Chapter 3

Optical morphology

Summary

Optical CCD images of the sample of starburst galaxies from the Gurushikhar 1.2 m telescope are presented in the form of contour maps and colour images. The emission line Hα images are also presented. We discuss the morphology of the starburst region and the underlying host galaxy based on the analysis of the contour maps, the colour and Hα images. We can broadly group the galaxies into three types: S0's/E's, spirals and irregulars/peculiars based on their morphology. The contours of most of the galaxies show some distortions in their isophotes. The presence of young stars as traced by the colour maps is not confined to the nuclear region alone but their distribution shows a variety of spatial distribution in the form of blue rings, superassociations at the ends of bars and even global star formation. The Hα emission shows a variety of morphologies and we classify them into four basic types and describe the characteristics of the emission. We find that in a few cases, the peak of emission is off-centered with respect to the optical nucleus.
3.1 Optical Morphology

Starburst galaxies are a very inhomogeneous morphological class of galaxies where the common property is the dominant starburst component. Observations of star forming galaxies reveal an obvious relation between the star formation rate and dynamical features. The possible association between nuclear activity and galaxy morphology has interested many workers (Sersic & Pastoriza 1967; Heckman 1978; Simkin et al. 1980). The dynamical processes experienced by a galaxy get reflected in its morphology. Thus the study of the morphology of a galaxy is basically a study of its dynamical history. Since most of the visible light in a galaxy is produced by stars, the morphology traces the stellar populations and its appearance varies at different wavelengths, depending on the stellar populations contributing to the luminosity in that waveband. For instance, in the $R$ and the NIR bands, a spiral galaxy appears smooth, while in the $U$ and $B$ bands, the spiral arms look thinner, ragged and show clumpy star forming regions. An inspection of a photographic atlas of barred galaxies reveals a variety of unique star formation properties - star forming knots concentrated along the bar or in spiral arms emanating from the bar. Giant HII regions are often present at the extremities of bars or in conspicuous hot spots in nuclear or resonance rings. The association of nuclear starbursts with stellar bars strongly suggests that it arises as a consequence of a bar-related phenomenon e.g. a resonance. The inner Lindblad resonance (ILR) in particular, is expected to be the site of enhanced molecular cloud density and star formation in the central region of barred spiral galaxies (Combes & Gerin 1985). The location of the ILR depends on the form of the mass distribution and is expected to be closest to the nucleus in galaxies with the highest central mass concentration.

It has been observed that nuclear starbursts occur preferentially in early-type barred spirals (Devereux & Hameed 1997). Elmegreen et al. (1990) present evidence that radial mass-transfer and star formation during an encounter can
change an unbarred late-type galaxy into a barred early-type galaxy. This might explain why nuclear star formation is so rare in late-type spirals. They give statistical evidence to prove that galaxy interactions produce strong spirals, which because of their torques lead to bar formation and a significant mass inflow in the disk. For a prolonged encounter, the mass inflow can apparently change a non-barred galaxy of intermediate Hubble-type Sbc-Scd, to a barred galaxy of early Hubble type SBa-SBb by increasing the density in the inner region and by removing a significant amount of the gas mass and star formation from the outer disk. The most spectacular starbursts occur in tidally interacting galaxies and mergers. Interactions with companion galaxies or merger processes leave their signature in the form of peculiar structures like distortions in the galaxy isophotes, tails, bridges, double nuclei, etc. Dynamical interactions and mergers can be responsible for periods of enhanced star formation (Larson & Tinsley 1978; Sharp & Jones 1980). Theoretical models have added substantially to our understanding of the merger process, in particular by demonstrating how it is possible to build up enormous concentrations of gas in the centers of merger remnants. The numerical simulations of Toomre & Toomre (1972) were successful in reproducing the tails observed in the Antennae by considering gravitational interactions and tidal forces. Numerical simulations now reproduce many features seen in starburst galaxies, including their disturbed morphologies and gas inflows fueling the starburst. Tidal forces have bipolar symmetry in the perturbed galactic disk which represent the differences of attraction forces from the companion over the whole disk. An attraction excess on one side and a corresponding lack on the other disrupt the disk. When the two interacting galaxies have equal masses, the two internal spiral features form a bridge, which will soon be accreted by one of the galaxies, the two external spiral arms will spread out in the form of two antenneae, which will subsist in 1 or 2 million years (Combes 1987). Two famous examples are The Antennae (NGC 4038-9) and The Mice (NGC 4676 A-B).

Though many of the optically selected starburst galaxies show peculiar morphologies, there are many cases where neither apparent evidence of interaction nor
the presence of non-axisymmetric structures like bars or oval distortions is evident on visual inspection. A detailed morphological study of the underlying galaxy and its structure is essential in addressing such cases and determining the cause of the burst especially in such cases where no apparent signatures are seen. A spatially resolved study of a sample of starburst galaxies will aid in understanding the underlying structure of the galaxy hosting the starburst. The morphology of the star forming regions can provide insights into the triggering mechanisms, while the morphology of the underlying component gives an indication of the nature of the gravitational potential well in which the starburst occurs.

