crawford, 1986, 1989) have proposed two dust components: a warm component ($\sim 60$K) associated with the star forming regions and a cool component ($\sim 16$ to 20K) associated with the interstellar radiation field. Assuming fixed dust temperatures for these components the relative abundance of the dust masses is then determined by the $S_{100}/S_{60}$ ratio. Assuming such a two-component dust distribution we derive dust masses, which are larger by one or two magnitudes than those derived with a single dust temperature, due to the dominant contribution of the cool dust, which radiates mainly longward of the IRAS bands ($\lambda > 120\mu$m). The cool dust mass therefore depends critically on the choice of the cool dust temperature. In Paper III we found 18 K and 60 K to be suitable values for the cool and warm dust temperature to obtain dust-to-gas mass ratios comparable with those found in our galaxy. In Fig. 5.7 we therefore also show lines of constant total dust mass derived from this two-component dust model with temperatures of 18 K and 60 K.
Summary and interpretation of the observations

5.2.6 The NaID absorption line

In most spectra, which predominantly show the nuclear light of our galaxies (see Paper I), we observe strong NaID ($\lambda$5890, 5896Å) absorption lines. In Table 4 of Paper I we listed the equivalent widths, which ranges from 1 Å to 6 Å. These lines can be generated in stellar atmospheres or they may be due to absorption in the interstellar medium. Because other stellar features generated in the same type of stars as the NaID doublet, like the MgI triplet, are absent or only marginally present, we conclude that the NaID lines are mainly due to absorption by sodium atoms in the interstellar gas.

Since the dust-to-gas mass ratio is generally more or less constant (see also Paper III), we expect that the equivalent width of the NaID lines will be correlated with the reddening by dust. In Fig. 5.8 we plot the reddening in the B-band towards star forming regions, $A_B$, derived from the Balmer decrement versus the equivalent width of the NaID lines. No clear correlation can be seen and in Sect. 5.6.2 we show that the reddening by dust towards star forming regions and the reddening elsewhere in the disk by ‘interstellar’ dust are rather unrelated, so that the gas which contains sodium is probably not associated with the gas and dust in and near star forming regions, but rather with gas and dust in between the stars of the older population (i.e. stars already existing before the beginning of the burst).

This means that in principle we can use these lines to estimate the amount of gas in the central regions of the galaxies. If the lines are not saturated, the following relation (Spinrad, 1962) for the equivalent width $W_\lambda$ of the NaID lines holds

$$W_\lambda = l \lambda^2 f \pi \frac{e^2}{mc^2} \quad [\text{Å}]$$

where $f=1$, $\lambda=5893$Å, $l$ is the path length and $N$ is the number density of neutral Na.
5.3. Morphological subgroups

5.3.5.3. Morphological subgroups

Taking a spherical distribution of gas with radius \( l \), a solar sodium abundance of \( \text{Na}/\text{H}=1.8 \times 10^{-6} \) (Allen, 1973) and an ionization degree of Na in an HI region of \( N_i/N_0=1500 \) (Spinrad, 1962), we derive a gas mass for the atomic hydrogen of

\[
M_{HI} = 9 \times 10^8 \text{W}_l l^2 \quad [M_\odot] \tag{5.4}
\]

where \( \text{W}_l \) is in Å and \( l \) is in kpc. Taking a reasonable path length \( l \) of about 1 kpc through an inclined (not edge-on) disk, we obtain HI gas masses of \( 1-5 \times 10^9 M_\odot \). It is clear that we have to consider this result with some caution due to the uncertain assumptions. However, in Paper III we report the detection of \( 5 \times 10^8-3 \times 10^9 M_\odot \) of molecular hydrogen in a subsample of our galaxies and since we expect the similar atomic and molecular hydrogen gas masses for the galaxies in our sample (see Mirabel and Sanders, 1989), it seems that we may indeed use the NaID equivalent width to derive crude estimates of the HI gas mass.

Summarizing, we find HI and \( \text{H}_2 \) gas masses of order \( 10^9-10^{10} M_\odot \) in the centres of our galaxies, where also most of the star forming regions are found (see Sect. 5.4). Van den Broek (1990) derives star formation rates of order \( 0.1-100 M_\odot \text{yr}^{-1} \), so that there is enough gas to sustain these star formation rates for at least \( 10^8 \) years.

5.3 Morphological subgroups

We listed the morphological classification of the observed galaxies in the extreme subsample in Table 5 of Paper I. These classifications together with the luminosities enable us to distinguish between various subgroups in the extreme subsample. We can globally divide the extreme subsample into three almost mutually excluding subgroups: (1) isolated dwarf galaxies (with \( M_B \geq -19 \text{ mag} \) or \( \log(L_B/L_\odot) \leq 9.6 \)), (2) barred spirals and (3) interacting systems with generally disturbed morphologies. This differentiation of the extreme subsample is rather complete, since the three subgroups cover about 90% of the extreme subsample and are almost completely disjunct; only No. 23 is a barred interacting spiral, and No. 7 is a barred dwarf spiral. In Fig. 5.9 we show histograms of \( L_{FIR} \) and \( L_{FIR}/L_B^2 \) for the subgroups and in Table 5.2 some global properties of the subgroups are presented.

The virtual absence of non-barred spiral galaxies in our sample (we find only one clear example) is a striking contrast with the high percentage (about 50%) of these ‘normal’ spirals in optically selected samples of field galaxies. The percentage of barred spirals in our sample (35%), however, is comparable with their occurrence (about 25%) in the optical samples.

In the following subsections we will give a short discussion of the properties of the various subgroups.

5.3.1 Dwarf galaxies

Some 20% of the extreme subsample consists of dwarf galaxies. Applying the same criterion to select dwarfs (\( \log(L_B/L_\odot) \leq 9.6 \)) to the extreme subsample fraction of the BGS sample (\( \log(L_{FIR}/L_B) \geq 0.5 \)) we find a fraction of 30% of dwarf galaxies, about 50% more than in the extreme subsample. This difference may be due to the fact that the BGS sample contains the Virgo Cluster, in which a relatively large number of
Table 5.2 Average properties for the subgroups of the extreme subsample

