Figure 3.3: MIPS maps of M33 at 40″ resolution (first column) and their wavelet decompositions for 4 different scales: 80″ (second column), 383″ (third column), 626″ (forth column), and 1024″ (fifth column). At the distance of 840 kpc, 1″ is equivalent to 4 pc. The maps at 24, 70, and 160 μm are shown from top to bottom. Before the decomposition, huge HII regions like NGC 604 were subtracted from the original images (Sect. 3.4). Maps are shown in RA–DEC coordinate system and centered at the center of the galaxy. The field size is 34′ × 41′. 

of 36 coverages is ≈ 220 μJy/beam. We also observed M33 at 20 cm with the B-band VLA\(^\text{2}\) D-array during 5 nights in November 2005 and January 2006 (from 06 to 08-11-05, 13-11-05, and 06-01-06). The reduction, calibration, and mozaicing of 12 fields were accomplished using the standard AIPS programs. The VLA interferometric data will miss much of the extended emission of the galaxy. For example, Viallefond et al. (1986b) showed that the WSRT interferometric map at 1.4 GHz accounted for only about 16% of the total emission. Therefore, we combined the VLA map with the new Effelsberg 20 cm map (Fletcher 2001) to recover the emission from extended structures in M33 (see Chapter 2). Both radio maps are shown in Fig. 3.1 at their original resolutions.

M33 was mapped in the IR by MIPS (Rieke et al. 2004) four times on 29/30 December 2003, 3 February 2005, 5 September 2005, and 9/10 January 2006. Each observation consisted of medium-rate scan maps with 1/2 array cross-scan offsets and covering the full extent of M33. The basic data reduction was performed using the MIPS instrument team Data Analysis Tool versions 3.02-3.04 (Gordon et al. 2005). At 24 μm extra steps

\(^{2}\)The VLA is a facility of the National Radio Astronomy Observatory. The NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.
Multi-scale study of radio and IR emission from M33

were carried out to improve the images including readout offset correction, array averaged background subtraction (using a low order polynomial fit to each leg, with the region including M33 excluded from this fit), and exclusion of the first five images in each scan leg due to boost frame transients. At 70 and 160 µm, the extra processing step was a pixel dependent background subtraction for each map (using a low order polynomial fit, with the region including M33 excluded from this fit). The background subtraction should not have removed real M33 emission as the scan legs are nearly parallel to the minor axis resulting in the background regions being far above and below M33.

The 24 µm image used consisted of just the 9/10 January 2006 observations as the depth reached in a single mapping was sufficient for this work. The 70 µm image used was a combination of the last three observations as the 29/30 December 2003 70 µm map suffered from significant instrumental residuals. These instrumental residuals were much reduced when the operating parameters of the 70 µm array were changed after the first M33 map was made and before the second. The 160 µm image used consisted of a combination of all four maps. The combination of multiple maps of M33 taken with different scan mirror angles results in a significant suppression of residual instrumental signatures (seen mainly as low level streaking along the scan mirror direction). The images used in this work have exposure times of ∼100, 120, and 36 seconds/pixel for 24, 70, and 160 µm, respectively.

The Hα observations by Hoopes & Walterbos (2000) were carried out on the 0.6 meter Burrell–Schmidt telescope at the Kitt Peak National Observatory, providing a 68′ × 68′ field of view. The MIPS and Hα images are shown in Fig. 3.2.

To obtain a proper comparison with the 3.6 cm radio map, all images of M33 were convolved to the angular resolution of 84″. For higher angular resolution studies, maps at 18″, 40″, and 51″ were also made. The PSF (point spread function) of the MIPS data is not Gaussian, in contrast to that of the radio data. Thus, convolutions of the MIPS images were made using custom kernels created using Fast Fourier Transforms (FFTs) to account for the detailed structure of the MIPS PSFs. Details of the kernel creation can be found in Gordon et al. (2007, in prep.). After convolution, the maps were normalized in grid size, rotation and reference coordinates. Then, they were cut to a common field of view (34′ × 41′ in RA and DEC, respectively).

In the following sections, we discuss the results with and without bright compact sources at each resolution to investigate how these sources affect the energy distribution at each wavelength and the correlations between wavelengths. After convolving to each resolution, the bright sources, common to all images, were subtracted using Gaussian fits including baselevels (‘Ozmapax’ program in the NOD2 data reduction system). For instance, the giant HII complexes NGC604 and NGC595 were subtracted at all resolutions. We also subtracted strong steep–spectrum background radio sources from the 20 cm image. Detailed descriptions of the source subtraction at each resolution are given in Sect. 3.4.

3.3 Wavelet analysis of IR emission

Wavelet analysis is based on a spatial–scale decomposition using the convolution of the data with a family of self–similar basic functions that depend on the scale and location
Table 3.2: Source subtraction thresholds $S(\lambda)$ and number of subtracted sources at different spatial resolutions.

<table>
<thead>
<tr>
<th>HPBW asec</th>
<th>Subt. sources</th>
<th>$S_{24\mu m}$ $\mu$Jy/asec$^2$</th>
<th>$S_{70\mu m}$ $\mu$Jy/asec$^2$</th>
<th>$S_{160\mu m}$ $\mu$Jy/asec$^2$</th>
<th>$S_{20\text{cm}}$ $\mu$Jy/b.a.</th>
<th>$S_{3.6\text{cm}}$ $\mu$Jy/b.a.</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>40</td>
<td>460</td>
<td>2650</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>51</td>
<td>15</td>
<td>115</td>
<td>1570</td>
<td>2865</td>
<td>7190</td>
<td>–</td>
</tr>
<tr>
<td>84</td>
<td>11</td>
<td>85</td>
<td>900</td>
<td>2340</td>
<td>8260</td>
<td>5780</td>
</tr>
</tbody>
</table>

of the structure. Like the Fourier transformation, the wavelet transformation includes oscillatory functions; however, in the latter case these functions rapidly decay towards infinity. As a result, Frick et al. (2001) show that the wavelet method is more resistant to noise and the smoother spectra allow better determination of the true frequency structure. The cross–correlation of wavelet spectra lets us compare the structures of different images systematically as a function of scale.

The wavelet coefficients of a 2D continuous wavelet transform are given by:

$$W(a, x) = \frac{1}{a^\kappa} \int_{-\infty}^{+\infty} f(x') \psi^* \left( \frac{x' - x}{a} \right) dx',$$

where $\psi(x)$ is the analysing wavelet, $x = (x, y)$, $f(x)$ is a two–dimensional function (an image), and $a$ and $\kappa$ are the scale and normalization parameters, respectively, (the * symbol denotes the complex conjugate). The above transformation decomposes an image into ‘maps’ of different scale. In each map, structures with the chosen scale are prominent as they have larger coefficients than those with smaller or larger scales. To obtain a good separation of scales and to find the scale of dominant structures in M33, we use the ‘Pet–Hat’ wavelet that was introduced by Frick et al. (2001) and applied there to NGC 6946. It is defined in Fourier space by the formula:

$$\psi(k) = \begin{cases} \cos^2 \left( \frac{\pi}{2} \log_2 \frac{k}{2\pi} \right) & \pi \leq k \leq 4\pi \\ 0 & \pi > k \text{ or } k > 4\pi, \end{cases}$$

where $k$ is the wavevector and $k = |k|$.

We decomposed the Spitzer images into 10 different scales $a$ to compare the morphologies at 24, 70, and 160 $\mu m$ at each scale. Fig. 3.3 shows the original maps and the decomposed maps at 4 scales. The original 24 and 70 $\mu m$ maps were smoothed to the MIPS 160 $\mu m$ PSF with FWHM (full width half maximum) = 40$''$ before decomposition. The maps at scale $a = 80''$ (0.3 kpc) show the smallest detectable emitting structures. Most of the morphological differences among the MIPS images are found at this scale. At scale $a = 383''$ (1.5 kpc), the prominent structures are spiral arms and the center of the galaxy. The central extended region is more pronounced at scale $a = 628''$ (2.5 kpc). The emission emerges from a diffuse structure at scale $a = 1024''$ (4 kpc), and it is not possible to distinguish the arm–structure anymore. This structure can be identified as an underlying diffuse disk with a general radial decrease in intensity. The similarity of the 4 kpc...
maps at different wavelengths indicates that the large-scale diffuse emission has the same structure at different mid– and far–infrared wavelengths.

At the smallest scale, the emission emerges from spot–like features aligned along filaments with the width of the scale. At 24 µm the spots corresponding to HII regions contain most of the energy at this scale (see Sect. 3.6). Diffuse filaments are more pronounced at 160 µm. As shown in the next section, the fraction of the energy at this scale at 160 µm is less than that at 24 µm. The situation in the 70 µm map is in between the 24 and 160 µm maps. It seems that the star forming regions provide most of the energy of the 24 and 70 µm emission, if the spots correspond to these regions, as is discussed in the following sections.
Figure 3.6: The wavelet spectra of the 3.6 cm radio and IR images at 84″ resolution before (left) and after (right) subtraction of the same sources. For comparison, the spectrum of the Hα emission is also plotted. The data points correspond to the scales 0.84, 1.00, 1.19, 1.42, 1.67, 2.02, 2.41, 2.87, 3.42, 4.08 kpc. The spectra are shown in arbitrary units.

3.4 Spectral characteristics of IR and radio maps

In this section, we demonstrate how the wavelet spectra can be used to investigate the scaling properties of the emission. This spectrum is defined as the energy in the wavelet coefficients of scale \(a\) (Frick et al. 2001):

\[
M(a) = \int_{-\infty}^{+\infty} |W(a, x)|^2 dx. \tag{3.3}
\]

After smoothing the 24 \(\mu m\) map to the MIPS 70 \(\mu m\) PSF with FWHM = 18″, about 40 bright sources (mostly corresponding to HII regions) were subtracted from both maps (equivalent to removing sources with fluxes higher than the lower limits, \(S(\lambda)\), given in Table 3.2.). Fig. 3.4 shows the wavelet spectra, \(M(a)\), of the 24 \(\mu m\) and 70 \(\mu m\) maps before and after source subtraction. Clearly, the small scales are the dominant scales before source subtraction. The scale at which the wavelet energy is maximum is \(\sim 70″\) (280 pc) at 24 \(\mu m\) and \(\sim 110″\) (440 pc) at 70 \(\mu m\). After source subtraction, the spectra become flatter. The larger size of the dominant scale at 70 \(\mu m\) caused by these sources (by a factor of \(\sim 1.6\) at this resolution) indicates a slightly more extended distribution of dust grains emitting at 70 \(\mu m\) than at 24 \(\mu m\) in the vicinity of star forming regions. Moreover, the ratio of the maximum to minimum energy in the original spectrum at 24 \(\mu m\) is larger (by a factor of 3) than that at 70 \(\mu m\). This indicates that either star forming regions provide more energy for the 24 \(\mu m\) emission, or the large-scale diffuse emission is stronger at 70 \(\mu m\) than 24 \(\mu m\).

At the next angular resolution, 51″, the HPBW (half power beam width) of the 20 cm radio map, 15 bright sources (HII regions) visible at all maps were subtracted from the 20 cm map and the smoothed 24, 70, and 160 \(\mu m\) IR maps. In addition to these sources, 9 background radio sources plus the supernova remnants SN1, SN2, and SN3 (Viallefond

\textsuperscript{4}It is also called ‘wavelet power spectrum’, however following some authors (e.g. Frick et al. 2001; Zhou & Adeli 2003), we refer to \(M(a)\) as the ‘wavelet energy’ (see Appendix B).
et al. 1986a) were subtracted from the 20 cm radio map. The wavelet spectra of the MIPS and 20 cm radio maps at this resolution are plotted in Fig. 3.5. The Hα spectrum is also given for comparison. The 24 and 70 μm maps show a smoothed version of their distributions in Fig. 3.4 (the linear smoothing factor is \( \sim 3 \) between Figs. 3.4 and 3.5). However, the effect of the sources can still be seen by comparing the left panel with the source subtracted spectra in the right panel.

The 160 μm map is hardly influenced by the smoothing, as its original resolution is 40″ (the smoothing factor is \( \sim 1.3 \)). The 160 μm spectrum is more similar to the 70 μm spectrum than to the other spectra. It seems that the compact sources have less effect on the energy distribution at 160 μm, because the smallest scale is not the dominant scale. Hence, there is no important change in the spectrum after the source subtraction. The energy shows an increase at the scale of complexes of dust and gas clouds (\( \sim 250″ \) or 1 kpc), then a second increase in transition to the large-scale structures or diffuse dust emission.

The spectrum of the 20 cm radio image is also dominated by bright sources. There is a maximum at the scale \( a = 140″ \) (560 pc), then a decrease towards the larger scales with a slope of -0.9. However, a flat spectrum remains for the scales less than the size of the central extended region (\( \sim 600″ \) or 2.4 kpc) after the source subtraction.

The spectra of all the maps at the resolution of the 3.6 cm data (HPBW = 84″)\(^5\) are shown in Fig. 3.6 (left panel). The spectra after subtracting the 11 brightest HII regions are plotted in the right panel. Again, because of these sources, the small scales are dominant at 3.6 cm. As shown in comparing the left and right panels, they also are seen in all the infrared bands, strongly at 24 μm and much more weakly at 160 μm. Here, the smoothing effect is seen in all 3 MIPS wavelet spectra.

Before source subtraction, the 20 and 3.6 cm spectra are similar to each other and to the Hα spectrum up to the scale of the central extended region, \( \sim 600″ \) (2.4 kpc). All three spectra become steeper between \( a \sim 2.4 \) kpc and \( a \sim 3.4 \) kpc, which means that the wavelet energy from structures with scales of about half of the size of the galaxy (\( \sim 900″ \) or 3.6 kpc) is not as significant as that from smaller structures. It seems that a minimum in the wavelet spectra of the radio and Hα emission, as was also shown in NGC 6946 (see Fig. 3.7 in Frick et al. 2001), is a characteristic of this scale. However, while this decrease disappears in the 3.6 cm and Hα spectra after source subtraction, it remains in the 20 cm spectrum. This implies that besides the bright HII regions there are sources of nonthermal emission within the spiral arms and central extended region which emit significantly at 20 cm.

To estimate how much of the wavelet energy \( M(a) \) is provided by the subtracted sources, we consider the following definition:

\[
\Delta(a) \equiv \frac{M_{or.}(a) - M_{s.s.}(a)}{M_{or.}(a)},
\]

where \( M_{or.}(a) \) and \( M_{s.s.}(a) \) represent the wavelet energy before and after source subtraction. Table 3.3 shows the fraction of energy produced by the 11 HII regions in IR and

\(^5\)Gaussian PSFs with FWHM = 51″ and 84″ are considered to convolve the IR maps to the angular resolutions of the 20 and 3.6 cm radio maps, respectively.
Table 3.3: Fractions of the wavelet energy provided by the 11 brightest HII regions at different scales (Eq. 4).