3.1.1 Morphology of the sample objects

As mentioned in Chapter 2, we have selected the sample objects with a variety of Hubble types. A visual inspection of the direct images reveals that the objects show a number of morphological peculiarities. The early type galaxies generally show smooth outer structure. Many of them like Mrk 190 and Mrk 439 appear circular in long exposures. However, their inner regions show a variety of non-axisymmetric structures or clumpy central regions. These structures are clearly brought out in the contour maps presented in Fig. 3.1a-s. A double nucleus is seen in one of the galaxies, Mrk 743. Non concentric outer envelopes are also seen in many of the objects belonging to this class. Such non concentric isophotes around galaxies present the strongest evidence for perturbations resulting from tidal interactions between galaxies. Using N-body simulations, Borne (1984) and Aguilar & White (1986) have shown that strong asymmetric envelope distortions can result from tidal interactions between galaxies. A displacement of the nucleus from the center of its envelope will quickly decay away and thus, this must reflect recent tidal perturbations.

Our sample contains 10 spirals. Of these, 8 are barred spirals. The spirals generally show disturbed, asymmetric spiral arms or sometimes, as in the case of Mrk 799, three spiral arms. Mrk 332 and Mrk 449 are the two spirals which show
neither a companion nor the presence of a bar. The appearance of the isophotes changes at different wavelengths. At shorter wavelengths, they appear clumpy due to the presence of star forming regions and dust, while they have a smoother appearance at longer wavelengths.

The irregulars/peculiars show highly distorted isophotes especially in the central regions. Some objects like Mrk 1134 show a clumpy structure throughout the body.

We discuss the morphological characteristics of each of the objects in detail in Section 3.4.

3.2 Colour Maps

Colour maps are good tracers of the stellar populations in a galaxy. Broad band photometry is relatively easy to obtain and gives an immediate impression of the spectral energy distribution of the galaxy. The star formation rates at two different epochs, namely a period about $10^9$ years ago and the present time can be traced by the $B$ luminosity and the Hα luminosity respectively. Hence, a comparison of broad band colour images like ($B - V$) or ($B - I$) and the Hα images can lead to an estimation of how the recent star formation history of a galaxy has taken place in different regions (Marquez & Moles 1994). The $UBVR$ colours are dominated by the mixture of the intermediate mass main sequence stars ($\sim 5-10 \, M_\odot$) and disk giants ($\sim 0.8-3 \, M_\odot$). Colours have been used to estimate the stellar population of galaxies (Searle et al. 1973; Tinsley & Danly 1980; Frogel 1985; Peletier & Valentijn 1989; Silva & Elston 1994). The spatial distribution of colours can be used to trace the locations of enhanced star formation activity, dust and stellar populations. The spatial organization of the star forming complexes can be a clue to the mechanism controlling the burst. A spatially resolved study through various passbands will help us understand the physical processes controlling star formation in such a dynamic environment. Previous studies by Hodge (1975) and Keel et. al (1985)
indicate a tendency for star formation to be concentrated around the nuclear region in interacting galaxies, although there are cases where there is significant star formation taking place at other locations.

3.2.1 Construction and interpretation of colour maps

The colour maps were constructed by dividing the intensity images in two bands and calibrating them using the transformation equations described in Section 2.6. To conduct a spatially resolved study of the stellar populations and the distribution of dust, we constructed \((B - V), (V - R)\) and \((B - I)\) colour maps. The colour maps were constructed after matching the PSFs in the two bands to avoid artifacts. This was achieved by degrading the better of the PSFs in the two bands by using a gaussian smoothing filter. The colour maps thus obtained were examined to identify features like star forming regions, dust lanes, etc. and study their photometric properties and their locations with respect to the underlying galaxy. The \((B - I)\) colour map is presented in the fourth panel in Figs. 3.1a-s. The grey scales have been chosen to maximize the contrast over the range of colour indices. Nearly all the galaxies in our sample show a blue nucleus indicating relatively higher star formation in this region as compared to the rest of the galaxy. In some cases, the nucleus does not appear blue which may be due to obscuration by dust or a dominant redder population, but the presence of massive stars in this region can be deduced from the presence of \(H\alpha\) emission (which suffers lesser attenuation) in this region. Mrk 333 and Mrk 1134 show global star formation while Mrk 332 shows intense star formation in the spiral arms and Mrk 799 shows intense star formation at one end of the bar, in addition to the nucleus. In general, the galaxies show more small-scale irregularities in the \(B\) band. This is due to two causes: (a) The distribution of young stellar population, which is distributed inhomogeneously in general and is more emissive in the blue and (b) the non-uniform distribution of dust, more effective in producing blue extinction than red. The colour maps convey two types of information whose combination can make interpretation quite
complex. The redder regions correspond to either an older population or obscuration by dust. Qualitatively, it is often possible to distinguish between these two effects (Prieto et al. 1992a,b) using the results of the ellipse fitting analysis, which will be dealt with in the next chapter.

3.3 \textit{H}α \textit{images}

The \textit{H}α emission from giant HII regions is a good tracer of OB star formation. The presence of \textit{H}α emission from gas is a sign-post indicating that at least one massive star has formed there recently. Massive stars emit Lyman continuum photons which ionize the surrounding hydrogen. In the subsequent recombination process, Balmer photons are emitted. Measurement of the integrated Balmer photon flux provides a direct estimate of the Lyman continuum luminosity and the corresponding OB star formation rate (SFR). These regions show \textit{H}α in emission, which has been used extensively by Kennicutt (1983) to derive SFRs in spirals. The regions of emission, thus delineate the location of star forming giant molecular clouds and the gas involved in star formation. Their locations can be used to detect the effects of perturbing forces which is supposed to be responsible for the anomalously high gas densities, subsequently leading to the triggering of the burst. In particular, the HII regions reflect the recent dynamic influence on the gas because of their short lifetimes (Hodge 1975).