<table>
<thead>
<tr>
<th></th>
<th>Dwarfs</th>
<th>Barred spirals</th>
<th>Interacting systems</th>
<th>Remaining sources</th>
<th>Extreme subsample</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>9</td>
<td>15</td>
<td>15</td>
<td>5</td>
<td>42</td>
</tr>
<tr>
<td>perc.</td>
<td>21</td>
<td>36</td>
<td>36</td>
<td>12</td>
<td>100</td>
</tr>
<tr>
<td>$L_{FIR}/L_B^0$</td>
<td>4.0</td>
<td>4.6</td>
<td>8.7</td>
<td>6.7</td>
<td>5.9</td>
</tr>
<tr>
<td>$\log(L_{FIR}/L_\odot)$</td>
<td>9.78</td>
<td>10.57</td>
<td>11.11</td>
<td>10.83</td>
<td>10.63</td>
</tr>
<tr>
<td>$\log(L_B^0/L_\odot)$</td>
<td>9.18</td>
<td>9.90</td>
<td>10.18</td>
<td>10.00</td>
<td>9.88</td>
</tr>
<tr>
<td>$D_{25}$ (kpc)</td>
<td>7.9</td>
<td>20.8</td>
<td>28.1</td>
<td>21.4</td>
<td>20.3</td>
</tr>
<tr>
<td>$S_{100}/S_{80}$</td>
<td>1.55</td>
<td>1.66</td>
<td>1.41</td>
<td>1.66</td>
<td>1.55</td>
</tr>
<tr>
<td>$S_{60}/S_{25}$</td>
<td>8.13</td>
<td>7.24</td>
<td>8.71</td>
<td>10.00</td>
<td>8.32</td>
</tr>
<tr>
<td>$S_{25}/S_{12}$</td>
<td>2.51</td>
<td>2.45</td>
<td>3.47</td>
<td>—</td>
<td>2.75</td>
</tr>
<tr>
<td>$A_B$ (mag)</td>
<td>3.7</td>
<td>5.8</td>
<td>5.5</td>
<td>5.8</td>
<td>5.3</td>
</tr>
<tr>
<td>$EW_{Na}$(Å)</td>
<td>2.0</td>
<td>3.5</td>
<td>3.3</td>
<td>3.7</td>
<td>3.2</td>
</tr>
<tr>
<td>$h_r/l_r$</td>
<td>40</td>
<td>60</td>
<td>70</td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td>SFR($M_\odot$yr$^{-1}$)</td>
<td>0.6</td>
<td>4</td>
<td>14</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

Notes: $h_r/l_r$ is ratio of high- to low-resolution radio continuum flux densities.

Dwarf galaxies can be detected by IRAS. Other studies of the BGS sample (Carico et al., 1988; Sanders et al., 1988) did not discuss these dwarf galaxies, because they only considered galaxies with the highest far-infrared luminosities ($\log(L_{FIR}) \geq 11$ $[L_\odot]$).

Our criterion that dwarfs have low blue luminosities could in principle imply that we have also selected large very dusty galaxies, whose blue luminosities are severely suppressed by dust extinction and which will therefore show high $L_{FIR}/L_B^0$ ratios. However, a high $L_{FIR}/L_B^0$ ratio is only observed for No. 22 (see below). All other dwarf galaxies appear to have lower $L_{FIR}/L_B^0$ luminosity ratios and $L_{FIR}$ luminosities than those of the other subgroups in the extreme subsample (see Fig. 5.9 and Table 5.2.), indicating that these galaxies are real dwarfs. The Balmer decrement and the equivalent width of the NaID lines of these dwarf galaxies confirm that their B-band extinctions $A_B$ and gas masses (see Sect. 5.2.6) are indeed below the average of the extreme subsample (see Table 5.2.).

All dwarfs are disk galaxies (see Paper I) and nearly all show extended Hα emission (see also Sect. 5.4.1). They are all isolated, except for No. 18, which is a member of a wide pair. No. 7 is a barred dwarf, for which the bar is quite pronounced in Hα. No. 31 is a rare, gas rich S0-type galaxy with rather blue colours (see also Paper III). Nos. 2, 8, and 19 are small ($D_{25} \sim 5$ kpc) blue galaxies with a high surface brightness belonging to the class of blue compact dwarf galaxies (see e.g. Loose and Thuan, 1985). No. 18, 25 and 42 are red spirals, for which the Balmer decrement gives an $A_B$ of about 5 magnitudes, indicating that dust plays a more important role here. They are also larger ($D_{25} \sim 10-15$ kpc). No. 22 is a quite faint and small ($\log(L_B^0/L_\odot)$=8.04, $D_{25}$=2.2 kpc) red S0-type galaxy with an exceptional high far-infrared-over-blue luminosity ratio, $\log(L_{FIR}/L_B^0)=1.69$, which shows only weak Balmer lines in its spectrum, while the NaID absorption lines are clearly present. This
5.3. Morphological subgroups

Figure 5.9 Histograms of a. (left) the $L_{FIR}$ luminosity and b. (right) the $L_{FIR}/L_B^0$ luminosity ratio for various subgroups in the extreme subsample. From top to bottom: Dwarf galaxies, Barred spirals, Interacting systems and remaining sources.

Could mean that its high $L_{FIR}/L_B^0$ luminosity ratio is largely due to dust absorption. On the other hand a strong TiO absorption band at $\sim6200\AA$ is observed, indicating the presence of large numbers of red supergiants from the star formation process (cf. van den Broek and de Jong, 1990). Its dustiness makes it peculiar since most dwarf galaxies have low metallicities due to a small star formation rate in the past, so that less dust can be formed.

Almost all dwarf galaxies are observed in the CO(J=1→0) line, but only two of them are detected (see Paper III). These detections and lowerlimits indicate that the star formation efficiency, as expressed by the $L_{FIR}/M_{H_2}$ ratio, is at least as large as for the barred spirals (see Sect. 5.3.2).

The spectra of our dwarf galaxies are all typical HII-type spectra, without any signs of nuclear or LINER activity. In most cases the [OIII] lines are weak, indicating also low excitation. An exception is No. 2, which shows strong emission lines with dominating [OIII] lines, indicating high excitation. Nevertheless its spectrum is still to be classified as an HII spectrum.
Summary and interpretation of the observations

### Table 5.3 Classes within the subgroups

<table>
<thead>
<tr>
<th>Dwarfs</th>
<th>Barred spirals</th>
<th>Interacting systems</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Class number</td>
<td>Class number</td>
</tr>
<tr>
<td></td>
<td>spirals 4</td>
<td>SB0/a+SBa 4</td>
</tr>
<tr>
<td></td>
<td>SO-types 2</td>
<td>SBab+SBb 7</td>
</tr>
<tr>
<td></td>
<td>BCDG 3</td>
<td>SBbc+SBc 4</td>
</tr>
</tbody>
</table>

Notes: 1) within brackets: number of systems for which both members are strong radio (and thus IRAS) sources

#### 5.3.2 Barred spirals

About one third of the extreme subsample consists of barred spirals (see Table 5.2.). A comparison with the BGS sample is not possible, since the morphological classification of the entire BGS sample has not yet been published. The barred spirals are rather equally distributed over the Hubble sequence from type SBO/a to SBc (see Table 5.3).

The average log($L_{FIR}/L_\odot$) ratio for the barred spirals is intermediate between that of the dwarf galaxies and the interacting systems (see Fig. 5.9).

The Hα-images show that in two-thirds of the barred galaxies Hα emission is present in the bar as well as in the nucleus, illustrating that active star formation can occur in bars. However, the observations also show that the bulk of the star formation is located in and near the nucleus (see Sect 5.4.2).