<table>
<thead>
<tr>
<th>λ</th>
<th>∆(210″)</th>
<th>∆(505″)</th>
<th>∆(1020″)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 μm</td>
<td>0.94</td>
<td>0.81</td>
<td>0.35</td>
</tr>
<tr>
<td>70 μm</td>
<td>0.80</td>
<td>0.57</td>
<td>0.14</td>
</tr>
<tr>
<td>160 μm</td>
<td>0.52</td>
<td>0.33</td>
<td>0.11</td>
</tr>
<tr>
<td>3.6 cm</td>
<td>0.86</td>
<td>0.69</td>
<td>0.16</td>
</tr>
</tbody>
</table>

at 3.6 cm for 3 different scales (at 84″ resolution). The corresponding fractions at 20 cm are not shown in this table, as some nonthermal radio sources were also subtracted at this wavelength. The emission at 24 μm has the largest energy fraction ∆(a) at all scales. The smallest ∆(a) occurs at 160 μm. This indicates that HII regions play a more important role in providing energy for dust emission at 24 μm than at 160 μm.

We estimate the uncertainties of the wavelet energies of each map by making a noise map with the distribution and amplitude of the real noise in the corresponding observed map. A linear combination of uniform and Gaussian distributions simulates the real noise in each observed image. The wavelet spectra of the derived noise maps were obtained using Eq. 3.3. The resulting wavelet energies of the noise maps are taken as the uncertainties of the wavelet energies of the observed maps at different scales. The estimated values are at least three orders of magnitude less than the wavelet energies of the observed maps. Therefore, the results from our wavelet spectrum analysis are not substantially affected by the noise in the maps.

3.5 Wavelet cross–correlations

A useful method to compare images at different wavelengths is the wavelet cross-correlation. The wavelet cross-correlation coefficient at scale a is defined as:

\[ r_w(a) = \frac{\int \int W_1(a, x) W_2^*(a, x) dx}{|M_1(a)M_2(a)|^{1/2}}, \]  

where the subscripts refer to two images of the same size and linear resolution. The value of \( r_w \) varies between -1 (total anticorrelation) and +1 (total correlation). Plotting \( r_w \) against scale shows how well structures at different scales are correlated in intensity and location. The error is estimated by the degree of correlation and the number of independent points, n:

\[ \Delta r_w(a) = \sqrt{\frac{1 - r_w^2}{n - 2}}, \]  

where, \( n = 2.13 \left(\frac{L}{a}\right)^2 \), and L is the size of the maps.

First, we examine the cross–correlations between the 3 MIPS maps of M33 (Fig. 3.7). There are significant correlations between each pair of the MIPS maps at different scales within 0.4 < a < 4 kpc, as \( r_w > 0.75 \) (Frick et al. 2001). These scales include gas clouds,
Figure 3.7: The cross–correlation between 24 and 70\,\mu m (top), 24 and 160\,\mu m (middle), and 70 and 160\,\mu m (bottom) images at 51'' resolution before (or.) and after (s.s.) source subtraction.
Figure 3.8: The cross–correlation between 3.6 cm radio and IR before and after subtraction of the same sources at 84″ resolution.

Second, we study the cross–correlations between the infrared and the radio continuum emission at 3.6 cm. As shown in Fig. 3.8, the correlations between 3.6 cm radio and the
Figure 3.9: The correlation of the 20 cm radio with IR before and after subtraction of the same sources at 51" resolution (please note that this figure starts from 100" and not 200").
three infrared emission are strong at all scales. At scales smaller than the width of the spiral arms (1.6 kpc), the correlations are higher between 3.6 cm and 24 µm emission (and also 70 µm) than between 3.6 cm and 160 µm emission. The source subtraction reduces the 3.6 cm–24 µm and 3.6 cm–70 µm correlations at scales smaller than the spiral arms. This indicates that young massive stars are the most common and important energy sources of the 3.6 cm, 24 and 70 µm emission at these scales.

Third, the cross–correlations with the radio continuum emission at 20 cm are presented in Fig. 3.9. Before the source subtraction, the correlations between 20 cm radio and the three IR bands are strong at scales smaller than the width of the spiral arms. After the source subtraction, the coefficients of the IR–20 cm correlations decrease dramatically so that they become less than 0.75 at small scales. The reason is possibly that besides HII regions there are other unresolved sources of the 20 cm radio emission like supernova remnants that are stronger than at 3.6 cm but do not emit significantly in the infrared. Studies within our Galaxy have demonstrated that the ratio of far-infrared to radio continuum emission for supernova remnants is much smaller than that for HII regions (Fürst et al. 1987).

Comparing Fig. 3.8 with Fig. 3.9, a drop in correlation coefficient at the scale of 800″ (3.2 kpc) is more prominent in the MIPS correlations with 20 cm than with 3.6 cm. This is due to the strong minimum in the 20cm spectrum at this scale (Fig. 3.5) that persists even after the source subtraction (in contrast to the situation in the 3.6 cm spectrum shown in Fig. 3.6).

### 3.6 Comparison with Hα

If we take the Hα emission as a tracer of star forming regions that both heat the warm dust and ionize the gas giving the free–free emission, we expect a correlation between Hα emission, IR and thermal radio emission. The cross–correlations involving Hα and IR images are shown in Fig. 3.10. The significant correlation of Hα with the 24 and 70 µm images at the smallest scale confirms that most of the compact structures in the MIPS decomposed maps at 24 and 70 µm (Fig. 3.3) correspond to the HII regions. The 160 µm emission is also correlated with Hα emission, although the correlations are weaker than the correlations at 24 and 70 µm. It is deduced that the role of star forming regions in heating the dust, even the cold dust (emitting mainly at 160 µm), is generally important at scales smaller than 4 kpc.

Between Hα and 3.6 cm there is a perfect correlation for both small–scale and extended structures: \( r_w \geq 0.95 \) (right panel in Fig. 3.10). This is not surprising as the wavelet spectra of the Hα and 3.6 cm maps are very similar (see Fig. 3.6). Thus, not only are the star forming regions mostly responsible for the 3.6 cm emission, but also the radio continuum emission is dominated by the thermal free–free emission at 3.6 cm for \( a < 4 \text{ kpc} \).

After smoothing the 20 cm map to the spatial resolution of the 3.6 cm map, we obtain the Hα–20 cm correlation (Fig. 3.10). At scales smaller than 600″ or 2.4 kpc, the coefficients are the same as for the Hα–3.6 cm correlation. This means that the bright HII regions are also important sources of the 20 cm radio emission. It seems that the correlation decreases at larger scales, but it is not certain because of the large errors.
3.7 Discussion

We studied the spectral characteristics of the MIPS mid– and far–infrared, radio and Hα maps and obtained cross–correlation coefficients between pairs of maps. Here, we discuss the implications of our results for the understanding of the energy sources powering the IR and radio emission from M33. Further, we compare the results of our analysis on M33 with that of Frick et al. (2001) on NGC 6946.

3.7.1 IR emission

From the wavelet analysis of the MIPS IR maps the following results are found.

- The 24 and 70 µm emission emerge mostly from the bright sources corresponding to star forming and HII regions. The influence of HII regions on the IR emission is highest at 24 µm (see Table 3.3). As expected, at small scales the 24 µm map is better correlated with the 70 µm than with the 160 µm map.

- The 160 µm emission emerges from both compact and extended structures. The compact structures correspond to star forming and HII regions. As shown in Table 3.3, the fraction of wavelet energy provided by the 11 brightest HII regions at 160 µm varies between 1/2 and 1/3 of that at 24 µm at different scales. The 160 µm map does not show small–scale dominance in its spectrum. The 160 µm spectrum shows an increase when it reaches the scale of complexes of dust and gas clouds of ∼ 1 kpc, and a second increase in transition to the large–scale structures or diffuse dust emission.

While it is clear that the ionizing stars heat the warm dust, the mechanism heating the cold dust is still in debate. According to our wavelet analysis, the direct role of the young stellar population decreases with increasing IR wavelength. As shown in Table 3.3, at small scales (< 200″ or 0.8 kpc), the relative contribution of the 11 brightest HII regions to the total emission energy is about 50% at 160 µm which means that the contribution of all HII regions of M33 is much larger than 50%. Hence, it seems that at least up to scales
of 0.8 kpc the cold dust is effectively heated by UV photons from massive ionizing stars. On the other hand, the 160 µm–\(H\alpha\) correlation coefficients are smaller than those of the 24 µm (or 70 µm)–\(H\alpha\) correlation (Fig. 3.10). This means that the number of structures with a specific scale emitting strongly in both IR and \(H\alpha\) becomes less at 160 µm. This indicates that besides UV photons from massive ionizing stars, other heating sources contribute also to heating the cold dust. These could be non–ionizing UV photons either from intermediate–mass stars (5–20 \(M_\odot\)) (Xu 1990) or from HII regions (Popescu et al. 2000, 2002; Misiriotis et al. 2001), or optical photons from solar mass stars (Xu & Helou 1996; Bianchi et al. 2000); they should contribute to an average radiation field as the 160 µm wavelet spectrum is smooth.

Our findings confirm the arguments of e.g. Hinz et al. (2004), Devereux et al. (1994); Devereux et al. (1996, 1997) and Jones et al. (2002) that the IR is powered predominantly by young O/B stars, specifically at 24 and 70 µm. This is not necessarily at variance or in accordance with the argument of Xu & Helou (1996) that only 27% of the diffuse dust emission from M31 can be attributed to the heating by UV photons, because of two reasons. First, our wavelet study does not include diffuse structures with scales larger than 4 kpc. Second, the late–type galaxy M33 is more densely populated with young stars than the earlier–type galaxy M31. This may mean that the relative role of young stars in heating the dust increases with later galaxy type (Sauvage & Thuan 1992). For a more precise comparison, it is necessary to accomplish wavelet analysis for other nearby galaxies.

Hoernes et al. (1998) showed that the cold dust emission in M31 has a weaker correlation with the thermal radio than with the nonthermal radio emission. Since the contribution of the thermal emission is higher at 3.6 cm than at 20 cm, one may expect a weaker correlation between the 160 µm and 3.6 cm emission. In M33, we did not find significant differences between the 160 µm–3.6 cm and 160 µm–20 cm correlations (Figs. 3.8 and 9) at scales of \(200''\) (0.8 kpc) < \(a\) < \(700''\) (2.8 kpc), even after subtracting strong thermal sources (bright HII regions). This could be due to the larger role of UV photons from O/B stars in heating the cold dust in M33 than in M31, as discussed in the previous paragraph. However, a better 160 µm correlation with the nonthermal than with the thermal radio is probable at the scale of the whole galaxy. For instance, Hinz et al. (2004) showed that the morphology of the smoothed 160 µm emission from M33 is most similar to that of the radio emission at 17.4 cm.

### 3.7.2 Radio emission and radio–IR correlation

From the wavelet analysis of the radio maps we obtain the following results for the 3.6 and 20 cm emission from M33.

- The shape of the 3.6 cm wavelet spectrum is very similar to that of the \(H\alpha\) spectrum (Fig. 3.6) and, hence, there is a perfect correlation between 3.6 cm and \(H\alpha\) at all scales (Fig. 3.10). This indicates that not only the star forming regions are mostly responsible for the radio emission at 3.6 cm, but also the thermal (free–free) emission is significant at this wavelength. But it could also be that the nonthermal (synchrotron) emission correlates well with the thermal emission. Our recent estimation of the thermal fraction of the 3.6 cm radio continuum emission gives
$f_{th} \sim 50\%$ for the whole galaxy including the extended disk emission (Tabatabaei et al., in prep.). As a higher percentage of the thermal fraction is expected at scales $\leq 4$ kpc, this result is consistent with our wavelet study. The nearly parallel 3.6 cm and H$\alpha$ wavelet spectra indicates that extinction is scale–independent and has no significant effect on H$\alpha$ emitting structures.

- The combined 20 cm (VLA+Effelsberg) wavelet spectrum represents both compact and diffuse structures of thermal and nonthermal emission. The bright HII regions (or complexes) give strong contribution to the 20 cm emission. The strong H$\alpha$–20 cm correlation at scales smaller than the width of the central extended region ($\sim 2.5$ kpc) also indicates that the nonthermal emission correlates perfectly with the thermal emission at these scales.

- Generally, there are strong 3.6 cm–IR correlations at all scales in the range of 0.8–4 kpc within M33 (Fig. 3.8). The 3.6 cm correlations with 24 and 70 $\mu$m are better than that with 160 $\mu$m before subtracting bright HII regions. However, these correlations become approximately the same after subtracting HII regions. That is because the 24 and 70 $\mu$m emission are more influenced by the HII regions than the 160 $\mu$m emission.

- The strong 20 cm–IR correlations are mainly due to the bright HII regions, as the correlations fall after source subtraction (Fig. 3.9). Here, the weakest correlation is between the 20 cm and the 24 $\mu$m maps. This indicates that the nonthermal sources which are associated with star forming regions are not as effective as HII regions in heating the dust.

In their multi–resolution analysis of the radio–IR correlation in the LMC, Hughes et al. (2006) found strong correlations in the regions where the thermal fraction of the radio emission is high. This is in agreement with our results that the 24 and 70 $\mu$m–radio correlations are higher before subtracting HII regions. Even, the 160 $\mu$m–20 cm correlation follows this pattern before subtracting the thermal radio regions. For NGC6946, Frick et al. (2001) also found a better correlation between the thermal 3.6 cm radio and IR emission up to scales of the width of spiral arms, although the nonthermal emission dominates in this galaxy (Ehle & Beck 1993). There are indications for similar trends in other nearby galaxies (Murphy et al. 2006).

### 3.7.3 Comparison with NGC 6946

It is instructive to compare the results of the wavelet analysis of M33 with those obtained by Frick et al. (2001) for NGC 6946, which is also a late–type Scd galaxy.

NGC 6946 was studied at a linear resolution of 0.4 kpc corresponding to our analysis at 84$''$ HPBW. Comparing Fig. 3.6 (in this paper) to Fig. 3.7 in the Frick et al. (2001) paper at scales between 0.8 and 4 kpc, the dominant scale of the H$\alpha$ wavelet spectrum is at the scale of the width of the spiral arms (1.5 kpc) in NGC 6946, while in M33 it is at the smallest scale ($\sim 200''$ or 0.8 kpc in Fig. 3.6). Even after subtracting the 11 brightest HII regions the scales corresponding to the spiral arms ($\sim 400''$) are not dominant in M33. This is because the spiral arms in M33 are not as pronounced as those in NGC 6946. Instead, the H$\alpha$ emission in M33 has a rather clumpy distribution.
The spectrum of dust emission from NGC 6946 at 12–18 \(\mu m\) shown in Fig. 3.7 in the Frick et al. (2001) paper is more similar to the spectrum of dust emission from M33 at 160 \(\mu m\) than to that at 24 \(\mu m\). So, the excess of hot dust emission near the massive stars found in M33 is not visible in NGC 6946.