3.3.1 \textit{Spatial distribution of star forming regions}

The sample of galaxies was observed with appropriately red shifted narrow band filters which were centered at red-shifted \textit{H}α. The large scale patterns of star formation were studied using continuum subtracted emission line images. A visual inspection of continuum subtracted \textit{H}α images shows that all the galaxies except Mrk 439 and Mrk 1194 show the nuclear region intensely in emission, signaling the presence of massive stars in the central region. On the basis of the emission-line
Figure 3.1a

Figure 3.1: Top row: left: $B$ isophotal contours, right: $I$ isophotal contours. Bottom row: left: $(B - I)$, right: Hα isophotal contours. North is at the top and East is to the left. Contours are plotted at intervals of $0^\prime\prime.25$ with the faintest one at $3\sigma$ of the background. The same order is followed in the figures (a) to (s).
Figure 3.1b
Figure 3.1c
MRK 743

Figure 3.1d
Figure 3.1e
Figure 3.1f
Figure 3.1g: Direct images in B, I and Hα are shown instead of the isophotal contours to clearly bring out the ring. The locations of the figures is the same as in all others.
MRK 213  —  10°

Figure 3.1h
Figure 3.1i
Figure 3.1: The bottom panel shows the variation in \((B - R)\) along a cut through the nucleus and dust lane at a position angle of 97°. The figures at the top and in the middle are in the same order as the rest of the figures.
Figure 3.1k
MRK 708
— 10°

Figure 3.11
Figure 3.1m: The continuum subtracted Hα image is shown instead of the isophotes in the fourth panel.
Figure 3.1n
Figure 3.10
Figure 3.1p
morphologies, we have divided the sample into the following four subclasses.

1. Galaxies showing Hα emission in the central region only. Mrk 1308, Mrk 14, Mrk 87, Mrk 449 and Mrk 1002 belong to this class.

2. Galaxies showing extended Hα emission or galaxies with extranuclear emission, in addition to nuclear star formation. This includes most of the spirals which show emission from either one or both the ends of the bar, or along the bar (e.g. Mrk 213, Mrk 1379, Mrk 799 and Mrk 602), Mrk 190 which shows extended emission in the nuclear region, Mrk 702 and Mrk 781, with emission in the spiral arms, are also included in this group. The ellipticals Mrk 743 and Mrk 603 also have extended regions in emission.

3. Galaxies with global massive star formation. Line emission extends, in some cases, out the body of the galaxy in Mrk 363 and Mrk 744, indicating a starburst. The fact that massive star formation in starburst galaxies occurs not just confined to the nuclear region alone is best illustrated in these cases by the strong stellar continuum at longer wavelengths (J, H and K bands with the fact that they are not young systems experiencing their first episode of star formation, but are old systems with a younger burst of star formation.

4. The last class includes starburst galaxies with peculiar emission characteristics. Mrk 439 and Mrk 1194 belong to this class. Mrk 439 shows extended Hα emission along a bar which is misaligned with the optical isophotes, while Mrk 1194 shows no emission from the central region but clearly shows a circumnuclear ring of massive star formation.

The radial distribution of the Hα emission was studied by synthetic aperture photometry in the regions of emission. The central intensity was normalized and the radial profiles thus obtained are shown in Fig. 3.2. A majority of the objects have a Hα distribution that is centrally peaked and falls off at a more or less exponential rate with increasing radius. A few cases like Mrk 1379 and Mrk 363 have Hα distributions that show a different behaviour. The fall-off in the line intensity with radial
Table 3.1: Characteristics of Hα emission

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Global pseudo E.W.</th>
<th>emission morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mrk 14</td>
<td>0.909</td>
<td>extended</td>
</tr>
<tr>
<td>Mrk 87</td>
<td>-</td>
<td>central</td>
</tr>
<tr>
<td>Mrk 190</td>
<td>0.537</td>
<td>central, resolved</td>
</tr>
<tr>
<td>Mrk 213</td>
<td>0.208</td>
<td>central, end of bar</td>
</tr>
<tr>
<td>Mrk 332</td>
<td>0.440</td>
<td>central, spiral arms</td>
</tr>
<tr>
<td>Mrk 363</td>
<td>1.127</td>
<td>global</td>
</tr>
<tr>
<td>Mrk 439</td>
<td>0.399</td>
<td>along a misaligned bar</td>
</tr>
<tr>
<td>Mrk 449</td>
<td>0.524</td>
<td>nuclear</td>
</tr>
<tr>
<td>Mrk 602</td>
<td>0.6918</td>
<td>central, along bar, ends of bar</td>
</tr>
<tr>
<td>Mrk 603</td>
<td>1.706</td>
<td>global</td>
</tr>
<tr>
<td>Mrk 708</td>
<td>0.812</td>
<td>nuclear, eastern end of bar</td>
</tr>
<tr>
<td>Mrk 743</td>
<td>1.374</td>
<td>extended</td>
</tr>
<tr>
<td>Mrk 781</td>
<td>1.374</td>
<td>central, spiral arms</td>
</tr>
<tr>
<td>Mrk 799</td>
<td>0.380</td>
<td>central, end of bar</td>
</tr>
<tr>
<td>Mrk 1002</td>
<td>0.565</td>
<td>central</td>
</tr>
<tr>
<td>Mrk 1134</td>
<td>0.490</td>
<td>global</td>
</tr>
<tr>
<td>Mrk 1194</td>
<td>0.709</td>
<td>along a ring</td>
</tr>
<tr>
<td>Mrk 1308</td>
<td>0.812</td>
<td>nuclear</td>
</tr>
<tr>
<td>Mrk 1379</td>
<td>1.025</td>
<td>central, end of bar</td>
</tr>
</tbody>
</table>

distance is much smoother in Mrk 1379, while in Mrk 363, the peak is off-centered from the nucleus.