It is sometimes argued that a bar instability is triggered by an interaction with another (dwarf) galaxy. The star formation activity in these systems could then also be considered as a consequence of such an interaction. For only 4 out of 15 barred spirals we find galaxies at distances smaller than 2 arcmin. We do not have redshift information for these possible companions and they can very well be background objects in view of their smaller diameters and relatively high surface brightness. Thus we conclude that most barred spirals are probably isolated, although inconspicuous interactions or mergers with tiny dwarfs cannot be excluded.

Hawarden et al. (1985) already showed that barred galaxies can show enhanced star formation from a study of their far-infrared properties. They found that most of the barred galaxies have high 25 to 12 μm flux density ratios ($\geq 2.22$), which they related to enhanced star formation. We indeed find an average $S_{25}/S_{12}$ flux density ratio of 2.45 for our barred spirals, confirming their results. However high values of the $S_{25}/S_{12}$ flux density ratio are also found for the other subgroups in the extreme subsample (see Table 5.2.).

About half of the barred spirals are observed and detected in the CO(J=1→0) line, showing that the average star formation efficiency, $L_{FIR}/M_{H_2}$, is about four times as high as found for optically selected normal spiral galaxies.

The barred spirals show mostly HII-type spectra. Only four galaxies show spectra typically found for active galactic nuclei (AGNs), of which No. 10 is the only SI-type spectrum. No. 15, which shows an extended circumnuclear ring of HII regions in Hα (see also Sect 5.4.2), shows an exceptionally low-excitation spectrum without detected
5.3.3 Interacting and merging systems

About one third of the extreme subsample consists of interacting and merging systems. This number is in good agreement with the statistics found for the BGS sample (Sanders, 1988). These systems have the highest average far-infrared luminosity and far-infrared over blue luminosity ratio in the extreme subsample (see Table 5.2.). Most systems are closely interacting (see Table 5.3); only one interacting pair and 4 merger candidates are present (see Paper I for a definition of these classifications). All these systems show disturbed morphologies and in the closely interacting pairs often tidal tails and bridges are seen. In three cases (Nos. 20, 21, and 41) a particularly bright tail is seen on the opposite side of the companion.

Of the 4 merger candidates only one system (No. 11) shows the characteristics of a ‘classical’ merger: a double nuclear structure in both the Hα-image and the radio continuum map, while the brightness profile follows a de Vaucouleurs r^1 law indicating a dynamically relaxed system of stars.

The Hα images of the interacting systems show that in almost all cases the nuclear region dominates the emission, as was already found by Bushouse (1987) for his optically selected sample of interacting galaxies. The radio continuum observations confirm that most of the star formation activity is located in and near the nucleus (see Sect. 5.4.3).

In about half of the (closely) interacting pairs both members are detected at radio wavelengths, indicating that the star formation rate is strongly enhanced in both members, while for the other half vigorous star formation seems to occur only in one member of a pair. Obviously interactions can enhance star formations rates in one as well in both members of a pair.

Only four interacting systems have been observed in the CO(J=1→0) line, of which three are detected. The star formation efficiencies, \( L_{FIR}/M_H \), for these galaxies are in the same range as for the barred spirals (see Sect. 5.3.2). However, these observed interacting systems are among the less extreme in this subgroup, so we cannot draw a conclusion for the whole subgroup.

The interacting systems show mostly HII-type spectra. AGN-type spectra are found in one member of five interacting systems and only in No. 21 do both members show an AGN-type spectrum. The spectrum of the western galaxy of No. 20 is peculiar because it is a SII-type spectrum with strong H\( \beta \) absorption, indicating a dominating population of A-type stars, which are only found in post-starburst galaxies.

5.3.4 Remaining sources

Five galaxies remain that do not fit in the three above mentioned subgroups. We will discuss them here.

No. 3. This S0-type galaxy is quite extreme in the far-infrared (\( \log(L_{FIR}/L_\odot) = 10.85 \) and \( L_{FIR}/L_\odot=0.95 \)) and is gas-rich, like the smaller galaxy No. 31, which has been classified as a dwarf in our subdivision of the sample (see Sect. 5.3.1 and Paper III). From the equivalent width of the NaI absorption lines we estimated (see
Sect. 5.2.6) a total HI mass of $5 \times 10^9 \, M_\odot$ for No. 3, implying an $M_{HI}/L_B^0$ ratio of $0.6\, M_\odot/L_\odot$, which is among the very highest values found for lenticulars (see Wardle and Knapp, 1986), and for No. 31 we estimate a ratio of $0.4\, M_\odot/L_\odot$; however, a comparison to the CO line data for No. 3 indicates that these $M_{HI}$ values may be overestimates, but even then these galaxies are quite gas-rich for their morphological types. The classification of No. 3 as an S0 is confirmed by its featureless appearance in the B, V and R bands, the presence of an exponential disk and a bulge in its luminosity profile (see Paper I) and its characteristically red colours. Its far-infrared properties are similar to those of a sample of S0 galaxies with warm infrared colours selected by Dressel (1988); optically selected lenticulars are rarely detected by IRAS and they have quite different global far-infrared properties (van Driel and de Jong, 1990). The star formation in this object seems to be concentrated in the nuclear region (see Sect. 5.4.4). The origin and evolution of these rare gas-rich lenticulars is not yet completely clear (see e.g. van Driel and van Woerden 1990; van Driel, 1987). Accretion of gas through a close encounter with a sizeable gas-rich galaxy is a likely source, but galaxies No. 3 and 31 seem to be quite isolated; however, the gas may also have an origin from within the galaxy itself.

No. 13. This peculiar galaxy is isolated and disturbed. It shows a double or ring-like structure in Hα. The radio observations show two clear spots on the ring.

No. 16. This may be a peculiar S0 galaxy with a low-surface brightness. Its high $L_{FIR}/L_B^0$ ratio may therefore be due to extreme dustiness.

No. 32. This spiral galaxy is isolated and highly inclined. Therefore it is not possible to detect a possible bar.

No. 39. This Sc spiral is the only example in our sample of a spiral galaxy where the star formation in the spiral arms is dominating. In particular the anomalous southern arm shows bright Hα emission. Its $L_{FIR}/L_B^0$ ratio is among the lowest found in the extreme subsample, in agreement with the conclusion that star formation in spiral arms can not enhance the far-infrared emission too much.

5.3.5 Conclusions

In our sample with high $L_{FIR}/L_B^0$ luminosity ratios we can distinguish three classes of galaxies: interacting, barred and dwarf galaxies. Interactions between galaxies appear to be the most effective way to enhance the star formation rate and the far-infrared emission. Bars in galaxies can also enhance the star formation rate, although to a lesser extent. Furthermore there exists a class of dwarf galaxies with substantial star formation rates, giving $L_{FIR}/L_B^0$ ratios which are extreme for dwarf galaxies, but not for the interacting and barred galaxies.