Frick et al. (2001) found signatures of three–dimensional Kolmogorov–type turbulence (Kolmogorov 1941) for the ionized gas (H\(\alpha\) and thermal radio continuum emission at 3.6 cm) at scales less than 0.6 kpc in NGC 6946. An increasing part of the spectrum (logI–log\(\alpha\)) with a slope of 5/3 is typical for this type of turbulence (Spangler 1991). They obtained this slope considering the first point at the scale of 0.3 kpc (the resolution of their maps was 0.4 kpc), making the slope estimate of 5/3 uncertain. At the same resolution we cannot investigate this turbulence for M33, as the smallest scale in Fig. 3.6 is larger than 0.6 kpc. However, at higher spatial resolutions the spectra of the radio, IR, and H\(\alpha\) emissions from M33 do not show such an increase at scales less than 0.6 kpc (Figs. 3.4 and 3.5). The steepest increasing slope is about 1.1 at scales between 140 and 320 pc (in the 24 \(\mu m\) spectrum) (Fig. 3.4). The slopes become less at 51″ resolution (Fig. 3.5). They vary between 0 and 0.6 at increasing parts of the spectra and between 0 and -0.9 at decreasing parts of the spectra. After subtracting HII regions, the slopes become even flatter.

Comparing Fig. 3.12 in the Frick et al. (2001) paper to Fig. 3.10 (in this paper), the 3.6 cm–H\(\alpha\) cross–correlation coefficients are less at the small scales in NGC 6946 than in M33. As the extinction is proportional to the dust density and because higher dust densities can be found at smaller scales, one expects more extinction of H\(\alpha\) at smaller scales. This leads to a weaker correlation with the radio free–free emission at smaller scales. Hence, it seems that absorption by dust at scales < 1.2 kpc (Fig. 3.12, Frick et al. 2001) is less significant in M33 than in NGC 6946. The existence of considerable extinction in NGC 6946 caused by a patchy dust distribution has been shown by Trewhella (1998).

3.8 Conclusions

Highly resolved and sensitive Spitzer MIPS images of M33 at 24, 70, and 160 \(\mu m\) enabled us to compare the morphology of different dust components of this galaxy. A 2D-wavelet transformation was used to find dominant scales of emitting structures and correlations of the MIPS images with new radio (3.6 and 20 cm) maps as well as with an H\(\alpha\) image of M33. We compared the results of wavelet analysis with and without bright HII regions at different resolutions (18″, 51″, 84″). We found that at a characteristic scale of 210″ or 0.8 kpc, 80% or more of the wavelet energy at 24 and 70 \(\mu m\) and 3.6 cm is from the 11 brightest HII regions. These sources cause better correlations between pairs of the 24 and 70 \(\mu m\) and 3.6 cm maps, while they cause a smaller 24–160 \(\mu m\) correlation. Bright HII regions improve the correlations between the 20 cm radio map and each of the MIPS IR maps. The H\(\alpha\) emission shows a better correlation with IR emission at 24 and 70 \(\mu m\) than at 160 \(\mu m\). It is perfectly correlated with the 3.6 cm radio emission out to scales of 4 kpc and also with the 20 cm radio emission out to scales of the width of the central extended region (\(\sim\) 2.5 kpc). This is understandable because the radio continuum emission at 3.6 cm is dominated by thermal emission and that at 20 cm by nonthermal emission.
The most important conclusions of this study are:

- The longer the IR wavelength, the more extended is the distribution of dust grains emitting at that wavelength (Sects. 3.3 and 3.4).

- HII regions influence the IR emission with a strength inversely depending on wavelength: more influence at 24 $\mu$m and less influence at 160 $\mu$m (Sect. 3.4).

- The nonthermal radio emission correlates well with the thermal radio and H$\alpha$ emission out to the scale of the central extended region, $\sim 2.5$ kpc (Sect. 3.7).

- The warm dust–thermal radio correlation is stronger than the cold dust–nonthermal radio correlation at scales smaller than 4 kpc (about half the size of the galaxy) (Sects. 3.5 and 3.7).

- The effect of extinction in H$\alpha$ is independent of the scale of structures in M33 and is smaller than in NGC6946.

In Chapter 4, we obtain maps of the thermal and nonthermal radio continuum emission and compare them with the IR emission, separately.
4 Thermal and nonthermal radio emission from M33

4.1 Introduction

The problem of separating the two components of the radio continuum emission, free-free (thermal) and synchrotron (nonthermal) emission, dates back to the beginnings of radioastronomy. The mostly applied techniques are based on either assuming a constant nonthermal spectral index (e.g. Klein et al. 1984) or a correlation between thermal radio and infra-red (IR) emission (Broadbent et al. 1989).

Although the assumption of constant nonthermal spectral index may be reasonable for global studies (Sect. 4.10), it does not lead to a feasible thermal/nonthermal distribution in detailed studies. Under this simplification, it is not possible to investigate the origin and energy loss processes of the electron component of cosmic rays (CRs) within a galaxy. Discrete synchrotron emitting sources are mainly identified as supernova remnants. The synchrotron emission from supernova remnants can be described as power law ($S_\nu \sim \nu^{-\alpha_n}$) with a typical spectral index of $\alpha_n \simeq 0.6$. Propagating from these sources, electrons suffer energy losses that steepens the power law spectrum. In the interstellar medium, the typical spectral index attributed to the emission under the leakage loss is $\simeq 0.9$, and under synchrotron loss and inverse Compton scattering $\simeq 1.1$ (Biermann 1995). These electrons further diffuse to the interarm regions and outer parts of spiral galaxies within their life time. Hence, variations of the nonthermal spectral index should be distinguishable particularly by comparing arms with interarm regions and outer parts of the galaxies.

The thermal/nonthermal separation based on the assumption that the radio-IR correlation is due to a correlation between the thermal radio and IR emission is not generally correct, as nonthermal phenomena e.g. super massive black holes or energetic CRs may stimulate the IR emission. For instance, the possibility of heating the diffuse dust (emitting in IR) by CRs was shown by Helou & Bicay (1993) and Bicay & Helou (1990). Moreover, supernovae, the ultimate sources of most of the nonthermal emission, explode close to the star-forming regions in which their progenitor stars formed. Together with the increased magnetic field strength in the spiral arms, this causes a correlation between the thermal and nonthermal sources, making a less direct link between the IR and thermal emission. Finally, the slope of the radio-IR correlation depends on the synchrotron spectral index (Niklas & Beck 1997).

Templates for free-free emission could be provided by emission of recombination lines as they originate from within ionized regions, like the free-free emission. The H$\alpha$
emission, the strongest Balmer line, is observationally most preferred, particularly from nearby galaxies. Both the $H\alpha$ and free-free emission are linearly proportional to the number of ionizing photons produced by massive stars. On the other hand, the $H\alpha$ emission suffers from extinction by dust leading to an underestimate of the free-free emission if no extinction correction is made. Note that the emission of radio recombination lines is extinction free and hence ideal for tracing the free-free emission. However, these kinds of emission are too weak from the diffuse ionized gas in external galaxies to be detected using the present facilities. For example, our attempt to map radio recombination lines emission from diffuse regions within IC 342 and M33 using the 6.2 cm receiver of the Effelsberg Telescope was not successful.

The nearest Scd galaxy, M33 (NGC 598), at a distance of 840 kpc ($1'' \approx 4$ pc, Freedman et al. 1991) has been extensively studied at radio and IR wavelengths. With an inclination of $i = 56^\circ$ (Regan & Vogel 1994), its spiral structure is well visible. So far, extinction studies in M33 have mostly focused on HII regions using either the Balmer (and Paschen) line ratios (e.g. Kwitter & Aller 1981; Melnick et al. 1987; Petersen & Gammelgaard 1997) or the ratio of $H\alpha$ to radio emission (e.g. Israel & Kennicutt 1980; Devereux et al. 1997). In the line ratio method the emission from the diffuse ionized medium can hardly be detected in most of these recombination lines. The method based on the radio emission only works well when the thermal component of the radio continuum is independently known. For instance, the radio emission from single HII regions (and not HII complexes with a possible nonthermal emission contribution like NGC 604 and NGC 595, Dodorico 1978; Gordon et al. 1993) may be considered as the thermal emission.

Using the ISOPHOT 60 and 170 $\mu$m data, Hippelein et al. (2003) found an anticorrelation between the flux density ratio of $H\alpha/60\mu$m and $170\mu$m flux density, suggesting the extinction to be related to the cold dust in M33.

We obtain the distribution of the dust optical depth at the $H\alpha$ wavelength for the whole M33 (an extinction map) by analysis of dust emission and absorption using the high sensitivity and resolution Multiband Imaging Photometer Spitzer (MIPS, Rieke et al. 2004) FIR data at 70 and 160 $\mu$m. This leads to an $H\alpha$ map corrected for extinction (deextincted $H\alpha$ map), our free-free template. The thermal and nonthermal maps at 3.6 and 20 cm are obtained at an angular resolution of $90''$ (equivalent to a linear resolution of 360 pc) by both the new (using a free-free template) and the standard method (assuming a constant nonthermal spectral index) and the results are compared. Further, we determine variations of the nonthermal spectral index across M33 as detected by the new method and discuss the exponential scale lengths of both thermal and nonthermal emission.

In Sect. 4.3 we derive distribution of dust color temperature. This temperature and the 160 $\mu$m flux density are used to obtain the dust optical depth (extinction) and its distribution in Sects. 4.4 and 4.5. We correct the $H\alpha$ emission for the extinction and then convert it to the thermal radio emission, following Dickinson et al. (2003) (Sect. 4.6). The nonthermal intensity and spectral index maps are produced in Sects. 4.7 and 4.8. We discuss and compare the results from the new and standard methods in Sect. 4.9. Finally, conclusions are presented in Sect. 4.10.
4.2 Data

The radio continuum data at 3.6 and 20 cm were presented in Chapter 2 (Tabatabaei et al. 2007c). At 3.6 cm, M33 was observed with the 100-m Effelsberg telescope of the MPIfR\textsuperscript{1}. The 20 cm data were obtained from observations with the Very Large Array (VLA\textsuperscript{2}) corrected for missing spacing using the Effelsberg data at 20 cm. We also used the latest combined epoches of MIPS Spitzer data at 70 and 160\,µm (as presented in Tabatabaei et al. 2007a, 2005). The He map is from Kitt Peak National Observatory (KPNO) (Hoopes & Walterbos 2000).

4.3 Temperature distribution of dust

The intensity $I_\nu$ towards a uniform dust layer of optical thickness $\tau_\nu$ and temperature $T$ is

$$I_\nu = B_\nu(T) \left(1 - e^{-\tau_\nu}\right), \tag{4.1}$$

so that an observer receives from a solid angle $\Omega$ the flux

$$F_\nu = B_\nu(T) \left(1 - e^{-\tau_\nu}\right) \Omega. \tag{4.2}$$

The flux ratio at two frequencies, marked by the subscripts 1 and 2, becomes

$$\frac{F_1}{F_2} = \frac{B_1(T)}{B_2(T)} \frac{[1 - e^{-\tau_1}]}{[1 - e^{-\tau_2}]} \frac{\Omega_1}{\Omega_2}. \tag{4.3}$$

It is customary to obtain the dust temperature from (4.3) under the following conditions:
- The emission is optically thin, which is usually true in the FIR.
- The observational frequencies do not lie in the Rayleigh-Jeans limit of the Planck function.
- The dust temperature in the source is uniform.
- The ratio of the dust absorption coefficients, $\kappa_1/\kappa_2$, over the frequency interval from $\nu_1$ to $\nu_2$, or equivalently the exponent $\beta$ in $\kappa_\nu \sim \nu^\beta$ (Sect. 1.4) is known.

Then Eq. (4.3) simplifies to

$$\frac{F_1}{F_2} = \frac{\nu_1^\beta}{\nu_2^\beta} \frac{B_1(T)}{B_2(T)}. \tag{4.4}$$

We use the Spitzer FIR maps at 70\,µm and 160\,µm and obtain an average dust temperature attributed to each pixel. The power law index of the absorption efficiency at the FIR wavelengths, $\beta$, is set to 2, which should be appropriate for interstellar grains at $\lambda > 30$\,µm (Krügel 2003; Andriesse 1974; Draine & Lee 1984). The MIPS FIR maps

\textsuperscript{1}The 100-m telescope at Effelsberg is operated by the Max-Planck-Institut für Radioastronomie (MPIfR) on behalf of the Max–Planck–Gesellschaft.

\textsuperscript{2}The VLA is a facility of the National Radio Astronomy Observatory. The NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.
Figure 4.1: *Left:* dust temperature map of M33 obtained from $I_{70\mu m}/I_{160\mu m}$ ratio (only pixels with intensity above $3\sigma$ level were used). The angular resolution of 40" is shown in the lower left-hand corner of the map. The bar at the top gives the dust temperature in Kelvin. *Right:* Histogram of the dust temperature map. It shows the population of pixels as a function of the temperature intervals. The number of bins used for this plot is 80.

at 70 and 160 $\mu$m have been smoothed to an angular resolution of 40" and normalized to the same grid and center position. The resulting dust temperature distribution is shown in Fig. 4.1, indicating variations between 19 and 28 K. Fig. 4.1 displays the relative frequency of occurrence of the temperature intervals in $10'' \times 10''$ pixels. The maximum is attained at 21.5 K, close to the mean value of 21.6 K. Warmer dust with $T > 25$ K dominates in star-forming regions and in the center of the galaxy. The highest temperatures are found in the HII complexes NGC 604, NGC 592, and IC 133.

### 4.4 Optical depth at 160$\mu$m

Having determined $T$, we obtain the optical depth from the equation

$$\tau_{160\mu m} = I_{160\mu m}/B_{160\mu m}(T),$$

(4.5)

where $I_{160\mu m}$ is the intensity. The distribution of $\tau_{160\mu m}$ over the disk in M33 is plotted in Fig. 4.2. Because the temperature variations are very moderate, the optical depth $\tau_{160\mu m}$ usually follows the 160$\mu$m intensity map quite closely (see Tabatabaei et al. 2007a). Nevertheless, for a fixed intensity, a warm region (26 K) has a three times lower optical depth than a cold one (19 K).
4.5 Distribution of extinction

To convert $\tau_{160\mu m}$ into the dust optical depth at the wavelength of the H\(\alpha\) line, $\tau_{H\alpha}$, we have to multiply it by $\kappa_{H\alpha}/\kappa_{160\mu m}$, the ratio of the dust extinction coefficient per unit mass at the corresponding wavelengths. Using the extinction curve given by a standard dust model for the diffuse medium (see, e.g. Figure 12.8 of Krügel 2003), we estimate $\tau_{H\alpha} \approx 2200 \tau_{160\mu m}$. Therefore, after multiplication with 2200, Fig. 4.2 gives also the distribution of $\tau_{H\alpha}$ across the galaxy at a linear resolution of 360 pc.