3.3.2 Pseudo equivalent widths of Hα

To study the regions of current star formation relative to the underlying continuum contributed by old stars, a pseudo equivalent width (p E.W.) of Hα was computed. This was done by dividing the Hα intensity by the stellar continuum intensity estimated from the scaled off-band continuum image. This is not a true equivalent width, however, it can be used to compare relative levels from galaxy to galaxy. It provides a measure of the current star formation rate relative to the recent past star formation rate, since the line emission is due to massive stars with ages \(<10^7\) years while the stellar continuum at these wavelengths is due to G and K giants which
Figure 3.1q
Figure 3.1r
Figure 3.1s
are typically a few billion years of age (Huchra 1977b; Kennicutt 1983). Since we
are interested only in the relative contributions, the units are arbitrary. Bushouse
(1986) uses a similar approach to derive pseudo equivalent widths for a sample
of interacting galaxies. However, he uses the total flux in the $R$ band while we
use the flux in the scaled off-band images. Global and radially dependent pseudo
equivalent widths were derived by the following procedure:

Synthetic aperture photometry was performed on the continuum subtracted
H$n$ images to derive the brightness distribution through concentric circular apertures. The apertures were centered on the nucleus, the position of which was determined from the $R$ band images. This convention was maintained irrespective of whether or not the H$n$ peak emission coincides with the $R$ band peak. The radial profiles of the line emission intensity were derived in this manner. Circular apertures were considered up to the radius where the signal falls to the 3$\sigma$ level of the background value in the line images. The same scaled images that were used for continuum subtraction served to derive a similar radial profile for the continuum in the emitting region. The ratio of the two intensities gives the radial distribution of the pseudo equivalent width. The global equivalent width was obtained by dividing the total line intensity by the total scaled continuum intensity over the emitting region. Table 3.1 lists the global pseudo E.W. and the locations of the H$n$ emission. In Mrk 87, the signal to noise ratio in the H$n$ image was poor, so we did not deduce the global pseudo E.W. for this galaxy. The radial dependence of the intensity distribution normalized to the central intensity plotted on a logarithmic scale and the radial dependence of the pseudo equivalent width (p E.W.) are presented in Fig. 3.2 for a few representative cases. The intensity is maximum at the center and falls off smoothly outwards. Many of the galaxies show an exponential decline in the H$n$ intensity. Mrk 332 is an exceptional case in which the intensity shows a marked increase at 10", corresponding to the star forming regions along the spiral arms. It was noted that the radial distribution of pseudo E.W. does not follow the same behaviour as that of the intensity profiles. The radial dependence of the pseudo equivalent widths can be grouped into the following types:
- Peaking in the central region and falling off steadily outwards as in Mrk 14, Mrk 213, Mrk 743.
- Peaking near the nucleus, but off-centered from it as in Mrk 1379, Mrk 1308, Mrk 439, Mrk 603 and Mrk 363.
- Showing multiple peaks as in Mrk 1002, Mrk 332. One of the peaks is close to the nuclear region and the other at a large distance from the center.

The global pseudo E.W. listed in Table 3.1 was compared with the pseudo E.W. in the central region. It was found that the central pseudo E.W. was higher than the global value in nearly all cases. This suggests that the star formation is more enhanced with respect to the underlying population in the central regions of these starburst galaxies. A few cases like Mrk 363, Mrk 439 and Mrk 332 showed that the ratio of the central pseudo E.W. to its global value was less than unity. All these three galaxies show a considerable amount of extranuclear star formation.

3.4 Individual galaxies

The sample can be divided into three broad morphological types: early type galaxies namely S0’s and E’s; spirals; and irregulars and ellipticals.

3.4.1 S0’s and E’s

The isophotal contours and colour maps of the galaxies belonging to this group are presented in Fig. 3.1a-f.

- Mrk 14:
  This galaxy has been classified as likely to be an S0 by Huchra (1977a) while it forms a part of the sample of distant irregulars in a study conducted by Hunter & Gallagher (1986). The contours in the outer regions look disturbed
(Fig. 3.1a). Keel & van Soest (1992) find no candidate companions near this galaxy. The only significant feature in the colour maps is the blue nucleus. The \((B - I)\) colour map does not show any features like dust lanes. On the whole, the colours get redder outwards. A sharp change is seen in the inner 8”; \((B - V)\) changes steeply from 0.15 to 0.75 in this region. Beyond this, the change is more gradual. The H\(\alpha\) image shows extended emission peaking in the nuclear region. The pseudo E.W. also shows a peak in the nuclear region and falls off smoothly with radial distance.

- **Mrk 190:**
  This galaxy has been classified as S0/E. The outer contours appear smooth and almost circular (Fig. 3.1b). The isophotes in the \(B\) band show the presence of an inner structure lying along east-west and a faint indication of spiral arms in the north-south direction. van den Bergh (1980) describes it as a very small face-on spiral with a bright core of extent 8” and a disk 29” in diameter. The \(U\) band contours show a double structure in the central region. Towards longer wavelengths, the contours become smoother and are nearly circular. The colour maps show a blue ring straddling the nuclear region, 400 pc wide with a \((B - V)\)~0.5 which is bluer by 0.2 as compared to the nuclear region. Li et al. (1994) have found from aperture synthesis observations of HI and CO that it does not show a central HI depression or an inner/outer HI ring. Most of the HI emission is within the de Vaucouleur’s radius. They find no indications for the nuclear burst to be a recent merger or interaction and suggest that it could be occurring periodically. Our H\(\alpha\) image shows that the emission is extended, consistent with Wrobel & Heeschen (1991) finding extended radio emission in Mrk 190.