The absence of normal non-barred spiral galaxies in our sample implies that star formation in spiral arms is not an efficient way to power the far-infrared emission and to get high $L_{FIR}/L_B^0$ luminosity ratios.

5.4 Star forming regions

In this section we discuss various aspects of the star forming regions observed in our galaxies, using star formation tracers like far-infrared, Hα line and radio continuum
5.4. Star forming regions

For our galaxies with a strong far-infrared excess the far-infrared emission is entirely due to reradiation of the observed ultraviolet photons from young hot stars in the starburst and it is not influenced by radiation from dust heated by the older stellar population. Since the far-infrared radiation is not weakened by dust absorption like in the optical and ultraviolet, the far-infrared can give us a good idea of the star formation rate. However we have no spatial information, because the beam size of the IRAS detector at 60 and 100 µm is about 3'-5', much larger than the $D_25$ diameters of our galaxies (on average 45 arcsec).

We do not have this resolution problem when we study the star forming regions in the Hα line with a seeing of 1''-2'', resolving structures down to sizes of 0.5-1 kpc at the average distance of 100 Mpc for the sample. However, the Hα emission is subject to severe dust absorption, as derived from the Hα/Hβ line ratio (see Section 5.6.3), and it appears that we observe on average only some 8% and in the worst cases only 1% of the Hα emission.

Perhaps the most useful way to study the star forming regions is therefore to observe the radio continuum emission. Since the discovery of a strong correlation between the far-infrared and the radio continuum emission (de Jong et al., 1985) it is clear that the radio continuum emission is closely related to the star formation process. The estimate that about 40% of the radio continuum emission at 6 cm in the galaxies of the extreme subsample has a thermal origin (Paper II), shows that at least a significant fraction should also be spatially correlated with the star forming regions. The non-thermal emission is synchrotron radiation generated by fast moving electrons, probably from supernovae explosions, which interact with the interstellar magnetic fields and this emission can be much more extended than the star forming regions. However it is also possible that the electrons already loose most of their energy in young supernova remnants as is observed in M82 (Bartel et al., 1989), so that also the non-thermal emission is spatially closely related to the star forming regions.

Radio emission is not disturbed by dust absorption. High resolution radio maps with resolutions (~ 1'') comparable to the optical observations can therefore in principle clearly reveal the regions with the most vigorous star formation. However, we do not detect extended radio emission with a surface brightness less than 0.5 mJy arcsec$^{-2}$ in the high-resolution observations with a beam size of about 1'' and a 3σ detection limit of 0.5 mJy/beam (see Paper II). This means that we cannot map the less active and extended star forming regions in detail. We found on average that only 60% of the total flux density detected at low-resolution is seen at high-resolution.

We can assume that the emission from the star forming regions consists of two components: a more extended diffuse component with low surface brightness emission and a compact component consisting of small regions of more intense star formation and emission. In the high-resolution radio observations we generally detect only the compact component, while in the low-resolution observations we see both components, although we cannot spatially resolve them. In Paper II it is shown that the ratio of high-to-low resolution radio continuum flux densities increases with increasing log$(L_{FIR}/L_B)$, indicating that when a galaxy forms stars more actively, it is doing so mainly in the compact star forming regions. In almost all cases these regions are only found in and near the nuclei of the galaxies (see Sect. 5.4.2 and 5.4.3).
Despite the severe extinction by dust, the Hα images show in general both the compact and diffuse component, so that a comparison of the Hα observations with the radio continuum observation gives a rather complete picture of the starforming regions. In the following subsections we will discuss the star forming regions for the various subgroups of the extreme subsample found in Sect. 5.3.

5.4.1 Dwarfs

In the Hα images of almost all dwarf galaxies we observe extended emission. This extended emission is in most cases also seen in the high-resolution radio maps at 6 cm. The average ratio between the high and low resolution flux densities at 6 cm is 40% (see Table 5.2), indicating that much of the radiation from the star formation process is generated in the diffuse component. The diameter of the Hα images is on average about 50% of the D25 diameter, i.e. 2–6 kpc.

In Nos. 7, 18, 19 and 31 the nucleus is the most prominent source of Hα and radio emission, while in No. 2 two point sources of comparable strength are observed in addition to the more diffuse component, of which the western peak is the nucleus. In Nos. 8, 25 and 42 the emission forms a plateau without an important contribution of the nucleus. For No. 22 no Hα image is available and this source is only marginally detected at radio wavelengths, so that no conclusions can be drawn.

It is not clear why these dwarf galaxies show enhanced star formation. They appear in general to be isolated, so that interactions with galaxies do not play a role here. Only No. 25 is a member of a wide pair without any signs of interaction. Maybe internal cloud-cloud collisions can trigger a burst of star formation (Norman, 1985). An interesting model that may be relevant for these dwarf galaxies is the so-called stochastic self-propagating star formation (Gerola et al., 1980; Feitzinger et al., 1981). A simple description of this model is that, given a region of presently active star formation in a dwarf galaxy, there is a finite probability that a new region of star formation will appear in its vicinity after a certain time. A starburst results when enough regions can be ignited within a short time.

Note, however, that although these dwarf galaxies have a relatively large star forming activity for their kind, they do not have extremely high L_{FIR}/L_α ratios (see Table 5.2) and star formation rates (see Paper V) compared to the barred spirals and interacting systems.

5.4.2 Barred spirals

In all barred spirals the nuclear region is the most important source of Hα line and radio continuum emission. In two-thirds of these galaxies the Hα emission is also seen in the bar. However the bars themselves are never seen in the high-resolution radio continuum observations, implying that the emission in the bars belongs to the diffuse component. The average ratio between the high and low resolution flux densities at 6 cm is 60% (see Table 5.2), indicating that most of the emission is from star forming regions in and around the nucleus and that the emission in the bars plays only a minor role. When Hα line emission is observed in bars, this emission is mostly concentrated at the outer ends of the bars. The size of the extended emission in the bars is of order of 2.5–10 kpc, while the sizes of the nuclear sources are quite small, since these
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sources are in most cases both unresolved in the Hα and radio continuum emission, indicating diameters of less than 0.2-0.6 kpc. Nos. 26, 27, and 40 show nuclear sizes of 2-3 arcsec, i.e. 0.6-1.8 kpc and No. 29 shows 2 blobs of emission at about 1.5-2 kpc from the nucleus in the high-resolution radio continuum maps. The line connecting these two regions is perpendicular to the main axis of the bar. No. 15 is a point source in the high-resolution radio observations, but it shows a nuclear ring with a radius of 0.8 kpc in Hα.