$\tau_{H\alpha}$ is around one half in the extended central region and in the two main arms, IN and IS, and it is somewhat smaller in other arms (mostly between 0.2 and 0.4). In the center of the galaxy and in massive star forming regions, specifically in the southern arm IS and the HII complexes NGC604, NGC595, and B690, $\tau_{H\alpha}$ exceeds 0.7. The highest dust optical depth one finds in the center of the galaxy and in NGC604 where $\tau_{H\alpha} \approx 0.97$ and 0.88, respectively (at the linear resolution of 360 pc). Therefore, M33 is generally almost transparent for photons with $\lambda \approx 6560\text{Å}$ propagating towards us.

To estimate how much the detected H\(\alpha\) radiation has been attenuated, we note that H\(\alpha\) photons are usually emitted from sources within the galaxy. The optical depth $\tau_{H\alpha}$ therefore only gives an upper limit. Following Dickinson et al. (2003), we define $f_d$, the effective dust fraction in the line of sight actually absorbing the H\(\alpha\) so that the effective thickness is $\tau_{\text{eff}} = f_d \times \tau_{H\alpha}$ with $f_d < 1$ (note that $f_d = 1$ or the whole thickness is used for correcting the H\(\alpha\) emission from background sources); the attenuation factor for the H\(\alpha\) flux is then $e^{-\tau_{\text{eff}}}$.

At 360 pc resolution, one may assume that the H\(\alpha\) emitters, ionized gas in HII regions

Figure 4.2: Distribution of the dust optical depth at 160 $\mu$m wavelength in M33. The bar at the top shows $10^6 \times \tau_{160\mu m}$. The main northern (IN) and southern (IS) spiral arms are indicated. The angular resolution of 40" is shown in the lower left-hand corner of the map.
and diffuse gas, are uniformly mixed with the dust, which would imply \( f_d \approx 0.5 \). Dickinson et al. (2003) found \( f_d = 0.33 \) for the Milky Way (because the z-distribution of the H\( \alpha \) emission is smaller than that of the dust) and we adopt their value also for M33. But, as will be shown in Sect. 4.9.4, the determination of the thermal fraction of the radio emission is not very sensitive to the particular choice of \( f_d \).

Of course, it would be preferable not to use a uniform value \( f_d \) for the whole galaxy, but one that is adapted to the geometry (well mixed diffuse medium or shell-like in HII regions, Witt & Gordon 2000) and the dust column density. This needs to specify the location of the stellar sources and the absorbing dust and to solve the radiative transfer problem with massive numerical computations. Gordon et al. (2000) developed a flux ratio method to determine the dust attenuation which accounts for different geometries using a Monte Carlo radiative transfer model together with a stellar evolutionary synthesis model. These models are not used in this study, as they would require additional assumptions as well as more data to constrain them.

An interesting related question is how the extinction in M33 changes with galactic radius \( R \). To investigate this, we integrated Spitzer FIR flux densities at 70 and 160 \( \mu \)m in rings of 0.5 kpc width in the galactic plane (inclination of 56°, Regan & Vogel 1994). We first derived the mean dust temperature of each ring and then the mean dust optical depth \( \tau_{\text{d}} \). Fig. 4.3 shows \( \tau_{\text{d}} \) versus the galactocentric radius \( R \). For \( f_d = 0.33 \), the dependence can be described by \( \tau_{\text{H}_\alpha}(R) = (-0.009 \pm 0.002) R + (0.24 \pm 0.03) \). As \( f_d \) rises, the slope gets steeper. The case \( f_d = 1 \) (for the full layer), which is appropriate for pure background sources of M33, is shown for comparison. Generally, a decrease of the extinction with galactocentric radius is expected as it reflects the decrease in surface density towards the periphery. From a comparison of H\( \alpha \) data with radio flux densities at 6.3 and 21 cm, Israel & Kennicutt (1980) and Berkhuijsen (1982, 1983) found a rather steep radial gradient of the extinction: considering 8 bright HII regions, Berkhuijsen (1982) derived the relation \( \tau_{\text{H}_\alpha} = A_{\text{H}_\alpha}/1.086 = (-0.038 \pm 0.003) R + (1.45 \pm 0.05) \), with \( R \) in arcmin. Qualitatively similar results were reported by Petersen & Gammelgaard (1997),
Thermal and nonthermal radio emission from M33

Figure 4.4: Thermal (left) and nonthermal (right) maps at 3.6 cm. The grey-scale gives the flux density in mJy/beam. The angular resolution is 90" (shown in the lower left of the images) with a grid size of 10". The bright HII complexes NGC604 (RA = 1h 34m 32.9° & DEC = 30° 47’ 19.6") and NGC 595 (RA = 1h 33m 32.4° & DEC = 30° 41’ 50.0") are clearly visible in both maps, whereas IC133 (RA = 1h 33m 15.3° and DEC = 30° 53’ 19.7") appears stronger in the nonthermal map.

using Balmer and Paschen emission lines, and by Hippelein et al. (2003) based on a study of the Hα to the 60 μm ISOPHOT flux ratio in HII regions. The only discrepant result by Devereux et al. (1997) who, from their pixel-to-pixel comparison of Hα and 6 cm thermal radio maps, did not find any systematic decline in A_V. Hippelein et al. (2003) were able to explain by assuming that the radial gradient of the cold dust (170 μm ISOPHOT) is stronger in the HII regions than in the diffuse gas.

4.6 Distribution of free-free emission

From the observed Hα intensity, I, and the effective extinction, τ_eff, we derive the intrinsic Hα intensity, I_0, according to

\[ I = I_0 e^{-\tau_{\text{eff}}} \]

Note that using this equation is likely that we solve the radiative transfer equation for an artificial absorbing medium with an effective thickness τ_eff in front of an only emitting medium. In a more realistic approach, one should solve the radiative transfer equation...
Figure 4.5: Thermal (left) and nonthermal (right) maps at 20 cm. The grey-scale gives the flux density in mJy/beam. The angular resolution is 90'' (shown in the lower left of the images) with a grid size of 10''.

corrected total \( \log_{10} \frac{S}{\text{mJy/beam}} \) maps out to a radius of 7.5 kpc yields a ratio of corrected to observed total \( \log_{10} \frac{S}{\text{mJy/beam}} \).

considering a mixed distribution of emitters and absorbers. Usually, solving the radiative transfer equation needs massive numerical computations and additional free parameters. However, for a homogeneous distribution of emitters and an optically thin condition (\( \tau \leq 1 \)) a mixed medium of sources and absorbers is equivalent to consider an effective absorber medium of \( \tau_{\text{eff}} = \frac{1}{2} \tau \) in front of the emitting medium (see Appendix C).

Integration of the \( \log_{10} \frac{S}{\text{mJy/beam}} \) maps out to a radius of 7.5 kpc yields a ratio of corrected to observed total \( \log_{10} \frac{S}{\text{mJy/beam}} \) of 1.13 for \( f_d = 0.33 \) and 1.25 for \( f_d = 0.5 \). Thus only 13\% (25\%) of the total \( \log_{10} \frac{S}{\text{mJy/beam}} \) emission is obscured by dust. The small extinction within M33 was predicted by the wavelet study of 3.6 cm and \( \log_{10} \frac{S}{\text{mJy/beam}} \) emission (Tabatabaei et al. 2007a).

The emission measure (EM) follows from the \( \log_{10} \frac{S}{\text{mJy/beam}} \) intensity via the expression Valls-Gabaud (1998)

\[
I_{\text{H}\alpha} = 9.41 \times 10^{-8} T_{e4}^{1.1017} 10^{-\frac{0.029}{T_{e4}}} \cdot \text{EM},
\]

where the electron temperature, \( T_{e4} \), is in units of \( 10^4 \) K, EM in cm\(^{-6}\) pc, and it is assumed that the optical depth of HI resonance lines is large (usually denoted as case B). Taking into account the contribution from the fraction of He atoms, all of which are assumed to be singly ionized, Eq. (1.2) is written as

\[
\tau_{\nu} = 8.235 \times 10^{-2} a T_{e4}^{1.35} \nu_{\text{GHz}}^{-2.1} (1 + 0.08) \cdot \text{EM}.
\]
The brightness temperature of the radio continuum emission, $T_b$, then follows from

$$T_b = T_e \left(1 - e^{-\tau_\nu}\right). \quad (4.9)$$

At $\nu = 1.4$ GHz, the calculated $\tau_\nu$ is smaller than $4 \times 10^{-4}$ in M33 (at 360 pc linear resolution), hence the optically thin condition is valid: $T_b = T_e \tau_\nu$. Finally, the free-free brightness temperature in terms of the H\(\alpha\) intensity is given by

$$\frac{T_b}{I_{H\alpha}} = 3.484 \times 10^4 a_{\nu_{GHz}}^{-2.1} T_e^{0.667} \tau_\nu^{0.622} \left(1 + 0.08\right). \quad (4.10)$$

Whereas the electron temperature in the Milky Way is known to increase with galactocentric radius (Shaver et al. 1983) as a result of decreasing metallicity (Panagia 1979), M33 does not show significant variations in metallicity (e.g. Willner & Nelson-Patel 2002; Magrini et al. 2007). Crockett et al. (2006) derived the electron temperature from forbidden line ratios in 11 HII regions with galactocentric distances from 1 to 7 kpc. Their $T_e$ values range from 7300 K to 12800 K with a mean value of 10,000 K and no clear radial gradient. As there are no $T_e$ measurements for the diffuse ionized gas in M33, we adopt a fixed value of $T_e = 10,000$ K.

The conversion factors from brightness temperature (K) to the observed radio flux density (Jy/beam) are 2.6 and 74.5 at 3.6 and 20 cm, respectively. The final free-free maps are shown in Figs. 4.4 and 4.5. At both wavelengths, the strongest thermal emission emerges from HII regions, in particular, the HII complexes NGC604 and NGC595, but the southern arm IS (Chapter 2) and the center of the galaxy are also very bright. At both wavelengths, the thermal fraction of the diffuse emission is $<25\%$ in interarm regions. The average error in the thermal fraction obtained using the error propagation method is 7%.

Table 4.1: Estimated thermal flux density and thermal fraction at 3.6 cm ($f_d=0.33$ and $T_e=10,000$ K).

<table>
<thead>
<tr>
<th>Object</th>
<th>Observed flux density (mJy)</th>
<th>Thermal flux density (mJy)</th>
<th>Thermal fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC604</td>
<td>50.44 ± 0.13</td>
<td>38.55 ± 0.08</td>
<td>76.4 ± 0.3</td>
</tr>
<tr>
<td>NGC595</td>
<td>17.95 ± 0.18</td>
<td>12.13 ± 0.11</td>
<td>67.6 ± 0.9</td>
</tr>
<tr>
<td>IC133</td>
<td>9.08 ± 0.11</td>
<td>2.66 ± 0.04</td>
<td>29.3 ± 0.5</td>
</tr>
<tr>
<td>B690</td>
<td>4.51 ± 0.11</td>
<td>3.11 ± 0.10</td>
<td>68.9 ± 2.7</td>
</tr>
<tr>
<td>B61/62</td>
<td>3.72 ± 0.11</td>
<td>2.24 ± 0.07</td>
<td>60.2 ± 2.6</td>
</tr>
<tr>
<td>IC132</td>
<td>4.89 ± 0.05</td>
<td>3.25 ± 0.02</td>
<td>66.5 ± 0.8</td>
</tr>
<tr>
<td>IC131</td>
<td>4.59 ± 0.07</td>
<td>3.26 ± 0.05</td>
<td>71.0 ± 1.5</td>
</tr>
<tr>
<td>NGC588</td>
<td>4.64 ± 0.09</td>
<td>3.24 ± 0.06</td>
<td>69.8 ± 1.8</td>
</tr>
<tr>
<td>IC142</td>
<td>3.51 ± 0.08</td>
<td>2.73 ± 0.10</td>
<td>77.8 ± 3.3</td>
</tr>
<tr>
<td>B691</td>
<td>4.60 ± 0.13</td>
<td>2.35 ± 0.06</td>
<td>51.1 ± 2.0</td>
</tr>
<tr>
<td>NGC592</td>
<td>4.28 ± 0.08</td>
<td>2.76 ± 0.06</td>
<td>64.5 ± 1.9</td>
</tr>
</tbody>
</table>

M33 (mJy):

| R < 7.5 kpc | 761 ± 63 | 391 ± 74 | 51.4 ± 10.6 |

The brightness temperature of the radio continuum emission, $T_b$, then follows from

$$T_b = T_e \left(1 - e^{-\tau_\nu}\right) . \quad (4.9)$$

At $\nu = 1.4$ GHz, the calculated $\tau_\nu$ is smaller than $4 \times 10^{-4}$ in M33 (at 360 pc linear resolution), hence the optically thin condition is valid: $T_b = T_e \tau_\nu$. Finally, the free-free brightness temperature in terms of the H\(\alpha\) intensity is given by

$$\frac{T_b}{I_{H\alpha}} = 3.484 \times 10^4 a_{\nu_{GHz}}^{-2.1} T_e^{0.667} \tau_\nu^{0.622} \left(1 + 0.08\right) . \quad (4.10)$$

Whereas the electron temperature in the Milky Way is known to increase with galactocentric radius (Shaver et al. 1983) as a result of decreasing metallicity (Panagia 1979), M33 does not show significant variations in metallicity (e.g. Willner & Nelson-Patel 2002; Magrini et al. 2007). Crockett et al. (2006) derived the electron temperature from forbidden line ratios in 11 HII regions with galactocentric distances from 1 to 7 kpc. Their $T_e$ values range from 7300 K to 12800 K with a mean value of 10,000 K and no clear radial gradient. As there are no $T_e$ measurements for the diffuse ionized gas in M33, we adopt a fixed value of $T_e = 10,000$ K.

The conversion factors from brightness temperature (K) to the observed radio flux density (Jy/beam) are 2.6 and 74.5 at 3.6 and 20 cm, respectively. The final free-free maps are shown in Figs. 4.4 and 4.5. At both wavelengths, the strongest thermal emission emerges from HII regions, in particular, the HII complexes NGC604 and NGC595, but the southern arm IS (Chapter 2) and the center of the galaxy are also very bright. At both wavelengths, the thermal fraction of the diffuse emission is $<25\%$ in interarm regions. The average error in the thermal fraction obtained using the error propagation method is 7%.
Table 4.2: Estimated thermal flux density and thermal fraction at 20 cm ($f_d = 0.33$ and $T_e = 10,000$ K).