- **Mrk 603:**
  Mrk 603 along with its two companions forms a triple system. It has been studied extensively by Petrosian & Burenkov (1993). They deduce the presence of about \(3 \times 10^8\) OB stars which photoionize the gas. They also detect
Figure 3.2:

The left panel shows the radial variation of the normalised Hα intensity plotted on a logarithmic scale and the right panel shows the radial variation of the pseudo equivalent width (p E.W.)
Figure 3.2 (contd.)
Figure 3.2 (contd.)
Figure 3.2 (contd.)
ongoing star formation in the host galaxy at a smaller rate as compared to that in the nucleus. We find that the contours are stretched out along the north-western side (Fig. 3.1c). The \((V - R)\) colour image shows a blue nucleus surrounded by a red clumpy region. The two companion galaxies also appear blue. This system shows global H\(\alpha\) emission, in the galaxy as well as in the companions, with the peak emission in the nuclear region of the galaxy. However, the pseudo E.W. is found to peak 4" away from the nucleus. It falls off steeply up to 10" and the fall is much smoother beyond 10".

- **Mrk 743**:  
  Mrk 743 is classified as a peculiar E0 galaxy in the Markarian catalogue. It forms a part of the sample of galaxies with double nuclei studied by Mazzarella & Boroson (1993). An inspection of the contour plots in the four bands reveals the presence of two nuclei surrounded by a common envelope (Fig. 3.1d). The envelope is asymmetric in the outer regions. Both the nuclei have comparable fluxes in the V band. The western nucleus appears brighter at longer wavelengths, while the eastern component becomes dominant at shorter wavelengths. Mrk 743 is one of the few HI sources among early type galaxies in which the HI distribution shows a central concentration, rather than the usual depression (Burstein et al. 1987). The HI distribution is in the form of a disk nearly as large as the galaxy diameter (van Driel & van Woerden 1991). Wrobel & Heeschen (1991) detect unresolved radio emission at 6 cm from this object. H\(\alpha\) shows an extended structure with its peak coinciding with the eastern nucleus. For deriving the variation of the line intensity and the pseudo E.W., the center was taken to be fixed on the eastern nucleus. The line intensity variation with radial distance follows a more or less exponential form, with its peak in the center. The pseudo E.W. remains constant in the central region up to a radius of 4" and then falls slowly outwards.

- **Mrk 1002**:  
  This galaxy is classified as S0 by Mazzarella & Balzano (1986) and as E1 in
the Markarian catalogue. The direct image appears smooth. On probing the contours we find that the central contours appear elliptical (Fig. 3.1e). At about 6", they start deviating from perfect ellipses and seem to give a faint indication of spiral arms. Beyond 12", they regain their elliptical nature. The colour maps show an interesting structure. We detect a S-shaped blue structure in the form of a spiral crossing the nucleus in the colour maps. Pogge & Eskridge (1993) have reported Hα emission in the nuclear as well as clumps of emission in the circumnuclear region in this galaxy. Our studies show that the line emission does not follow the structure seen in the colour maps but just shows extended emission in the central region. The Hα emission is peaked in the center and falls smoothly. However, the radial distribution of pseudo E.W. shows a lot of structure. It peaks in the center and falls off till 2" and then rises again to peak at 4", before falling off smoothly outwards.

- **Mrk 1308:**
  This is a small nearby galaxy of SO type extending about half an arcminute. It has a small linear companion located at 30" towards the west, which has been confirmed to be a physical neighbour (Doublier et al. 1997). The contours in the B and I filter bands appear smooth (Fig. 3.1f). Besides the blue nuclear region, there are no other features detectable in the colour maps. The (B − V) colour for Mrk 1308 is 0.05 in the central regions and gets redder outwards, reaching a value of 0.7 near the periphery. The companion is a red object having a mean (B − V) of 0.9. The colour and the Hα images show that the star formation activity is confined to the nuclear region. Radio imaging at 6 cm (Neff & Hutchings 1992) shows that the emission at 6 cm is in the form of a ring-like structure of diameter ≈ 3". Our Hα image shows emission in the central region. The pseudo E.W. peaks 3" away from the nuclear region.
3.4.2 Spirals

The sample contains 10 spirals. The isophotal contours and colour maps of these galaxies are given in Figs. 3.1g-p.

- Mrk 87:
  Mrk 87 is a barred spiral with a prominent ring surrounding the bar as is clear from Fig. 3.1g. It is paired with the SBa galaxy KPG 160B. The ring appears more prominently in the B band and the \((B - I)\) colour map and starts merging with the underlying galaxy at longer wavelengths. Rings of stars and gas are often seen in barred spiral galaxies. They are believed to be formed by gas accumulation at the bar’s Lindblad resonances. They are blue in colour and are the sites of enhanced star formation (Buta 1986). Arsenault (1989) has shown that the bar and ring features occur with a higher frequency in starburst galaxies as compared to normal galaxies. The H\textalpha{} image shows emission only in the nuclear region and in the companion galaxy.