Most of the barred galaxies appear to be isolated. Only the barred galaxy No. 23 (see Sect. 5.3.2) is closely interacting with a dwarf galaxy, which itself also shows signs of enhanced star formation as indicated by its Hα emission. The lack of interaction indicates that the cause of the enhanced star formation is very likely closely related to the presence of the bar. That bars are associated with enhanced star formation has already been known for some time. Hawarden et al. (1987) noted that many barred spirals have nuclei surrounded by luminous ring-like complexes of HII regions, with radii of a few hundred parsecs to a kiloparsec, closely associated with dust lanes, which run down the edge of bar. These dust lanes are known to trace out shock fronts generated in the interstellar medium by the rotating ellipsoidal potential of the bar, and models (Schwarz, 1985) indicate that these fronts curl around the nucleus and cause an efficient movement of gas inwards along the bar. Timescales of 10^8 yr are found in these models for the gas to be driven inwards within one bar radius. The bar-driven inflow predicted by these models is supported by both HI (Sancisi et al., 1981) and optical (Blackman and Pence, 1984) observations. The inflow of gas must be a function of the strength of the non-axisymmetric component of the potential. For any galaxy with a strong central concentration of mass this non-axisymmetric component must decline in importance very close to the centre and consequently there must be a radius at which the inflow will cease. This implies that there must be a circumnuclear stagnation zone in which the gas driven by the bar accumulates and which is a very likely location for vigorous star formation (see Hawarden, 1987). For most of the barred galaxies in our sample these stagnation zones appear to have radii smaller than 0.2 kpc, since the nuclear sources are unresolved in both the Hα and radio continuum observations. Only the two blobs of radio continuum emission for No. 29 and the circumnuclear ring of Hα emission for No. 15 may indeed be such stagnation zones.

5.4.3 Interacting systems

In these systems the Hα emission is clearly confined to the nuclear regions, which is supported by the high-resolution radio continuum observations. An exception may be No. 5, where we find two compact regions of Hα and radio continuum emission 3.5 kpc to the west of the nucleus of the brighter galaxy. It is not clear whether the emission originates from the nucleus of the ‘background’ galaxy or from the ‘contact’ zone between the two interacting galaxies.

The average ratio between the high- and low-resolution flux densities at 6 cm is 70% (see Table 5.2). Obviously most of the emission from star forming regions belongs to the compact component and the more distributed diffuse emission is of less importance, indicating that once star formation is triggered at a location, stars
Summary and interpretation of the observations

are formed quite intensively at that location.

The sizes of the sources are on average larger than the stagnation zones in the barred galaxies. About half of the sources are unresolved and have sizes less than 1 kpc, while the rest have diameters between 2 and 7 kpc. The sources in the merger candidates are small (∼ 1 kpc), except No. 36 which has a diameter of 7 kpc. Merger candidates No. 11 and 36 show a double structure. In half of the (closely) interacting pairs only one member is detected at radio wavelengths, while for the other half both members have a comparable brightness. No. 17 is exceptional since the Hα is comparable for both members, while the radio observations only show a source in the southern galaxy, indicating that the extinction by dust is much more extreme in the southern than in the northern galaxy, which is indeed inferred from the Balmer decrement. The north-eastern component of No. 21 is the only galaxy in our sample with a radio power well above the value expected from the far-infrared/radio correlation, indicating an active nucleus in a radio galaxy. The detection at radio wavelengths of the south-western component is uncertain, so that it is difficult to decide where most of the star formation is located on the basis of the radio observations. The Hα images show emission in both galaxies, while the extinction derived from the Balmer decrement is comparable, so that probably both galaxies show enhanced star formation.

It is clear that the interaction causes the enhanced star formation and in fact the most (ultra-)luminous galaxies in the far-infrared are always interacting or merging (see Sanders et al., 1987). The interacting systems in the extreme subsample belong to the most luminous far-infrared emitters (see Sect. 5.3.3) in our sample. Our interacting galaxies clearly show typical tidal distortions (tails, bridges) of the stellar system and their velocity fields are probably also distorted by the gravitational perturbations produced by the interactions. This may lead to dynamical friction between gas clouds, which in turn leads to a radial gas inflow towards the nucleus and consequently to accumulation of gas in the nuclear region. A precondition for star formation is that the gas cools, since the orbital kinetic energy is transformed by friction into increased random motion of the gas particles. N-body simulations by Negroponte and White (1983) have demonstrated that this energy can be dissipated by cloud-cloud collisions, thereby cooling the gas in the nuclear regions (see also Bushouse, 1987). Obviously this leads to vigorously star forming regions which can extend to a few kiloparsecs from the center, as indicated by our observations.

It is also clear that interactions are a more efficient way to transport gas towards the centre than bars are, since the interacting systems show on average larger and more active star forming regions than the barred spirals.

5.4.4 The remaining sources

In this section we discuss the properties of star forming regions for the five remaining sources which do not belong to one of the previous subgroups (cf. Sect. 5.3.4).

No. 3. This source is unresolved in both the Hα and radio observations, indicating a diameter less than 0.6 kpc. The ratio between the high- and low-resolution radio continuum flux density is 100%, so actually all emission is confined within a radius of 0.3 kpc from the center.
5.5. AGN-type spectra

No. 13. This source is clearly extended in both the Hα and the radio observations. The size of the source is about 6 kpc in diameter. The ratio between the high- and low-resolution radio continuum flux densities is 60%, so that a substantial part of the emission belongs to the diffuse component. The Hα emission shows a kind of double or ring-like structure. The high resolution radio maps show various compact regions scattered over an area within a radius of 3 kpc from the center, of which the two brightest regions form a double structure, which do not however coincide with the brightest Hα regions.

No. 16. The Hα image shows a slightly extended nuclear source with a diameter of 3 kpc. In the high-resolution radio data only a point source is observed, while the ratio of high- to low-resolution flux density is 85%, indicating that most of the emission is generated close to the nucleus, within a radius of 0.4 kpc.

No. 32. The Hα image shows an unresolved nuclear source, with a smaller point source to the south. The radio maps only reveal a nuclear point source, while the high- to low-resolution radio flux density is 75%, indicating that most of the emission is generated in a nuclear region with a diameter of less than 0.5 kpc.

No. 39. The Hα image shows that star formation is extended over the whole disk of this spiral galaxy with a radius of 5 kpc. Sources in the disk are as prominent as the nuclear source. The radio continuum emission is also extended, both at high and low resolution, indicating a source of at least 3 kpc in radius. The high- to low-resolution radio flux density ratio is 30%, indicating that most of the emission is in the diffuse component.

5.4.5 Conclusions

We conclude that active star formation is found in both compact regions and extended regions. The dwarf galaxies with relatively low star formation rates predominantly show extended star forming regions, while the more active barred spirals and the interacting systems mainly show compact star forming regions, which in most cases are found within a radius of about 1 kpc from the nucleus, implying that if stars are formed more actively, the larger activity is mainly found in the compact regions.