<table>
<thead>
<tr>
<th>Object</th>
<th>Observed thermal flux density (mJy)</th>
<th>Thermal flux density (mJy)</th>
<th>Thermal fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC604</td>
<td>62.75 ± 0.21</td>
<td>45.46 ± 0.09</td>
<td>72.4 ± 0.2</td>
</tr>
<tr>
<td>NGC595</td>
<td>20.50 ± 0.22</td>
<td>14.31 ± 0.14</td>
<td>69.8 ± 1.0</td>
</tr>
<tr>
<td>IC133</td>
<td>5.35 ± 0.07</td>
<td>3.11 ± 0.03</td>
<td>58.1 ± 0.9</td>
</tr>
<tr>
<td>B690</td>
<td>5.80 ± 0.12</td>
<td>3.69 ± 0.12</td>
<td>63.6 ± 2.5</td>
</tr>
<tr>
<td>B61/62</td>
<td>4.00 ± 0.21</td>
<td>2.69 ± 0.08</td>
<td>67.2 ± 4.1</td>
</tr>
<tr>
<td>IC132</td>
<td>5.52 ± 0.05</td>
<td>3.81 ± 0.02</td>
<td>69.0 ± 0.7</td>
</tr>
<tr>
<td>IC131</td>
<td>4.12 ± 0.07</td>
<td>3.84 ± 0.06</td>
<td>93.2 ± 2.1</td>
</tr>
<tr>
<td>NGC588</td>
<td>4.67 ± 0.17</td>
<td>3.74 ± 0.06</td>
<td>80.0 ± 3.2</td>
</tr>
<tr>
<td>IC142</td>
<td>4.14 ± 0.08</td>
<td>3.09 ± 0.13</td>
<td>74.6 ± 3.4</td>
</tr>
<tr>
<td>B691</td>
<td>7.40 ± 0.20</td>
<td>2.43 ± 0.04</td>
<td>32.8 ± 1.0</td>
</tr>
<tr>
<td>NGC592</td>
<td>5.43 ± 0.14</td>
<td>3.27 ± 0.08</td>
<td>60.2 ± 2.2</td>
</tr>
<tr>
<td>M33 (mJy):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R &lt; 7.5 kpc</td>
<td>2722 ± 60</td>
<td>478 ± 85</td>
<td>17.6 ± 3.1</td>
</tr>
</tbody>
</table>

Integrating the thermal maps in rings around the galaxy center out to a radius of 7.5 kpc, we obtain the total thermal flux densities and thermal fractions at 3.6 and 20 cm (see Tables 4.1 and 4.2). These Tables also give the thermal flux densities and thermal fractions at the position of the 11 brightest HII regions (the coordinates of these HII complexes are listed in Chapter 2).

### 4.7 Distribution of nonthermal emission

Subtracting the maps of the thermal emission from the observed maps at each wavelength, maps of the nonthermal emission are obtained (Figs. 4.4 and 4.5). The latter maps exhibit diffuse emission extending to large radii. They also show strong features in the spiral arms and central region of the galaxy. The strongest nonthermal emission emerges from the HII complexes NGC604 and NGC595 at both 3.6 and 20 cm. Typically, HII complexes host tens of young O/B stars, many of which end as supernovae whose remnants contribute to a mixed (thermal and nonthermal), flat spectrum of the total radio emission from these regions (as discovered in NGC 604 and NGC 595, Dodorico 1978; Gordon et al. 1993; Yang et al. 1996). Supernova remnants with central energy sources in the form of young pulsars (Crab-like remnants) also have flat nonthermal spectra. Note that using a lower electron temperature decreases the thermal fraction and increases the nonthermal contribution (see Eq. 4.10). For example, the thermal fraction decreases from $\sim 76\%$ to $57\%$ and from $\sim 68\%$ to $52\%$ in the position of NGC604 and NGC595, respectively, using $T_e = 7000$ K.

Another strong feature in the 20 cm nonthermal map belongs to the active star-forming region in the central southern arm IS. This confirms our previous conclusion about the
Figure 4.6: The wavelet spectra of the 3.6 and 20 cm thermal and nonthermal emission at 90" resolution. The data points correspond to the scales 0.36, 0.48, 0.64, 0.86, 1.14, 1.52, 2.03, 2.72, 3.63 kpc.

Figure 4.7: The same 20 cm nonthermal map as shown in Fig. 4.5 with supernova remnants (crosses) superimposed. The supernova remnants with a signal-to-noise ratio of larger than 0.7 were selected from the catalogue of Gordon et al. (1998). The circle shows an HII region with nonthermal spectral index (Gordon et al. 1999).

Spatial coupling of the nonthermal emission with the starforming regions (Chapter 2). There are also other point-like sources which are not resolved. Looking at the 3.6 cm map, the giant HII region IC133 (RA = 1 h 33 m 15.3 s and DEC = 30° 53' 19.7'') is also strong, but not at 20 cm. Hosting the two strongest optically thick HII regions (Johnson et al. 2001), IC133 has an inverted spectrum. The appearance of this source in the 3.6 cm nonthermal map is due to the assumption that the free-free emission is optically thin (equivalent to the thermal spectral index of 0.1 when $S_{\text{th}} \sim \nu^{-0.1}$). Furthermore, IC133 probably contains some nonthermal emission as Schulman & Bregman (1995) found it associated with a bright X-ray source located in a hole in the HI layer of the galaxy, indicating energetic stellar winds and supernovae from massive stars.
Tabatabaei et al. (2007a) discussed the wavelet spectrum of the total radio continuum maps. Here, we present the wavelet energy of the thermal and nonthermal emission at different scales. Fig. 4.6 shows that the wavelet spectrum of the nonthermal emission is smoother than that of the thermal emission at both wavelengths. Furthermore, the distribution of the nonthermal wavelet energy is smoother at 20 cm than at 3.6 cm. Scales smaller than the width of the spiral arms (≃ 400″ or 1.6 kpc) and larger than the size of the giant star-forming regions (≃ 100″ or 0.4 kpc) at 20 cm are not as prominent as those at 3.6 cm, where the synchrotron photons have higher energies. In fact the synchrotron emission distribution reflects the combined distribution of the interstellar magnetic field and the cosmic ray electrons. Hence, assuming that the distribution of the interstellar magnetic field is the same at both wavelengths, one can conclude: the higher the energy of CRs, the more dominant the localized structures (which can be linked to the cosmic ray ‘sources’ e.g. supernova remnants). This is expected as energy losses of CR electrons increase with electron energy and field strength. Studying propagation effects with self-consistent Galactic wind simulations, Breitschwerdt et al. (2002) predicted a similar energy-dependence for the CR nucleon distribution in our Galaxy. They expect that the high energy (TeV) \( \gamma \)-rays from CR sources dominate the diffuse \( \gamma \)-ray emission, while the Galactic \( \gamma \)-ray observations in the GeV range (with EGRET and COS-B) have shown a roughly uniform distribution of the \( \gamma \)-ray emissivity in the Galactic plane.

The dominant scales of the wavelet spectra of the thermal (at 3.6 and 20 cm) and the 3.6 cm nonthermal emission are the same, indicating that the distribution of the cosmic ray sources is similar to that of the thermal sources. At scales larger than \( a = 214'' \) (0.86 kpc), the 3.6 cm nonthermal spectrum decreases twice as fast as the 20 cm nonthermal spectrum. The smaller energy losses of the CR electrons with lower energies (at 20 cm) than of those with higher energies (at 3.6 cm) may cause a smoother distribution of the emission at all scales. This indicates that besides the CR sources embedded in the star-forming regions, there is another component of the synchrotron emission in the form of a diffuse disk or a galactic halo that is better visible at 20 cm than 3.6 cm. This could be verified by multiwavelength observations of edge-on galaxies at resolutions higher than those of the existing data.

Fig. 4.7 shows the the supernova remnants from Gordon et al. (1998) superimposed on the nonthermal 20 cm map. There is general coincidence between nonthermal features and supernova remnants, the powerful sources of the relativistic electrons. Gordon et al. (1999) diagnosed 17 supernova remnants embedded in HII regions. They also found some 30 HII regions with nonthermal radio components of which it was not clear whether they belong to these regions or were external radio sources. The circle in Fig. 4.7 shows the position of the strongest (\( S_{20} = 7.0 \pm 0.2 \) mJy, \( \alpha = 0.2 \)) HII region with nonthermal emission. As this HII region is not resolved in our thermal maps with 90″ resolution, it is not listed amongst the bright HII regions in Tables 4.1 and 4.2.

### 4.8 Nonthermal spectral index

From the nonthermal radio fluxes at 3.6 and 20 cm, we obtained the spectral index of the nonthermal emission which was only computed for pixels with flux densities of at least three times the rms noise \( \sigma \) at both frequencies. Fig. 4.8 shows that the nonthermal
Figure 4.8: Nonthermal spectral index ($\alpha_n$) map obtained from the nonthermal radio fluxes at 3.6 and 20 cm. The spiral arms are indicated by contours of the total radio emission at 3.6 cm superimposed. Contour levels are 1.5, 4.5, and 12 mJy/beam. The angular resolution is 90'' with a grid size of 10''.
spectral index, $\alpha_n$, has a clumpy distribution. Note that the fainter regions have steeper spectra. The most probable value of $\alpha_n$ distributed across the galaxy is 0.95 (Fig. 4.9). This is in perfect agreement with the mean nonthermal spectral index derived by Klein (1988) for a sample of galaxies. In the star-forming regions, the nonthermal spectrum is relatively flat with an average value of $\alpha_n$ of 0.6±0.1, the typical spectral index of supernova remnants, but $\alpha_n$ increases to 1.2±0.2 in the interarm regions and outer parts of the galaxy. This indicates energy losses of the relativistic electrons while they diffuse away from their origin in star-forming regions towards the interarm regions and the outer parts of the galaxy. For the first time, a nonthermal spectral index map can be used to achieve more realistic models for the propagation of CR electrons.

Integration of the nonthermal intensity in rings of 0.5 kpc in the galactic plane yields the mean nonthermal spectral index in each ring. The radial variation of the ring mean spectral index is shown in Fig. 4.10, where the ring mean spectral index of the total radio continuum emission is also plotted for comparison. Up to R $\simeq$ 4 kpc, there is no increas-
Thermal and nonthermal radio emission from M33

ing trend for the nonthermal spectral index with radius as for the total spectral index. Here the ring mean nonthermal spectral index varies between 0.65 and 0.9, indicating that CRs are injected by sources related to massive stars, and under leakage and synchrotron losses (Biermann 1995). Towards the outer parts of the galaxy the nonthermal and total spectral indices converge, confirming that the total radio continuum emission is mostly nonthermal at $R > 4.5$ kpc. This region corresponds to the synchrotron and inverse Compton loss dominated regime as $\alpha_n \simeq 1$ on the average (Biermann 1995). Note that changing the electron temperature from 10,000 K to 7000 K changes $\alpha_n$ from $\simeq 0.18$ to 0.31 and from $\simeq 0.01$ to 0.03 for NGC604 and NGC595, respectively, and hence does not make their flat nonthermal spectra much steeper. This may indicate a strong fee-free energy-loss in these HII complexes.

It seems that the nonthermal emission have a steeper spectrum from the southern than the northern half of the galaxy, indicating a more important role of synchrotron and leakage losses in the southern half.

4.9 Discussion

4.9.1 Comparison with the standard method

In this section, we first obtain the distribution of the thermal and nonthermal emission assuming that the nonthermal spectral index is constant across the galaxy (standard method). Then we compare the results from the two methods.

Because the thermal emission is weak in the outer parts of the galaxy, one may consider the total spectral index from these parts as the pure nonthermal spectral index$^3$, $\alpha_n$ (e.g. Berkhuijsen et al. 2003). The total spectral index map of M33 gives $\alpha_n = 1.0 \pm 0.1$ (see Fig. 2.9). For a total spectral index, $\alpha$, obtained from the observed flux densities at frequencies $\nu_1$ and $\nu_2$ and the constant value of $\alpha_n$, the thermal fraction at frequency $\nu_1$ is given by

$$F^{\nu_1}_{th} = \left[ \left( \frac{\nu_2}{\nu_1} \right)^{-\alpha} - \left( \frac{\nu_2}{\nu_1} \right)^{-\alpha_n} \right] / \left[ \left( \frac{\nu_2}{\nu_1} \right)^{-0.1} - \left( \frac{\nu_2}{\nu_1} \right)^{-\alpha_n} \right],$$

(Klein et al. 1984). Then the thermal flux density at frequency $\nu_1$, $S^{\nu_1}_{th}$, is obtained from

$$S^{\nu_1}_{th} = S^{\nu_1} \times F^{\nu_1}_{th},$$

(4.12)

and the nonthermal flux density at frequency $\nu_1$, $S^{\nu_1}_n$ is

$$S^{\nu_1}_n = S^{\nu_1} - S^{\nu_1}_{th}.$$  

(4.13)

Using the data at 3.6 and 20 cm in the above formulae, the corresponding thermal and nonthermal maps are derived; those at 20 cm are shown in Fig. 4.11. The main difference between the standard and our new method (Fig. 4.5) concerns the distribution of the nonthermal emission, while the thermal maps show almost the same structures. The nonthermal emission from the standard method is weaker than that from the new method.

$^3$This is confirmed by the new method, as mentioned in Sect. 4.8.
and hardly shows emission from star-forming regions in the arms. Often it is even weaker in the arms than in between the arms and in the outer parts of the galaxy.

In contrast to what is assumed in the standard method, large variations of the nonthermal spectral index are found across M33 by the new method (Fig. 4.8). We interpret this as clear evidence that CR electrons suffer energy losses diffusing away from their places of origin in the arms towards interarm and outer regions.

Table 4.3 lists the thermal fractions of the 11 bright HII regions and of M33 (from the integrated flux density maps up to R = 7.5 kpc) at 3.6 cm obtained from both methods. The thermal fractions of all the sources are larger when obtained from the standard method than from the new method. Some even exceed 100%, causing very weak or negative nonthermal fluxes. The thermal fraction of M33 from the standard method is $23\% \pm 14\%$ higher than that from the new method. In Chapter 2, we used the standard method with $\alpha_n = 1.0 \pm 0.1$ to estimate the thermal fraction from the integrated spectrum, based on data at 35.6, 21.1, 17.4, 11.1, 6.3, 6.2, 3.6, and 2.8 cm, as $0.49 \pm 0.15$ which agrees with the value $0.51 \pm 0.04$ obtained from the new method. This indicates that the assumption of a constant nonthermal spectral index is reasonable to estimate mean values for global studies, when the integrated spectrum is used.
4.9.2 Radial scale lengths

Fig. 4.12 shows the exponential distributions of the thermal and nonthermal intensities at 3.6 and 20 cm with galactocentric radius. The radial profiles of the nonthermal emission are smoother and flatter than those of the thermal emission at both wavelengths. The fluctuations in the thermal profiles at $2 < R < 4$ kpc cause similar fluctuations observed in the profile of the total emission (presented in Tabatabaei et al. 2007c).