- Mrk 213:
  This is a barred spiral galaxy. A faint arm is seen emerging from the south eastern end and curving around towards the north western side where it is attached to an almost stellar condensation (Fig. 3.1h). The contour plots of Mrk 213 in both \(B\) and \(I\) bands clearly show that the contours in the inner regions have a position angle different from that of the outer region. The contours in the central region appear elliptical. The \((B-I)\) colour map shows that this galaxy gets bluer outwards. The colour map also shows a dust lane starting from the nucleus, curving around it before proceeding towards the NW direction. Line emission is present in the nuclear region and at the ends of the primary bar. The isophotal contours in the H\textalpha{} image show that the emission in the central region follows the contours seen in the direct images. The pseudo E.W. shows the same trend as the intensity profile.
• Mrk 332:

The galaxy shows a bright nucleus and two spiral arms (Fig. 3.1i). A faint secondary arm-like structure starting from the eastern tip of the eastern spiral arm and going towards north is also seen. Though this feature is not apparent in the isophotal contours shown in the figure, it can be seen clearly in the direct images of Mrk 332. Inspection of the images shows that the spiral arms are embedded in a diffuse envelope. A number of knots are seen along the spiral arms especially in the $U$, $B$ and Hα images. The $R$ and $I$ images appear much smoother than the $U$ and $B$ images. The $U$ and $B$ images do not show any indications of a bar but the isophotes at longer wavelengths show faint indications of a bar or a central oval distortion. This is discussed in detail in Chapter 4. The $U$ and $B$ band images show a number of knots tracing the inner boundary of the spiral arms and forming a ring. Towards the longer wavelengths, these images get smoother gradually and the $I$ band isophote is devoid of any distinct knotty structure. The continuum subtracted Hα image also exhibits structure similar to that observed in the $U$ and $B$ bands confirming that these are knots of enhanced star forming regions, forming a ring at about $2.1$ kpc from the nucleus and not a result of patchy extinction. Mrk 332 is a spiral galaxy with two spiral arms which show a number of clumpy star forming regions at shorter wavelengths. The nucleus appears highly reddened. The $(B-V)$, $(B-I)$ maps shows a blue region associated with the nucleus, which is a little off-centered with respect to the nucleus, surrounded by a much redder region on the inner side of the ring. The diameter of this ring is deduced to be $\sim 4.2$ kpc with a width of $\sim 600$ pc; from the $(B-I)$ image. The nucleus is the highest surface brightness region in all the bands. The nuclear region shows a disturbed morphology in the emission-line image. The contours are not smooth and Hα is brightest in a region which is off-centered from the nucleus, similar to the structure seen in the $(B-I)$ image. In Hα, two of the brightest condensations seen along the spiral arms are comparable in brightness with the nucleus.
• **Mrk 449:**

Mrk 449 is the most inclined galaxy in our sample. We derive an inclination of 75° for this galaxy. In the direct image, this galaxy appears lenticular. The contour maps (Fig. 3.1j) show the presence of a central elongated nuclear region with another bright region lying towards the west separated by a constriction from the nuclear region. The constriction becomes shallower at longer wavelengths leading us to believe that it is probably caused by extinction due to dust. An inspection of the colour maps shows a reddened vertical band in this region. We infer that this is due to a dust lane. This dust lane lies neither along the major axis of the galaxy, nor along its minor axis, but is at an intermediate angle. Hawarden et al. (1981) observed such "skew" dust lanes in a small fraction of early type galaxies. They suggest that the properties of the galaxies with such "skew" dust lanes are best attributed to the accretion of cool material at a fairly recent epoch. The signature of this is also seen as a reddened region in the colour image. A cut across the dust lane taken at a position angle 97° is presented in Fig. 3.1j which clearly shows the extent and the reddening in \((B-R)\) due to the dust lane. \((B-R)\) changes from 0.8 in the nuclear region to 1.5 at the location of the dust lane. The Hα emission is confined to the central region and the distribution is elongated in the East-West direction.

• **Mrk 602:**

This is a galaxy with a strong bar. It has been classified as SBbc. The northern spiral arms is forked and a small companion galaxy is seen 52" to its north. The colour map shows a blue nucleus and blue regions at the ends of the bar. The Hα image shows intense emission from the nuclear region and some faint emission along the bar, in addition to two blobs of emission located at the ends of the bar.

• **Mrk 708:**

This galaxy has been classified as possibly being a barred spiral in the UGC
and the RC3 catalogues. The UGC catalogue describes it as a spiral with very
broad ill-defined arms and with 3 or 4 stellar objects superimposed on it. The
colour image (Fig. 3.11) shows a reddened central region and the galaxy gets
bluer outwards. The Ha image shows strong emission in the central region
and a faint blob of emission on the north-eastern side. The central reddening
in colour could be either due to dust obscuration or due to a dominant redder
population. This will be discussed in Chapter 4.

• Mrk 781:

Mrk 781 is a barred, flocculent spiral. The contour map in the B band looks
ragged while that in the R band appears much smoother (Fig. 3.1m). The
colour map reveals the presence of a blue nuclear region \((B - V) \approx 0.6\),
surrounded by a much redder region with \((B - V) \approx 0.8\) in the bar region. The
colours get bluer again at the spiral arms. The Ha image also shows strong
emission in the nuclear region. The starburst activity is mainly confined to
the nuclear region in Mrk 781.