5.5 AGN-type spectra

In Paper I we classified the spectra of the extreme subsample, as HII-, LINER- and Seyfert-type spectra, using diagnostic diagrams based on emission line ratios, following Veilleux and Osterbrock (1986). In Table 5.4 we give some statistics for each class. In this Section we discuss the nature of the sources with LINER- and Seyfert-type spectra in our sample, which we will refer to these spectra as AGN-type spectra.

In Fig. 5.10 we show the distribution of the $L_{\text{FIR}}$ luminosities and the $L_{\text{FIR}}/L_B^0$ luminosity ratios of the AGN-type galaxies in Field I. The AGN-type sources have on average significantly higher far-infrared luminosities as well as higher $L_{\text{FIR}}/L_B^0$ ratios than those of the non-AGN galaxies in the extreme subsample. There also seems to be a cut-off in the far-infrared luminosity ($\log(L_{\text{FIR}}/L_\odot)=10.3$), below which no AGN-type sources are found at all (cf. Fig. 5.10 and Fig. 5.1).
Summary and interpretation of the observations

Table 5.4 Statistics of spectra

<table>
<thead>
<tr>
<th>Spectral-type</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>HII-type (HII)</td>
<td>74</td>
</tr>
<tr>
<td>LINER-type (L)</td>
<td>8</td>
</tr>
<tr>
<td>LINER/Seyfert II-type (SII/L)</td>
<td>11</td>
</tr>
<tr>
<td>Seyfert II-type (SII)</td>
<td>5</td>
</tr>
<tr>
<td>Seyfert I-type (SI)</td>
<td>2</td>
</tr>
</tbody>
</table>

Comparing these results with the results for the BGS sample (Sanders et al., 1987), see Table 5.5, we conclude that the extreme subsample has a higher percentage of active galaxies, especially between log(L_{FIR}/L_{\odot})=10 and 11. One should however bear in mind that selection of sources for the extreme subsample in this luminosity interval is subject to a selection effect (see Sect. 5.2.2). Predominantly the higher luminosities were selected, giving a higher percentage of AGN-type sources, since the percentage of AGN-type galaxies increases with luminosity.

5.5.1 The far-infrared/radio correlation

An active nucleus will probably contribute to the far-infrared luminosity by emission of dust that is heated by the radiation from the nucleus. On the other hand, active galactic nuclei often show strong radio continuum emission. For example luminous radio galaxies always have active galactic nuclei. These contributions from active nuclei will in general cause the galaxies to deviate from the standard far-infrared/radio correlation, which is attributed to the birth and death of recently formed stars (de
5.5. AGN-type spectra

Table 5.5 Percentage of AGN-type spectra

<table>
<thead>
<tr>
<th>( \log(\text{L}<em>{\text{FIR}}/\text{L}</em>\odot) )</th>
<th>10–11</th>
<th>11–12</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Field I</strong></td>
<td>25%(24)</td>
<td>50%(12)</td>
</tr>
<tr>
<td><strong>BGS</strong></td>
<td>10%(80)</td>
<td>30%(80)</td>
</tr>
</tbody>
</table>

Notes: between brackets the number of sources

Jong et al., 1985). De Grijp (1990) indeed finds a considerable fraction of galaxies with radio powers larger than those expected on the basis of the far-infrared/radio correlation in his sample of galaxies with high 25 to 60 \( \mu \)m flux density ratios, which contains a high percentage of active nuclei. Obviously it is mainly the radio power which is affected by the presence of an active nucleus. In the extreme subsample however only one galaxy has an exceptionally large radio power (No. 21NE, classified as a LINER) and deviates significantly from the correlation. The correlation for all other AGN-type sources in the extreme subsample does not differ from the correlation for the HII galaxies in the extreme subsample and it shows the same dispersion (Paper II), indicating that both the radio and the far-infrared emission of almost all AGN-type galaxies in the extreme subsample is dominated by recently formed stars.

5.5.2 The \( S_{60}/S_{25} \) flux density ratio

Miley et al. (1986) found that a significant fraction of optically selected Seyfert galaxies have a smaller \( S_{60}/S_{25} \) flux density ratio than HII galaxies (see also de Grijp et al., 1985). In order to compare our infrared selected AGN sources in the extreme subsample with optical selected Seyferts, we selected all NGC and Markarian Seyfert I and II galaxies in the compendium of Véron-Cetty and Véron (1984, hereafter VCV), for which 25, 60, and 100 \( \mu \)m IRAS flux densities are available following Miley et al. Furthermore, we constrained this VCV sample to far-infrared luminosities exceeding \( \log(\text{L}_{\text{FIR}}/\text{L}_\odot) \geq 10.3 \), in order to select Seyfert galaxies comparable with our AGN sources. Indeed the \( \log(\text{L}_{\text{FIR}}) \) and \( \log(\text{L}_{\text{FIR}}/\text{L}_B) \) distributions of this sample are very similar to those of our AGN sources (cf. Fig. 5.10). In Fig. 5.11 we plot the \( \log(S_{60}/S_{25}) \) ratio against the \( \log(S_{100}/S_{60}) \) ratio for all sources of the extreme subsample in Field I and the sources of the VCV sample; also shown in Fig. 5.11 is the median for the Seyfert galaxies in the VCV sample. Of our AGN-type galaxies only one galaxy (No. 24SE) lies below the median line in Fig. 5.11, while the rest (90%) has ratios comparable to the HII galaxies, which could imply that optically selected Seyferts have on average much smaller \( S_{60}/S_{25} \) ratios than the far-infrared selected Seyferts in our sample. However, this is not easy to understand, since both samples have similar \( L_{\text{FIR}} \) and \( L_{\text{FIR}}/L_B \) distributions, implying that we have selected similar kind of galaxies.

Perhaps the relative absence of AGN sources in our sample with small \( S_{60}/S_{25} \) ratios is related to the deficiency of sources in the extreme subsample with small \( S_{100}/S_{60} \) ratios (see Sect. 5.2.2). Inspection of Fig. 5.4d, which shows the distribution of \( \log(S_{60}/S_{25}) \) for the high- and low far-infrared flux subsets of the extreme subsample.
Summary and interpretation of the observations

Figure 5.11 The $S_{60}/S_{25}$ versus the $S_{100}/S_{60}$ flux density ratio for the AGN-type sources in the extreme subsample (stars), the HII-type sources in the extreme subsample (+) and Seyfert galaxies in the VCV Seyfert sample (circles). The line in the Figure represents the median of the VCV Seyfert sample.

(part A and B, respectively; see Sect. 5.2.2), shows that the average differences between both distributions is not significant ($1 \sigma$) implying that the absence of sources with small $S_{60}/S_{25}$ ratios is real and not due to this selection effect.

The most likely explanation is that the extreme subsample contains only a few ($\sim 2$) Seyfert galaxies, which are comparable with 'optical' Seyfert galaxies, and that the remaining sources with AGN-type spectra are of a different nature.