The same profiles obtained from the standard method are shown in Fig. 4.13 for comparison. The nonthermal radial profiles are slightly smoother (especially at 3.6 cm) than those from the new method, caused by the assumption of a constant nonthermal spectral index. Although the thermal radial profiles exhibit the same variations as those in Fig. 4.12, the over-estimation of the thermal emission from the standard method is obvious.

The exponential scale length, $l$, is obtained by fitting an exponential function of the form $I(R) = I_0 \exp(-R/l)$, where $I_0$ is the intensity at $R=0$. Table 4.4 shows the
Table 4.3: Thermal fractions at 3.6 cm obtained from the new and standard methods. It is shown that the thermal fraction obtained from the standard method is over-estimated especially for the HII complexes.

<table>
<thead>
<tr>
<th>Object</th>
<th>$\alpha_{(3.6,20)}$</th>
<th>$F_{th}$ (new method)</th>
<th>$F_{th}$ (standard method)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC604</td>
<td>0.12 ± 0.01</td>
<td>76.4 ± 0.3</td>
<td>99.2 ± 0.4</td>
</tr>
<tr>
<td>NGC595</td>
<td>0.07 ± 0.03</td>
<td>67.6 ± 1.3</td>
<td>101.6 ± 1.4</td>
</tr>
<tr>
<td>IC133</td>
<td>-0.30 ± 0.03</td>
<td>29.3 ± 0.8</td>
<td>106.5 ± 1.6</td>
</tr>
<tr>
<td>B690</td>
<td>0.14 ± 0.05</td>
<td>68.9 ± 3.9</td>
<td>99.1 ± 3.6</td>
</tr>
<tr>
<td>B61/62</td>
<td>0.04 ± 0.08</td>
<td>60.2 ± 3.7</td>
<td>104.3 ± 4.2</td>
</tr>
<tr>
<td>IC132</td>
<td>0.07 ± 0.02</td>
<td>66.5 ± 1.0</td>
<td>101.6 ± 1.5</td>
</tr>
<tr>
<td>IC131</td>
<td>-0.06 ± 0.03</td>
<td>71.0 ± 2.2</td>
<td>107.2 ± 2.4</td>
</tr>
<tr>
<td>NGC588</td>
<td>0.00 ± 0.05</td>
<td>69.8 ± 2.6</td>
<td>103.1 ± 2.9</td>
</tr>
<tr>
<td>IC142</td>
<td>0.09 ± 0.04</td>
<td>77.8 ± 4.6</td>
<td>96.9 ± 3.6</td>
</tr>
<tr>
<td>B691</td>
<td>0.27 ± 0.05</td>
<td>51.1 ± 2.6</td>
<td>93.0 ± 3.4</td>
</tr>
<tr>
<td>NGC592</td>
<td>0.13 ± 0.04</td>
<td>64.5 ± 2.6</td>
<td>97.9 ± 2.8</td>
</tr>
<tr>
<td>M33 :</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R&lt; 7.5 kpc</td>
<td>0.72 ± 0.04</td>
<td>51.4 ± 10.6</td>
<td>63.2 ± 13.4</td>
</tr>
</tbody>
</table>

exponential scale lengths of the thermal emission, $l_{th}$, and nonthermal emission, $l_n$, from both methods. Generally, the scale lengths of the nonthermal emission are larger than those of the thermal emission (by a factor of $\simeq 2$). In Sect. 4.7, we show that the CR sources follow the distribution of the thermal sources, i.e. star-forming regions. Hence, the radial distribution of the CR sources decreases faster than that of the synchrotron emission. This is a direct observational result indicating diffusion of the cosmic rays from their places of origin to larger distances.

Using the standard method, Buczilowski (1988) determined the scale length of the 6.3 cm thermal and nonthermal emission as $1.8 \pm 0.2$ kpc and $4.2 \pm 0.3$ kpc, respectively. These scale lengths are smaller than those obtained here (even smaller than those obtained from the standard method), although the ratio of the nonthermal to thermal scale lengths is the same ($\simeq 2$). Due to the low signal-to-noise ratio of the old 6.3 cm Effelsberg receiver used by Buczilowski (1988) much of the diffuse emission in the outer parts of the galaxy had been missed, leading to steeper radial profiles and smaller scale lengths. For the same reason also the scale lengths derived by Berkhuijsen & Klein (1985) are too small. They obtained the distribution of the thermal emission at 6.2 cm from a catalogue of HII regions in H$\alpha$ (Boulesteix et al. 1974) where the diffuse emission was not completely included.

In case of equipartition between the magnetic field and CRs, the scale length of the CR electrons is given by $l_{cr} = l_n(3 + \alpha_n)/2$ and that of the magnetic field by $l_B = 2l_{cr}$ (e.g. Klein et al. 1982). Taking $\alpha_n \simeq 1$, we obtain $l_{cr} \simeq 12$ kpc and $l_B \simeq 24$ kpc.

For NGC6946, Walsh et al. (2002) found a nonthermal scale length of $l_n \sim 4$ kpc which gives a smaller CR scale length of $l_{cr} \sim 8$ kpc. Although NGC6946 is a Scd-type galaxy like M33, it is a starburst system and it hosts stronger star formation in its central region than M33. This may cause a steeper radial profile of the total intensity and consequently a smaller nonthermal (and cosmic ray) scale length than in M33.
Table 4.4: Exponential scale lengths of the thermal ($l_{th}$) and nonthermal ($l_n$) components of the radio continuum emission from M33 at 3.6 and 20 cm. Results from both methods (new and standard) are listed.

<table>
<thead>
<tr>
<th>$\lambda$ (cm)</th>
<th>$l_{th}$ (kpc)</th>
<th>$l_n$ (kpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>new</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 cm</td>
<td>2.4 ± 0.2</td>
<td>5.8 ± 0.5</td>
</tr>
<tr>
<td>3.6 cm</td>
<td>2.6 ± 0.2</td>
<td>6.1 ± 0.7</td>
</tr>
<tr>
<td>standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 cm</td>
<td>3.5 ± 0.5</td>
<td>6.2 ± 0.7</td>
</tr>
<tr>
<td>3.6 cm</td>
<td>3.7 ± 0.5</td>
<td>8.9 ± 0.9</td>
</tr>
</tbody>
</table>

Table 4.5: North-South ratios of the integrated flux densities of the thermal, nonthermal, and total radio emission. Results from both methods (new and standard) are listed.

<table>
<thead>
<tr>
<th>$\lambda$ (cm)</th>
<th>$S^N_{th}/S^S_{th}$</th>
<th>$S^N_n/S^S_n$</th>
<th>$S^N_T/S^S_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>new</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.6 cm</td>
<td>0.89 ± 0.05</td>
<td>1.15 ± 0.08</td>
<td>1.10 ± 0.08</td>
</tr>
<tr>
<td>20 cm</td>
<td>0.86 ± 0.05</td>
<td>0.75 ± 0.07</td>
<td>0.82 ± 0.07</td>
</tr>
<tr>
<td>standard</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.6 cm</td>
<td>1.20 ± 0.07</td>
<td>0.67 ± 0.07</td>
<td>1.10 ± 0.08</td>
</tr>
<tr>
<td>20 cm</td>
<td>1.14 ± 0.06</td>
<td>0.77 ± 0.08</td>
<td>0.82 ± 0.07</td>
</tr>
</tbody>
</table>

4.9.3 North–south asymmetry

From Figs. 4.4 and 4.5 it seems that the thermal emission is stronger in the southern than in the northern half of M33. To investigate this north-south (N-S) asymmetry, we obtain the integrated flux density of the thermal, nonthermal, and total emission in each half separately. Table 4.5 shows the results from both the new and the standard method. The thermal emission from the new method is slightly stronger in the southern than in the northern half of the galaxy at both wavelengths. This may be the reason for the higher Faraday depolarization found in the southern half than in the northern half (Tabatabaei et al. 2007c). In Chapter 5, we will discuss whether the asymmetry in the Faraday depolarization can be caused by this N-S asymmetry in the thermal emission distribution. Note that, from the standard method, the thermal emission in the southern half is weaker.

The nonthermal emission at 20 cm from the new method in the southern half is also stronger than in the northern half (in contrast to the 3.6 cm nonthermal emission). This is expected as the stronger supernova remnants are concentrated in the southern half especially in the arm IS, which produce stronger nonthermal emission at longer wavelengths. The existence of the strong optically thick HII regions (e.g. IC133) in the northern half of the galaxy also causes the different N-S ratios of the nonthermal emission at 3.6 cm.
4.9.4 Uncertainties

How do the assumptions of the new method of separating thermal and nonthermal emission influence the results? We take the thermal fraction (e.g. at 3.6 cm) as the final result and define $U$ as the uncertainty in $F_{th}$ when one of the assumptions changes,

$$U \equiv \frac{|F_{th} - F'_{th}|}{F_{th}}.$$  (4.14)

$F_{th}$ and $F'_{th}$ are the thermal fractions before and after changing an assumption, respectively.

One of the assumptions is the choice of effective extinction factor $f_d = 0.33$ (non-uniform ionization). For a homogeneous distribution of dust and ionized gas, $f_d = 0.5$, the average uncertainty in the thermal fraction at 3.6 cm is only $U = 2\%$ with a standard deviation of 1\%.

Changing $T_e$ from the adopted 10,000 K to 8000 K, the most probable uncertainty across the galaxy is $U = 17\%$ with a standard deviation of 3\%. Fig. 4.14 shows that the thermal fraction decreases with decreasing electron temperature. Larger differences in the thermal fraction are found for regions with higher thermal emission like HII regions, and the influence of changing $T_e$ is relatively small in diffuse regions with small $F_{th}$. Thus, we find that the uncertainty resulting from the new method is mainly determined by uncertainty of the electron temperature.

Another question is which method, the new method with its electron temperature assumption or the standard method with its constant nonthermal spectral index assumption, faces larger uncertainty in the thermal fraction. For this comparison, we first obtain the nonthermal spectral indices for different electron temperatures. For $T_e = 10,000$ K the most probable nonthermal spectral index is 0.9, while it is 0.8 for $T_e = 8000$ K. Then, from the standard method, we calculate the thermal fractions assuming $\alpha_n = 0.9$ and 0.8, respectively, which leads to an uncertainty of $U = 40\%$, much larger than that determined from our method (17\%). We conclude that the thermal fraction is more sensitive to vari-
Table 4.6: Average thermal fraction of M33 at 3.6 cm for different assumptions. The uncertainty $U$ of each assumption is calculated with respect to the case $T_e = 10,000$ K and $f_d = 0.33$.

| $T_e$ (K) & $f_d$ & $F_{th}$ (%) & $U$ (%) |
|---------|---------|-----------|--------|
| 10,000 & 0.33 & 51        & (...)  |
| 10,000 & 0.50 & 54        & 5      |
| 8000  & 0.33 & 41        & 20     |
| 8000  & 0.50 & 43        & 16     |

ations of the nonthermal spectral index in the standard method than to variations of the electron temperature in the new method.

Table 4.6 shows the thermal fractions obtained from the thermal and total flux densities of M33 (integrated for $R < 7.5$ kpc) for different combinations of the assumptions of $T_e$ and $f_d$.

### 4.9.5 Thermal/nonthermal radio–IR correlation

The correlation between the IR and total radio continuum emission was presented at different scales of emitting structures in Chapter 2. Assuming that the radio emission is mostly thermal at 3.6 cm and mostly nonthermal at 20 cm, we concluded that the warm dust–thermal radio correlation is stronger than the cold dust–nonthermal radio correlation. However, a more precise conclusion requires comparison with the thermal and nonthermal radio emission, separately.

We obtained the wavelet cross-correlations between the MIPS IR maps and the 3.6 cm thermal and nonthermal maps separated from the new method. The results not only confirm the stronger warm dust–thermal radio than the cold dust–nonthermal radio correlation, but also show a stronger warm dust–nonthermal radio than the cold dust–nonthermal radio correlation at some scales (Fig. 4.15). It is also found that the cold dust has a better correlation with the thermal than the nonthermal emission. This is in contradiction with what Hoernes et al. (1998) found in M31. This could be due to a) the spatial correlation of the nonthermal emission with the thermal emission e.g. because of a stronger magnetic field or cosmic rays with higher density in the location of the star forming regions and b) the larger role of UV photons from O/B stars in heating the cold dust in M33 than in M31 at least up to the scales of 3.5 kpc, as discussed in Chapter 2.

Another interesting point is that the IR correlations with the ‘nonthermal’ emission is better at a medium scale of $\sim 200'' - 500''$ (or 0.8 kpc-2 kpc, including the size of the giant molecular clouds and star forming regions, spiral arms, and the central extended region of M33), whilst the IR correlation with the ‘thermal’ radio emission increases with scale, monotonically.
Figure 4.15: The cross–correlation between the thermal/nonthermal components of the 3.6 cm and 24 µm (top), 70 (middle), and 160 µm (bottom) images at 90'' resolution.
4.9.6 Spinning dust emission

It was supposed that the radio continuum emission consists of the thermal and nonthermal components. On the other hand, it is claimed that spinning dust also emits radio continuum radiation with a peak at around 20 GHz (e.g. Watson et al. 2005) and with a possible contamination at 3.6 cm (8.35 GHz). Then a question is how much of the total emission from M33 at 3.6 cm is provided by spinning dust. We investigated the contribution of the spinning dust emission from M33 by using the nonthermal spectral index obtained from the integrated nonthermal flux densities at 20 and 6.2 cm, $\alpha_n(\simeq 0.8)$. Assuming that this nonthermal spectral index is constant between 20 and 3.6 cm, the integrated nonthermal flux density at 3.6 cm, $S_n(8.35)$, is obtained by:

$$S_n(8.35) = S_n(1.42) \left( \frac{8.35}{1.42} \right)^{-\alpha_n}. \quad (4.15)$$

The total flux density of the spinning dust emission, $S_{\text{dust}}$, can be obtained by subtracting $S_n(8.35)$ from the integrated nonthermal flux density obtained from the new method, $S'_n(8.35)$:

$$S_{\text{dust}} = S'_n(8.35) - S_n(8.35) \quad (4.16)$$

Substituting the corresponding values in (6.1) and (6.2) and taking the errors into account, we derive $S_{\text{dust}} = (370 \pm 60) - (463 \pm 73)$ mJy, indicating an unimportant (if any) contribution of the spinning dust in the total radio continuum emission from M33 at 3.6 cm. In case of a steeper nonthermal spectrum between 6.2 and 3.6 cm, e.g. taking $\alpha_n = 1$, we receive $S_{\text{dust}} = (370 \pm 60) - (296 \pm 73)$ mJy, which is also negligible within the errors.