• Mrk 799:

Mrk 799 is a barred spiral galaxy. The UGC catalogue describes the galaxy
as having a very broad, slightly curved bar and three arms, one of which
is off center. It contains an extremely luminous HII region showing very
strong Wolf-Rayet emission features (Contini et al. 1997) at one end of its
bar. In Fig. 3.1n, this region lies to the SE of the nucleus and is at a distance
of 20\" from it. It is clear from the colour image shown in Fig. 3.1n that
this superassociation is the bluest region in the galaxy. Contini et al. (1997)
also find that the nuclear region is dusty and they detect a circumnuclear
ring of semi major axis length 3\".5. The colour image shows a blue nuclear
region surrounded by a reddened region. Curved dust lanes are also seen
in the colour image. The Ha emission in the nuclear region shows a double
structure. The strongest Ha emission is seen in the superassociation.
• **Mrk 1194:**

Mrk 1194 is an edge-on barred spiral. The contours in the inner regions are misaligned with the outer contours (Fig. 3.1o). The central region shows different structures in the $B$ and the $I$ bands. The $I$ band shows a well-defined nucleus while the nuclear region appears elliptical in the $B$ band. The $(B - I)$ colour map shows two blue blobs along the NS direction and a dust lane curving around it. The colour map and the $H\alpha$ image shows that star formation is concentrated in a circumnuclear ring of diameter 4 kpc. Contini et al. (1995) have reported the detection of this ring.

• **Mrk 1379:**

Mrk 1379 is a VV object (Vorontsov-Velyaminov 1977), with nests of interacting objects (Fig. 3.1p). The nucleus is blue in colour with $(B - V) \approx 0.4$, surrounded by a redder region with $(B - V) \approx 0.8$. Strong $H\alpha$ emission is seen in the nuclear region and diffuse emission is seen along the bar. Blobs of emission are seen at the ends of the bar and in the companion galaxies. The companion is the bluest with $(B - V)$ between 0.2 and 0.3. The $(B - I)$ image shows nuclear star formation in the form of a ring as well as extranuclear star formation. Knots of star formation are seen in the nuclear region as well as along the western periphery of the galaxy at the point where the spiral arms start. In addition to this, global star formation is detected in both the companions lying to the East.

### 3.4.3 Irregulars and Peculiars

Three galaxies namely Mrk 363, Mrk 439 and Mrk 1134 are classified under irregulars/peculiars. Refer to Fig. 3.1q-s for the isophotal contours and the colour maps of these three galaxies.

• **Mrk 363:**

This peculiar Sc type galaxy has been classified by Geller & Huchra (1983).
as belonging to a group made up of seven galaxies, based on their proximity in space and their radial velocities. A neutral hydrogen mapping by van Moorsel (1988) shows a central concentration of H\textsc{i}. Radio emission extended over the galaxy has been observed by Wrobel & Heesen (1988). An inspection of the contours in the $B$ and the $I$ band (Fig. 3.1q) reveals that the morphologies are quite different in the two spectral windows. The blue continuum has an extended structure in the central region with no well defined nucleus while the $I$ band image shows a well defined nucleus in the central region. The contours appear highly disturbed and asymmetric in both the bands, though they are more so in the $B$ band. The contours in the $B$ band are stretched out in the north more than those in the $I$ band suggesting the presence of dust in the region at $\approx 9''$ from the nuclear region. The $(B - I)$ map (Fig. 3.1q) clearly shows a highly reddened region coinciding with this feature. This region has a mean $(B - V)$ of 0.7 while the nuclear region has a mean value of 0.3. The $I$ band image shows a pointed structure starting from the nuclear region and extending upto 4'' along the SE direction. There is another pointy structure starting at 6'' and extending upto 12'' along the southern direction. H\alpha emission is global but the morphology of the emission is quite disturbed and clumpy. The peak of H\alpha emission is off-centered by 3'' with respect to the optical nucleus and lies on the NE side of the nucleus. The clumpy nature could be due to the presence of dust and this will be explored in detail in Chapter 4.

- **Mrk 439:**

  This galaxy is classified as S0/Sa in the Markarian catalogue. The outer contours of the galaxy in the $R$ band appears smooth and nearly circular. However, the inner region of the galaxy shows a very complex light distribution with clumps and drawn out plumes (Fig. 3.1r). The central region is elliptical and is elongated in the NS direction. Two distinct plumes are seen emerging - one along the NW direction and the other along the West. Faint indications of spiral arms in the NE direction are seen in the isophotal maps as well as

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the colour image. The contour maps show indications of a bar-like feature along the NW-SE direction, the signature of which becomes progressively prominent at shorter wavelengths. Wiklind & Henkel (1989) report the detection of a molecular bar in the central region in this galaxy. The colour maps show a blue elongated bar-like feature corresponding to that seen in the isophote map. Many galaxies with weak stellar bars have been found to contain strongly bar-like gas distributions similar to the one found in Mrk 439 e.g. the center of the nearby Scd galaxy IC 342 harbors a bar-like molecular gas structure about 500 pc in extent and a modest nuclear starburst about 70 pc in extent. (Lo et al. 1984; Ishizuki et al. 1990; Turner & Hurt 1992) In addition, there is another blue clump present at the south-eastern end of the bar. The nucleus is the bluest region with a $(B – V) \approx 0.3$.

The continuum subtracted Hα image shows an elongated bar corresponding to the one seen faintly in the contour maps and the colour maps. Hα emission is seen along the bar in the form of clumps. Emission is most intense at the ends of the bar, though it is found to extend throughout the body of the galaxy. A comparison of the broad band images and the Hα emission-line image shows that the regions that are bright in the continuum are spatially separated from the regions that are bright in the emission-line image.