5.5.3 Line widths and nuclear appearance

The FWHM of the forbidden lines in Seyfert spectra is generally 500 km s$^{-1}$ or more (Weedman, 1977). We have shown in Table 4 of Paper I that for most of the AGN-type galaxies in the extreme subsample the FWHM of the forbidden lines is typically 200 to 400 km s$^{-1}$. Only four galaxies (Nos. 10, 20W, 21SW, and 58SE (Field II)) show FWHMs of 500 to 600 km s$^{-1}$.

Classical Seyfert galaxies generally show bright star-like nuclei. Such a nuclear
appearance is indeed found for Nos. 10, 20W, 24SW and 58SE.

5.5.4 Luminosity function of Seyfert galaxies

Meurs and Wilson (1984) published an optical luminosity function for Seyfert I and II galaxies using blue Zwicky magnitudes. We determined the $L_{\text{FIR}}/L_B^0$ distribution for these galaxies using the 60 and 100 $\mu$m IRAS flux densities. Convolving the optical luminosity function with that part of the $L_{\text{FIR}}/L_B$ distribution for which $L_{\text{FIR}}/L_B^0 \geq 3$, we obtained an infrared luminosity function (shown in Fig. 5.5) for Seyfert I and II galaxies with $L_{\text{FIR}}/L_B^0$ ratios larger than 3. This luminosity function can therefore be compared with the infrared luminosity function derived for the extreme subsample in Sect. 5.2.3. This comparison shows that we should expect only a few (2-3) Seyfert I and II galaxies for the extreme subsample in Field I, significantly less than the total of 12 AGN-type sources found in the extreme subsample. In the following subsection we will consider possible explanations for this discrepancy.

5.5.5 Discussion

From the previous subsections we conclude that star formation dominates the far-infrared and radio continuum emission of the AGN-type sources in our sample. Using a derived far-infrared luminosity function for Seyfert galaxies and $S_{60}/S_{25}$ flux density ratios we expect that the extreme subsample in Field I contains only a few Seyfert galaxies and indeed only four sources (Nos. 10, 20W, 21SW and 24SW) resemble classical 'optical' Seyfert galaxies, showing broad emission lines and a star-like nucleus. The remaining spectra, which are all LINER-types or intermediate LINER/Seyfert II-types, are obviously not classical AGN-type sources. If their spectra do not originate from gas that is absorbing the hard ultraviolet power-law continuum from an AGN, we should look for processes that are related to the enhanced star formation in these galaxies for an explanation of their spectral properties. Obviously the star formation rate must be quite high, since these spectra are only observed in sources with far-infrared luminosities $\log(L_{\text{FIR}}/L_\odot) \geq 10.3$. Furthermore, these sources only are found in barred spirals and interacting systems, which have the bulk of their star forming regions in and near the centre. Processes able to produce line ratios observed in LINER-type spectra, are shock-heating of the gas and absorption of the ultraviolet continuum of extremely hot Wolf-Rayet stars by the gas. We will shortly discuss two models found in the literature.

5.5.5.1 The superwind model

Chevalier and Clegg (1985) proposed a scenario in which a starburst located in the centre of a galaxy produces a large number of supernovae, when the massive stars formed in the starburst are at the end of their lives after a few times 10 Myr. When the kinetic energy in the ejecta is thermalized, a highly overpressured medium develops from which a high-speed wind is driven outward, usually in a bipolar flow. When this wind interacts with ambient gas clouds shocks arise, producing emission line ratios typical for LINER-type spectra. For a more thorough discussion of this model see Heckman et al. (1990).
5.5.5.2 The warmer model

Terlevich and Melnick (1985) proposed that Wolf-Rayet stars, which they called 'warmers', produce LINER- and Seyfert II-type spectra. Loosing their outer layers due to severe mass loss, these massive ($\geq 40 \, M_{\odot}$) stars do not evolve into red supergiants, but eventually consist of hot bare helium and carbon cores. The effective temperature of these cores is $1-2 \times 10^{5}$ K, which is hot enough to generate radiation, which produces, once absorbed in the gas, line ratios as found in LINER- and Seyfert-like spectra. Terlevich and Melnick calculated the evolution of metal-rich (solar abundance) giant HII regions and showed that their emission-line spectra can indeed evolve into LINER- and Seyfert II-like spectra. High metallicity of the gas is required, because the mass loss rate is more or less proportional to the metallicity, so that the number of Wolf-Rayet stars increases with metallicity. In our AGN-type galaxies we indeed expect about solar abundances, since the optical continuum (see Sect. 5.6) shows that these galaxies have already formed numerous stars in the past, implying that lots of Wolf-Rayet stars will be formed in the starburst.

5.5.6 Conclusions

Eight of 12 AGN-type spectra are obviously not generated by an active nucleus, but due to the starburst process. We mentioned two models, which address the question how vigorous star formation could give rise to this kind of spectra. Both models are consistent with the observation that AGN-type spectra are only found for the more far-infrared luminous sources. The superwind model seems to be fairly well established now (Heckman et al., 1990). For the warmer model the question arises whether the doubtlessly numerous Wolf-Rayet stars dominate the ultraviolet radiation field. To investigate this further it would be worthwhile to search for Wolf-Rayet features like the HeII line at 4686 Å.

5.6 Optical emission

In this section we will determine whether the optical continuum emission is dominated by the starburst or by the stars of the older population. Furthermore we investigate the reddening of the starlight and the extinction towards the star forming regions.

5.6.1 The origin of the optical continuum

The star formation process produces lots of massive stars, which are very luminous in the optical and especially in the ultraviolet. The extinction in the star forming regions is high ($A_V \sim 5$ mag, on average, see Sect. 5.6.3), weakening the optical emission of the stars in the star forming regions. It is not clear whether at the location of the starburst the optical continuum is dominated by the light of the star forming regions or by the light of stars already existing before the burst, i.e. the older population. Van den Broek and de Jong (1990, Chapter 7) found in model calculations simulating a starburst that the optical light of the starburst, weakened by dust extinction, is too weak to explain the observed optical fluxes of a sample of IRAS galaxies. Another argument that the starburst does not dominate the optical light is the fact that in
far-infrared complete samples $L_{FIR}$ correlates well with the $L_{FIR}/L_B^2$ ratio (see Fig. 5.2b) with a slope of order unity. This means that the starburst is only seen in the far-infrared and not in the optical, since the B-band flux is rather unaffected, while the far-infrared flux varies.

Perhaps the most direct way to determine the contribution of the starburst to the optical continuum is to compare the Hα equivalent width (i.e. the ratio of the Hα line flux to the red continuum flux density) in light from the region where the bulk of the star formation is located, i.e. in the centers of the galaxies (see Sect. 5.4), with that in light completely dominated by star forming regions alone, which are mainly found in the outer regions of galaxies. If the Hα equivalent width in the centres is smaller than in the star forming regions in the outskirts, this has to be due to the influence of the older population, which only contributes to the red optical continuum and not to the Hα-line flux. Furthermore, the Hα equivalent width is a suitable parameter, since both contributions from the star forming regions and the older population are in itself reddening free. If the reddening differs between those contributions the total Hα equivalent width will not be reddening free, which is however not of influence on the results we derive in the following.