4.9.7 Comparison with the 49 cm data

The HII complexes NGC604 and NGC595 are strong features appearing in our nonthermal maps. This seems to contradict to what is known from HII regions as ‘thermal nebulae’. Although the fact that these sources are not single HII regions but a collection of about 200 O/B stars in different evolutionary phases answers the question, it would be interesting to check these sources at longer wavelengths, where the thermal emission is much weaker than the nonthermal emission. A map of M33 at 612 MHz (49 cm) observed with the Westerbork Synthesis Radio Telescope (WSRT) interferometer shows that not only NGC604 and NGC595 are strongest sources but also other similarities with our nonthermal maps can be confirmed (Fig. 4.16). Note that we could not use this data in our separation because of its lack of diffuse emission (due to the missing spacings problem of interferometry).

4.10 Summary and conclusions

We have developed a new method to separate the thermal and nonthermal radio emission from a galaxy. We used the highly resolved and sensitive Spitzer 70 and 160 $\mu$m data of M33 to correct the H$\alpha$ map of Hoopes & Walterbos (2000) for extinction. From this map, we calculated the thermal (free-free) emission at 3.6 and 20 cm and obtained maps
Figure 4.16: The WSRT 49 cm image of M33 at 90” resolution.

of the nonthermal emission as well as a map of the nonthermal spectral index in M33. The distribution of the nonthermal spectral index greatly helps to understand the origin and propagation of cosmic ray electrons in a galaxy. In brief, the results and conclusions are as follows:

- The distribution of the dust extinction is similar to that of the 160 μm emission. The mean extinction in rings in the galactic plane exhibits a shallow radial gradient.

- With a nonthermal fraction of about 30%–60% at 3.6 cm, the spiral arms and star-forming regions have a considerable contribution to the nonthermal emission. This contribution is negligible in the nonthermal maps obtained from the standard separation method. The radial profiles of the surface brightnesses and the wavelet spectra show that the distribution of the nonthermal emission from the standard method is smoother than that derived from the new method. This is caused by the assumption of a constant nonthermal spectral index in the standard method.

- The nonthermal emission from the new method is still more smoothly distributed than the thermal emission. The exponential scale lengths of the nonthermal emission are more than twice as large as those of the thermal emission.

- The standard method over-estimates the thermal fraction, especially at the position of giant HII regions. For galactocentric radius R < 7.5 kpc, the thermal fractions at 3.6 cm are 51 ± 11% and 63 ± 13% from the new and standard methods, respectively.
• For the first time, we derived a map of the nonthermal spectral index. In the star-forming regions, the nonthermal spectrum is relatively flat with an average value of $\alpha_n$ of $0.6 \pm 0.1$, the typical spectral index of supernova remnants, but $\alpha_n$ increases to $1.2 \pm 0.2$ in the interarm regions and outer parts of the galaxy. This shows that the relativistic electrons lose energy when diffusing from their origin in star-forming regions towards interarm regions and the outer parts of the galaxy. The mean spectral index of the nonthermal emission becomes equal to that of the total emission at $R \approx 4.5$ kpc. This indicates that the total radio emission is mostly nonthermal at $R > 4.5$ kpc in M33, where the spectral index is dominated by synchrotron and inverse Compton loss processes.

• The wavelet transform of the nonthermal maps revealed that the nonthermal emission is smoother at 20 cm than at 3.6 cm, indicating that high energy CR electrons experience more energy losses, and hence diffuse less than low energy CR electrons.

• Assuming equipartition between the magnetic field and CRs, the scale length of the CR electrons and of the magnetic field estimated are $l_{cr} \approx 12$ kpc and $l_B \approx 24$ kpc in this galaxy.

• Generally, the integrated results from the two methods match with each other within the errors, indicating that the assumption of a constant nonthermal spectral index is a proper approximation for ‘global’ studies.

• At scales smaller than 4 kpc, not only the warm dust but also the cold dust emission is better correlated with the thermal than with the nonthermal radio emission, indicating the important role of UV photons in heating the dust at these scales.
5 Magnetic fields in M33

5.1 Introduction

Magnetic fields in galaxies can be traced by radio polarization measurements. Synchrotron radio continuum emission in a uniform magnetic field is about 70% linearly polarized intrinsically. Turbulent magnetic fields, depolarization effects and telescope beam smearing reduce the observable degree of polarization. The linearly polarized intensity gives information about the magnetic field component in the plane of the sky, while Faraday rotation measurements enable us to determine the magnetic field component along the line of sight.

M33 with its large angular size and medium inclination of 56° allows determination of the magnetic field components both parallel and perpendicular to the line of sight equally well. Our high-resolution and -sensitivity polarization data at 3.6, 6.2, and 20 cm enable us to study rotation measure (RM), magnetic field structure and strength, and depolarization effects in detail.

Previous RM studies of M33 based on polarization observations at 11.1 and 21.1 cm (Beck 1979) suggested a bisymmetric large scale magnetic field structure in the disk of M33. Buczilowski & Beck (1991) confirmed the presence of this bisymmetric field using two further polarization maps at 6.3 and 17.4 cm. However, this result might be affected by a lack of polarization and RM in the southern half of M33, due to the low-sensitivity observations.

Tabatabaei et al. (2007c) found a north-south asymmetry in the polarization distribution that is wavelength-dependent, indicating a possible north-south asymmetry in the Faraday depolarization. Investigating this possibility, requires a knowledge about the distribution of RM and turbulent magnetic field in the galaxy.

We obtain the intrinsic RM map with a spatial resolution higher than before (3′ or 0.7 kpc) and probe its mean value in rings in the galactic plane in Sect. 5.2. We also determine the nonthermal degree of polarization using the new nonthermal maps (Sect. 5.3). The magnetic field structure and strengths are discussed in Sect. 5.4. We derive a map for the observed depolarization and discuss possible depolarization sources in Sect. 5.5.

5.2 Rotation measures

As the linearly polarized radio waves propagate in a magneto-ionic medium, their polarization vector is systematically rotated. The amount of this rotation depends on the wavelength of the radio emission, the strength of the magnetic field along the line of sight
Magnetic fields in M33

\( B_\parallel \), and the number of thermal electrons along the line of sight \( (n_e) \):

\[
\Delta \phi \text{ rad} = 0.81 \left( \frac{\lambda}{m} \right)^2 \int_0^{L/\text{pc}} \left( \frac{B_\parallel}{\mu G} \right) \left( \frac{n_e}{\text{cm}^{-3}} \right) \, \text{d} \left( \frac{l'}{\text{pc}} \right),
\]

(5.1)

with \( L \) the path length through the magneto-ionic medium. Hence, the measured polarization angle \( (\phi = \frac{1}{2} \tan^{-1} \frac{1}{k}) \) differs from the intrinsic polarization angle \( (\phi_i) \) as

\[
\phi - \phi_i = \Delta \phi \equiv \lambda^2 \text{RM}.
\]

(5.2)

Practically, RM can be obtained from measurements of the polarization angles at two wavelengths:

\[
\frac{\text{RM}}{\text{rad m}^{-2}} = \frac{(\phi_1/\text{rad}) - (\phi_2/\text{rad})}{(\Delta \lambda/\text{m})^2 - (\Delta \lambda/\text{m})^2}.
\]

(5.3)

In this definition, the unknown intrinsic polarization angle of the source (or sources along the line of sight) cancels. Positive RM indicates that \( B_\parallel \) points towards us.

Using the linearly polarization data of M33, we first obtained the distribution of RM between 3.6 and 20 cm (Fig. 5.1, left panel), showing smooth variations in the northern half of the galaxy. However, lots of RM variations and flips in the direction of \( B_\parallel \) exist in the southern half of the galaxy, which resist by adding \( \pm n.73 \text{ rad m}^{-2} \) ambiguity. As presented in Chapter 2, weak polarized emission in the southern half at 20 cm could be linked to these RM variations. Between 3.6 and 6.2 cm, RM varies smoother than that between 3.6 and 20 cm in the south of the galaxy (Fig. 5.1, right panel). Usually, only part of RM is caused in interstellar medium of external galaxies (RM_{i}), the rest is due to the Galactic foreground medium (RM_{fg}) and \( \text{RM} = \text{RM}_{i} + \text{RM}_{fg} \). The foreground rotation measure of M33 is mainly caused by the extended Galactic magnetic bubble region \( A \) (Simard-Normandin & Kronberg 1980). Assuming that the intrinsic contributions of the extragalactic sources 3C41, 3C42, and 3C48 themselves cancel out and the intergalactic contribution is negligible, Broten et al. (1988) and Tabara & Inoue (1980) found a rotation measure of \(-57 \pm 10 \text{ rad m}^{-2}\). For the polarized sources in the \( 2^\circ \times 2^\circ \) M33 field, Buczilowski & Beck (1991) found a foreground RM of \(-55 \pm 10 \text{ rad m}^{-2} \) (about the same value was obtained by Johnston-Hollitt et al. 2004). In the following we use this value as it is consistent with our measurements as well. Figure 5.2 shows RM_{i} between 3.6 and 6.2 cm which varies in a range including both positive and negative values. Comparing the RM_{i} map with the overlayed contours of PI\(^1\), an agreement between the ordered magnetic field in the plane of the sky and the regular magnetic field in the line of sight is indicated in the north and along the minor axis. This is better visible in the magnetic filament in the north-west of M33 (see Chapter. 2), where RM_{i} shows small variation within the PI contours. This indicates that the strong ordered magnetic field in this region is mainly regular. The RM_{i} map also indicates that the magnetic field is directed towards us on the western minor axis, but has an opposite direction on the eastern part. Furthermore, large RM values on the minor axis indicate that \( B_\parallel \) is strong in these regions. Sign variations of the RM_{i} are more frequent in the southern than the northern

\(^1\)Note that PI is related to \( B_\perp \) which is a combination of both anisotropic (compressed or sheared random field) and regular fields in the sky plane. RM_{i} is related to \( B_\parallel \) that is regular field along the line of sight.
Figure 5.1: \textit{Left}: observed rotation measure map of M33 between 3.6 and 20 cm with contours of 3.6 cm polarized intensity. Contour levels are 0.1, 0.2, 0.4, 0.6, 0.8 mJy/beam. \textit{Right}: observed rotation measure map of M33 between 3.6 and 6.2 cm with contours of 6.2 cm polarized intensity. Contour levels are 0.3, 0.4, 0.8, 1.2, 1.6 mJy/beam.

half of the galaxy, where there is no correlation with PI. This indicates that the regular magnetic field is less confined to the disk in the south than in the north of M33.

Among the three brightest HII complexes at 3.6 cm (NGC604, NGC595, and IC133, see Chapter 2), the rotation measure is highest at the position of NGC595, RA = 1\textdegree\ 33\textarcmin\ 32.4\textdegree\ & DEC = 30\textdegree\ 41\textarcmin\ 50.0\textarcsec. This means that the electron density $n_e$, and/or the magnetic field component in the line of sight $B_\parallel$ is larger at the position of NGC595 than in the two other HII complexes.

Figure 5.3 shows the azimuthal variations of RM$_i$ in rings. Starting from a distance of 1 kpc from the center, the rotation measure was averaged in the galactic plane in 6 rings of 1 kpc radial width over sectors of 10\degree width. The azimuthal angles shown in this figure were corrected for inclination of the galaxy, $\theta_0 = \arctan(\tan \theta / \cos i)$, with $\theta$ the azimuthal angle on the sky and $i$ the inclination of the galactic plane against a face-on view. $\theta_0 = 0\degree$ and 180\degree correspond to the northern and southern major axis, 90\degree and 270\degree to the eastern and western minor axis. As shown, the RM$_i$ variations in this galaxy is very disordered and do not follow a periodic pattern (Sect. 5.4) in general. The only periodicity is found in the ring 2-3 kpc in which RM$_i$ is asymmetric with its minimum and maximum on the eastern and western minor axis.
Figure 5.2: Rotation measure map of M33 between 3.6 and 6.2 cm after correction for the foreground RM. Overlayed are contours of 6.2 cm polarized intensity. Contour levels are 0.3, 0.4, 0.8, 1.2, 1.6, 3.2, 6.4 mJy/beam. The distribution of the estimated error in RM is shown in the right panel.

Figure 5.3: Azimuthal behavior of RM in M33 in different rings of 1 kpc width around the center of the galaxy.
Table 5.1: Integrated nonthermal flux densities and average nonthermal degree of polarization at 180°.

<table>
<thead>
<tr>
<th>$\lambda$ (cm)</th>
<th>$S_{nth}$ (mJy)</th>
<th>$S_{PI}$ (mJy)</th>
<th>$P_{nth}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6</td>
<td>370 ± 60</td>
<td>38 ± 4</td>
<td>10.3 ± 2.0</td>
</tr>
<tr>
<td>6.2</td>
<td>696 ± 110</td>
<td>79 ± 5</td>
<td>11.3 ± 1.9</td>
</tr>
<tr>
<td>20</td>
<td>1740 ± 65</td>
<td>115 ± 10</td>
<td>6.6 ± 0.6</td>
</tr>
</tbody>
</table>

Figure 5.4: Nonthermal degree of polarization at 3.6 cm. Overlayed are contours of the linearly polarized intensity at 3.6 cm with levels of 0.1 and 0.3 mJy/beam.

5.3 Nonthermal degree of polarization

To verify the polarization due to synchrotron emission, the so-called nonthermal degree of polarization $P_{nth} = PI/I_{nth}$ is usually studied, where PI is the linearly polarized emission and $I_{nth}$ is the flux density of the nonthermal emission. Using PI maps (Chapter 2) and the nonthermal maps (Chapter 4), we derived the maps of $P_{nth}$ at different wavelengths. Fig. 5.4 shows $P_{nth}$ at 3.6 cm. High nonthermal degrees of polarization ($P_{nth} > 30\%$) are found in the northern part of the magnetic filament (see chapter 2, corresponding to the second contour at DEC $> 30^\circ 54'$ in Fig. 5.4).

Integrating the polarized and nonthermal intensity maps in the galactic plane and for a galactocentric radius of R $\leq$ 7.5 kpc, the average nonthermal degree of polarization $\bar{P}_{nth} = S_{PI}/S_{nth}$ is calculated. Table 5.1 gives $\bar{P}_{nth}$ together with the integrated values of the nonthermal flux density and polarized intensity at different wavelengths. At the same angular resolution of 180°, $\bar{P}_{nth}$ is the same at 3.6 and 6.2 cm, confirming that Faraday depolarization effects are not significant at these wavelengths, generally. However, these effects are important at 20 cm providing a low $\bar{P}_{nth}$.
5.4 Magnetic field

Correcting the polarization angles for the rotation measure \( \phi_i = \phi - \lambda^2 \mathrm{RM}_i \), the intrinsic direction of the magnetic field component in the plane of the sky \( (B_\perp) \) was obtained. Fig. 5.5 shows the corrected \( B_\perp \)-vectors superimposed on an optical image of M33. The orientation of \( B_\perp \) shows a spiral magnetic field pattern with open arms with approximately the same pitch angle of the optical arms in the north and south, but even larger in the east and west of the galaxy.