- **Mrk 1134:**

This galaxy has been classified as an H galaxy. It is a small object and is paired with the larger Sc galaxy NGC 7753. The western arm of the spiral is connected to this galaxy by a bridge. The contours show an off-centered nucleus (Fig. 3.1s) with its center lying towards the region where the bridge from the larger spiral touches this galaxy. The large Sc galaxy and the bridge are not seen in this figure as we have only displayed the region covered by Mrk 1134. An image of the interacting system is given in Fig. 2.2. The colour image shows the bluest region to be coincident with the nucleus in $D$. A reddened region is seen to the South of this blue nucleus. The emission line image shows global massive star formation in this galaxy, with the peak of


Hα emission coinciding with the optical nucleus. The contours in the central region are elliptical with a slight protrusion towards the southern side. Another blob of emission is seen towards the western end of the galaxy. There is no structure corresponding to this blob in either the colour image or the isophotal contours.

3.5 Discussion and Conclusions

Analysis of the galaxy images and their isophotes reveals that the sample of starburst galaxies can be split up into three major morphological types: the SO’s and ellipticals; the spirals; and the irregulars and peculiars.

The SO’s and ellipticals forming the first class of starburst galaxies generally show smooth outer isophotes. However, distortions are seen in the form of disturbed inner isophotal contours or outer isophotes being off-centered with respect to the nucleus. They are generally isolated and do not show the presence of companions except in a few cases like Mrk 603 which is a clearly interacting system. Only one other galaxy, Mrk 1308 shows the presence of a companion nearby which could be responsible for triggering the starburst in Mrk 1308 due to tidal interaction with it. On probing the inner regions, we find structures like faint spiral arms as in Mrk 1002 and Mrk 190 or double nuclei as in Mrk 743. The contours in the inner regions of many of these galaxies appear more disturbed than the outer regions. Star formation is seen only in the central region with an extent of a few arcsecs in all the SO’s/E’s except in the interacting galaxy, Mrk 603 where the star formation activity is present globally. The companion galaxies of Mrk 603 also show global enhancement in star formation. The pseudo E.W. peaks at the nucleus or within 3” of the nucleus.

The sample contains 10 spirals. Out of these 10 galaxies, 8 are barred spirals. Star formation enhancement is seen in the nuclear region and at the ends of bars in most cases. Mrk 332 and Mrk 449 are the two objects where there are no
clear indications of the presence of a bar. In case of Mrk 332, intense star forming activity is seen along a ring like structure tracing the spiral arms. The arms show a disturbed morphology are are embedded in a smooth outer envelope. Structural analysis of Mrk 332 (Chapter 4) shows faint indications of a bar. Mrk 1194 and Mrk 213 show indications of a nuclear bar misaligned with the primary bar. Only one spiral, Mrk 1379 is part of an interacting system. As in Mrk 603, star formation activity is enhanced globally in the companion galaxies.

We classify three galaxies viz. Mrk 363, Mrk 439 and Mrk 1134 under irregulars/peculiars because of their highly disturbed isophotal contours. Mrk 363 and Mrk 1134 exhibit a global starburst while the third galaxy, Mrk 439 though not a global starburst, nevertheless shows extended H\alpha emission. The H\alpha isophotal contours do not trace the optical contours and the peak of H\alpha emission also does not coincide with the optical nucleus in Mrk 363 and Mrk 439.

The colour maps show that star formation is generally concentrated in the central region in all galaxies. Some galaxies like the irregulars Mrk 363 and Mrk 1134 show global enhancement of blue colour. On the basis of the colour maps and the emission line images, it is evident that the star forming regions show a wide variety of morphologies and locations like spiral arms, ends of bars, along the bar, in the circumnuclear region in the form of clumps or rings. Cases discussed in the present study show that the star formation though predominantly found to occur in the central region, is not always confined to the inner few kpc. In general, the regions with intense H\alpha emission correspond to the bluest regions seen in the colour maps. However, it is found in certain cases like Mrk 439 that rather blue areas do not show H\alpha emission. This probably indicates that the HII region seating there in the relatively recent past was turned off.

Simulated concentric aperture photometry of the H\alpha images shows that the line emission peaks in the central region and falls off nearly exponentially outwards in almost all cases. However, the radial distribution of pseudo E.W. does not show a uniform behaviour. This seems to indicate that though the intensity

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is maximum at the center, the relative star formation shows different trends. The nuclear pseudo E.W. is higher than the global pseudo E.W. in most of the galaxies. In a few cases like Mrk 363, Mrk 439 and Mrk 332 which show intense extranuclear star formation, the nuclear pseudo E.W. is lower than its global value. This suggests that the induced star formation relative to the underlying population is higher at locations other than the nucleus in these cases. In Mrk 1308, the pseudo E.W. peak is off-centered by 3". The pseudo E.W. traces the efficiency of star formation with respect to the underlying old population. In Mrk 1308, the efficiency is maximum at 3" from the center and is about 30% higher than that in the central region. This suggests that the physical conditions in this region are conducive to conversion of gas into stars. Radio observations of Mrk 1308 also reveal a molecular ring of the same size around the nucleus. Based on their study of isolated spiral galaxies, Hodge & Kennicutt (1983) concluded that the radial distribution of star formation in isolated spirals approximately follows the integrated light of the stellar disk. This would imply a more or less constant radial distribution of equivalent width, which is not consistent with the distribution of pseudo E.W.s found in the sample of starburst galaxies in the present study. A study of interacting galaxies by Bushouse (1986) also does not show a constant radial distribution of E.W.s and they conclude that the interaction induced star formation usually does not follow the same pattern of pre-interaction star formation, but occurs preferentially near the nuclear regions. In our sample, we find that the E.W. is generally maximum at the center or near the center.