The Hα equivalent widths measured in the central regions of the galaxies in our sample are typically of order 50-100 Å. To find star forming regions, which dominate the optical continuum light, we have to go to the outer regions of spiral galaxies where the red continuum surface brightness of the older population is low. Searle (1971) found Hβ equivalent widths of typically 150 Å for HII regions in the outskirts of M101 and M33. Using an Hα/Hβ line ratio of 3 and accounting for the blue continua in these spectra we estimate Hα equivalent widths of ~1000 Å for these regions. Comparable values for the Hα equivalent width are found for the few bright star forming regions in the outskirts of the galaxies in our sample, which appear to dominate the local optical continuum.

Thus the optical light from the older population completely dominates the optical continuum in the centres of our galaxies (by at least a factor of about 10). A problem may be that the star formation process in the outskirts of galaxies may differ from that in starbursts in the centres of galaxies. There are indications that in starbursts predominantly massive stars are formed (See Paper V), while in the more quiescent star forming regions, like those in the outskirts of galaxies, also stars with lower masses are formed (Scalo, 1986). However the model calculations by van den Broek and de Jong (1990) show that when only massive stars are formed the optical continuum emission decreases, while the Hα emission is unaffected, implying that the older population would then dominate even more.

### 5.6.2 Optical colours and extinction

To investigate the relation between the extinction by dust and the optical colours we have plotted in Fig. 5.12 the (B-V)$_0$ versus the (V-R)$_0$ colours, corrected for galactic extinction and redshift. The redshift correction is on average -1.7z mag for B-V and negligible for V-R in the redshift range of z=0-0.2 (Coleman, 1980). The colours in Fig. 5.12 are correlated with a slope which is comparable with the slope of the interstellar reddening curve. However, since the optical continuum is dominated by
Summary and interpretation of the observations

stars of the older population (see Sect 5.6.1) it cannot be excluded that the range in colours is due to different star formation histories. To investigate this we have plotted (Fig. 5.13) the global average blue surface brightness, \( L_\text{B} D_{25}^{-2} \), versus the corrected (B-R)_0 colour (see above). The rather good correlation (r=0.68) in this Figure has about the same slope as the reddening vector, implying that the decrease in average surface brightness is due to the global interstellar extinction in the disk, so the internal extinction is indeed the dominant effect causing the variation in the colours.

To investigate how the dust extinction in the older population is related to the star forming activity we have plotted in Fig. 5.14 the corrected colour (B-R)_0 versus the log(\( L_{\text{FIR}}/L_\text{B}^0 \)) luminosity ratio. The data show a weak correlation for the dwarf galaxies and barred spirals (r=0.69), but not for the interacting systems, which show on average higher \( L_{\text{FIR}}/L_\text{B}^0 \) ratios than the other subgroups, while their (B-R)_0 colours are comparable to those of the barred spirals. Apparently the interacting systems form more stars without having more dust extinction in the disk.

5.6.3 Extinction towards the star forming regions

We derived in Paper I from the Hα/Hβ line ratios B-band extinctions \( A_\text{B} \) towards the star forming regions, which range from 1.5–8 mag (average 5). The extinction is due to dust in and near the star forming regions, as well as to dust in the line of sight in the disks and bulges of the galaxies. The extinction \( A_\text{B} \) for the dwarf galaxies is significantly less than for the barred spirals and interacting systems and ranges from

- Figure 5.12 The (B-V)_0 colour versus the (V-R)_0 colour for the dwarfs (+), barred spirals (boxes), interacting and merging systems (circles) and remaining sources (crosses). Both colours have been corrected for galactic extinction and the B-V colour has also been corrected for redshift.
5.6. Optical emission

Figure 5.13 The blue surface brightness \((L_B^0 D_{25}^{-2})\) versus the \((B-R)_0\) colour, corrected for redshift and galactic extinction, for the subgroups in the extreme subsample. Symbols as in Fig. 5.12.

Figure 5.14 The \((B-R)_0\) colour, corrected for redshift and galactic extinction, versus the \(L_{FIR}/L_B^0\) luminosity ratio for the subgroups in the extreme subsample. Symbols as in Fig. 5.12.

A_B=1.5–5 mag, while the latter two subgroups have comparable extinctions, ranging from A_B=3.5–8 mag. This implies that we observe 8-50% of the total emitted Hα
light from the dwarf galaxies, and 1.5–15% from the barred spirals and interacting systems.

Above in Sect. 5.6.2 we argued that the range in the \((B-R)_0\) colour is mainly due to reddening by dust mixed with the older population in the disks and bulges of the observed galaxies. To investigate how the extinction \(A_B\) towards the star forming regions is related to the reddening in the optical colours we have plotted \(A_B\) versus \((B-R)_0\) in Fig. 5.15. The correlation in Fig. 5.15 is only weak and the data do not follow the extinction vector, implying that \(A_B\) and the reddening in \((B-R)_0\) are of different origin. This means that \(A_B\) is mainly due to dust in and near the star forming regions and not to dust in the line of sight in the disk and bulge.

To investigate the relation between the extinction towards star forming regions and the star forming activity we have plotted \(A_B\) versus \(\log(L_{\text{FIR}}/L_B)\) in Fig. 5.16. The correlation in Fig. 5.16 is also rather weak, implying that \(A_B\) does not depend much on the star formation activity. Since the amount of dust is more or less coupled to the molecular gas mass, we expect that the molecular gas mass itself is also not a strong indicator for the star formation activity. Indeed Young et al. (1989) showed that galaxies that are forming large numbers of stars are doing so through efficient conversion of their molecular gas into stars, rather than through an increase in the amount of gas.

We also found (see Paper III) a correlation between the \(L_{\text{FIR}}/M_{H_2}\) ratio, which is considered to be a measure of the star formation efficiency, and two parameters which measure the ratio of the present star formation rate and the average past star formation rate: the equivalent width of the H\(\alpha\) line and the \(L_{\text{FIR}}/L_B^0\) ratio, thus
confirming the interpretation of Young et al. (1989).

To explain the observed range of extinction in $A_B$ we have to look for other causes than star formation. A parameter which is likely to be of importance for the formation of dust is metallicity. The dwarf galaxies which are known to have low abundances, indeed show the smallest extinctions. The higher extinctions in the nuclear star forming regions in the barred spirals and interacting systems would then indicate higher metallicity, to be expected since they formed substantial numbers of stars in the past. The observed large range in extinctions would then indicate that the metallicity varies strongly from galaxy to galaxy.

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