The regular magnetic field \( B_u \) in the disk of spiral galaxies is generally assumed to be dynamo-generated. The dynamo single modes of axisymmetric-loopy structure (ASS) and bisymmetric-loopy structure (BSS) can be distinguished from the azimuthal RM variation (as shown for M51, M81, and IC342 Tosa & Fujimoto 1978; Krause et al. 1989b,a). This analysis assumes that the magnetic field resides in the disk (or in a plane parallel to the disk), \( n_e \) is constant, and the field vectors follow spirals with constant pitch angles. In the ASS model, the RM variation can be fitted by the periodic function:

\[
\mathrm{RM}(\theta_0) = A \cos (\theta_0 - \psi) + \mathrm{RM}_\text{fg},
\]

with \( \psi \) the pitch angle of the magnetic field vectors. Thus in the ASS model, the minimum and maximum of RM should be found near the northern and southern major axis.

In the BSS model,

\[
\mathrm{RM}(\theta_0) = A \cos (2\theta_0 - \psi - \mu) + A \cos (\mu - \psi) + \mathrm{RM}_\text{fg},
\]

with \( \mu \) the position angle of the magnetic spiral at a certain radius in the plane of the galaxy.

For M33, Beck (1979) and Buczilowski & Beck (1991) found that the BSS model can be best-fitted to the azimuthal RM variations. However, their RM information was only restricted to the northern half of this galaxy as they used low sensitivity polarization data. Such field structures can not be fitted to the RM variations obtained from our more complete and sensitive data (see Fig. 5.3). The least-squared fits failed to decrease the original standard deviation substantially. Besides to the RM variations in the south of M33 (Sect. 5.2), this may be other indication to a regular magnetic field that is not confined to the disk or a plane parallel to the disk (particularly in the southern half) and hence cannot be explained by only single modes of the dynamo action.

The strengths of the total magnetic field \( B_t \) and its regular component \( B_u \) can be found from the total synchrotron intensity and its degree of linear polarization \( P_{\text{nth}} \). Assuming equipartition between the energy densities of the magnetic field and cosmic rays \( \varepsilon_{CR} = \varepsilon_{B_t} = B_t^2/8\pi \), Beck & Krause 2005),

\[
B_t = \left\{ 4\pi(2\alpha_n + 1)(K + 1)I_n \frac{E_p^{1-2\alpha_n} \left(\nu/2c_1\right)^{\alpha_n}}{\left(2\alpha_n - 1\right)c_2(\alpha_n)lc_3}\right\}^{1/(\alpha_n+3)}
\]

where \( I_n \) is the nonthermal intensity, \( K \) the ratio between the number densities of cosmic ray protons and electrons, \( l \) the pathlength through the synchrotron emitting medium, and \( \alpha_n \) the mean synchrotron spectral index. \( E_p = 938.28 \text{ MeV} = 1.50 \times 10^{-3} \text{ erg} \) is the
Figure 5.5: Optical image of M33 with overlayed vectors of the linearly polarized emission at 3.6 cm corrected for the Faraday rotation. A vector length of 1′ represents a polarized intensity of 0.37 mJy/beam.
proton rest energy and
\[
\begin{align*}
c_1 &= 3e/(4\pi m_e^3 c^5) = 6.26428 \cdot 10^{18} \text{ erg}^{-2} \text{ s}^{-1} \text{ G}^{-1}, \\
c_2(\alpha_n) &= \frac{1}{4} c_3 (\alpha_n + 5/3) / (\alpha_n + 1) \Gamma[(3\alpha_n + 1)/6] \\
&\quad \times \Gamma[(3\alpha_n + 5)/6]
\end{align*}
\]
(5.7)

For a region where the field is completely regular and has a constant inclination \(i\) with respect to the sky plane (\(i = 0^\circ\) is the face-on view), \(c_3 = [\cos (i)]^{(\alpha_n+1)}\). If the field is completely turbulent and has an isotropic angle distribution in three dimensions, \(c_3 = (2/3)^{(\alpha_n+1)/2}\). If the synchrotron intensity is averaged over a large volume, \([\cos (i)]^{(\alpha_n+1)}\) has to be replaced by its average over all occurring values of \(i\).

The strength of the regular magnetic field in the plane of the sky can be estimated from the observed nonthermal degree of polarization (Segalovitz et al. 1976):
\[
P_{nth} = \left(\frac{3\gamma + 3}{3\gamma + 7}\right) \left[1 + \frac{(1 - q) \pi^{1/2} \Gamma[(\gamma + 5)/4]}{2q\Gamma[(\gamma + 7)/4]F(i)}\right]^{-1},
\]
(5.8)
\[
F(i) = \frac{1}{2\pi} \int_0^{2\pi} (1 - \sin^2 i \sin^2 \theta)^{(\gamma+1)/4} \, d\theta,
\]
with \(B_u/B_r = q^{2/(1+\gamma)}\), \(\gamma = 2\alpha_n + 1\), and \(\theta\) the azimuthal angle (\(B_r\) is the turbulent magnetic field). This formula assumes that the ordered magnetic field has a single orientation, is parallel to the disk and, taken over the galaxy as a whole, has no further preferential orientation with respect to any fixed direction in space.

The determined average values of \(I_n, \alpha_n,\) and \(P_{nth}\) with the assumed values of \(K(\sim 100)\) and \(l(\sim 1 \text{ kpc})\) lead to \(B_t \simeq 6.4 \mu\text{G}\) and \(B_u \simeq 2.5 \mu\text{G}\) for whole M33 (\(R < 7.5 \text{ kpc}\)). The strongest ordered magnetic field is found in between the arms IV N and V N (in the magnetic filament, see Chapter 2) with \(B_u \simeq 6.6 \mu\text{G}\) where \(B_t \simeq 8.3 \mu\text{G}\).
Using the mean synchrotron flux density, spectral index, and degree of polarization in rings, we also derive the average field strengths in rings. Fig. 5.6 shows some fluctuations but no systematic increase or decrease of these strengths with galactocentric radius (although \( B_t \) falls considerably in the last ring). The small bump at \( 4.5 < R < 5.5 \) kpc is due to the M33’s magnetic filament.

As the polarized intensity (PI) is related to the regular magnetic field, and the non-thermal intensity \( (I_n) \) to the total magnetic field in the plane of the sky, \( I_n - PI \) gives the nonthermal emission due to the turbulent magnetic field \( B_r \). This intensity with Eqs. (5.6) and (5.7) and assuming a completely turbulent field led to derive the distribution of \( B_r \) across the galaxy. Figure 5.7 shows strong \( B_r (> 7 \mu G) \) in the central region of the galaxy, the arm IS, and parts of the arm IN.

### 5.5 Depolarization

The observed depolarization at a certain wavelength is defined as the ratio of the nonthermal degree of linear polarization \( P_{nth} \) and the theoretical value \( p_0 \). Generally, it may be caused by instrumental effects as the bandwidth and beamwidth of the observations or by the wavelength-dependent Faraday depolarization. Bandwidth depolarization oc-
Magnetic fields in M33

curs when the polarization angles vary across the frequency band, reducing the observed amount of polarized emission. It is given by \( \text{sinc}(2RM\lambda^2 \delta\nu/\nu) \), where \( \delta\nu \) is the bandwidth of the observations (e.g. Reich 2006). In our study, the wavelengths, bandwidths and RM values lead to a negligible bandwidth depolarization.

Beam depolarization occurs when polarization vectors of different orientation are unresolved by the telescope beam. In order to compensate this effect, the ratio of the nonthermal degree of polarization at two wavelengths and at a same angular resolution is used,

\[
DP_{\lambda_2/\lambda_1} = \frac{P_{\lambda_2}^{\text{nth}}}{P_{\lambda_1}^{\text{nth}}},
\]

where, \( \lambda_2 > \lambda_1 \). Then, the observed depolarization \( DP_{\lambda_2/\lambda_1} \), that is wavelength-dependent, and called Faraday depolarization.

We derived the depolarization \( DP_{20/3.6} \) using the maps of the nonthermal intensity and polarization at 20 and 3.6 cm at the same angular resolution of 180" (Fig. 5.9, top panel). Generally, the southern half of the galaxy is highly depolarized. While \( DP_{20/3.6} \) changes between [0-0.5] in the south, it varies between [0.3 -1] in the north. Considerable depolarization are found at the positions of NGC604, NGC595 and IC133. However, the strongest depolarization in the inner galaxy is found in the main southern arm IS. No depolarization (\( DP \simeq 1 \)) is seen in the eastern edge of the minor axis and some northern regions.

According to Burn (1966) Faraday depolarization could be caused by the regular magnetic field and thermal electrons along the line of sight (depolarization due to differential Faraday rotation): when synchrotron emission originates in a magneto-ionic medium containing a regular magnetic field, the polarization plane of the radiation produced at different depths within the source is rotated over different angles by the Faraday effect. This results in a decrease in the degree of polarization of the integral emission observed. Faraday depolarization could also be caused by the turbulent magnetic field and thermal electrons along the line of sight (the so-called ‘Faraday dispersion’: depolarization due to dispersion in Faraday RM). When this dispersion is intrinsic to the source, it is called internal Faraday dispersion. In case of a dispersion in an external screen it is called external Faraday dispersion².

Generally, dealing with Faraday depolarization effects is very complicated and needs several free parameters which practically cannot be constrained. Here I only discuss simple models and try to find a qualitative agreement between the observed distribution of depolarization and results of these models.

Considering the dispersion in RM, \( \sigma_{\text{RM}} = 0.81 \langle n_e \rangle B_r \sqrt{L \cdot d/ f} \), the internal Faraday dispersion is given by

\[
DP_r = 1 - e^{-2\sigma^2_{\text{RM}} \lambda^4} \frac{\lambda^4}{2\sigma^2_{\text{RM}} L} \]

(Sokoloff et al. 1998), with \( L \) the pathlength through the ionized medium, \( f \) the filling factor of the Faraday-rotating gas along the line of sight (\( \simeq 0.5, \) Beck 2007), and \( d \) the turbulent scale (\( \simeq 50 \text{ pc}, \) Ohno & Shibata 1993). Using the H\( \alpha \) emission measure \( (EM = \))

²This depolarization effect cannot be responsible for the north-south asymmetry in polarized emission from M33, as no asymmetry in the foreground distributions of RM (from galactic RM data by Johnston-Hollitt et al. 2004) and H\( \alpha \) emission (from Wisconsin H\( \alpha \) mapper) was found.
$\int n_e^2 \, dl$) and a clumping factor $f_c = \langle n_e \rangle^2 / \langle n_e^2 \rangle$ describing the variations of the electron density, $\langle n_e \rangle$ can be determined by $\langle n_e \rangle = \sqrt{f_c \, EM / L}$. For the local interstellar medium, Manchester & Mebold (1977) found $f_c \simeq 0.05$. Assuming a thickness of $\simeq 1$ kpc for the thermal electrons in the disk of the galaxy (the Galactic value, Cordes & Lazio 2002) and correcting for the inclination of M33, we approximate $L \simeq 1800$ pc. Then the H\(\alpha\) ($EM$) map of M33 leads to a distribution of $\langle n_e \rangle$ across the galaxy with a mean value of $\simeq 0.05$ cm\(^{-3}\) and a most probable value of $\simeq 0.03$ cm\(^{-3}\) (Fig. 5.8), that is in agreement with the estimated values in our galaxy (Lyne et al. 1985) and nearby galaxies IC382 (Krause et al. 1989b) and NGC5907 (Dumke et al. 2000). Note that a more realistic approach would consider different filling factors and electron densities for the thin and thick disk of the galaxy. However, because the only information we have is a superposition of these components along the line of sight, we are not able to distinguish the role of each component in this study. The resulting $\langle n_e \rangle$ with $B_r$ obtained (Fig. 5.7) enable us to estimate DP\(_r\) at 3.6 and 20 cm. The left-bottom panel in Fig. 5.9 shows DP\(_r\) between 20 and 3.6 cm.

The next Faraday depolarization effect, differential Faraday rotation, for a symmetric layer is given by Sokoloff et al. (1998),

$$DP_u = \text{sinc} \, (2 \, RM_i \, \lambda^2).$$  \hspace{1cm} (5.11)

Using the RM\(_i\) map (Fig. 5.2), DP\(_u\) between 20 and 3.6 cm was computed and shown in the right-bottom panel in Fig. 5.9.

In a qualitative comparison, both kinds of Faraday depolarization seem to be responsible for the observed depolarization in the galaxy. The global phenomenon, the north-south asymmetry in depolarization, is visible in DP\(_u\). However, locally i.e. at the positions of HII complexes and the arm IS, the observed depolarization can be explained by DP\(_r\). The contribution of each DP\(_u\) and DP\(_r\) varies region by region. A knowledge of how to combine DP\(_u\) and DP\(_r\) across the galaxy is required for a more quantitative comparison and needs detailed modeling. Furthermore, it is necessary to know the distribution of filling factors $f$ and $f_c$, pathlength $L$, and the turbulent scale $d$ across the galaxy.

Hence, we conclude that the highly turbulent southern arm IS with its chain of star-forming regions together with a magneto-ionic medium, which is probably not confined to
Figure 5.9: *Top:* observed depolarization between 3.6 and 20 cm. *Left-bottom:* depolarization due to dispersion in Faraday rotation, and *right-bottom:* depolarization due to differential Faraday rotation as measured between 3.6 and 20 cm.
the plane of the galaxy, containing a regular magnetic field, reduce the degree of polarization of the integral emission from the southern half and cause the wavelength-dependent north-south asymmetry in this galaxy.

The change of the optical spiral structure in M33 begins at a radius of about 4 kpc, where the HI warp begins. The inclination of the disk then tilts by about 40°. This is attributed to an external gas accretion, as recent optical and HI observations have detected extensions like a bridge between M33 and M31 (Ibata et al. 2007; Braun & Thilker 2004). Hence, M33’s warp and/or a tidal force from its massive neighbor M31 may perturb the distribution of the ionized gas + regular magnetic field in the disk of the galaxy.

5.6 Conclusions

The linearly polarized intensity and polarization angle distributions at 3.6, 6.2, and 20 cm along with the nonthermal intensity and spectral index maps allowed to determine high-resolution distributions of RM, nonthermal degrees of polarization, and Faraday depolarization in M33. We found a nonthermal degree of polarization of \( \approx 10\% \) (at 3.6 cm) for the whole galaxy which is \( > 30\% \) in the northern parts of the magnetic filament. Faraday depolarization is strong at 20 cm with reducing \( P_{\text{nth}} \) to \( \approx 6\% \).

We found an average total magnetic field strength of \( B_t \approx 6 \mu G \), stronger than that obtained by Buczilowski & Beck (1991) (\( \approx 4 \mu G \)). This is probably due to an underestimate of the nonthermal intensity in the separation method used by Buczilowski & Beck (1991). The ordered magnetic field strength is higher within the ring at \( 4.5 < R < 5.5 \) kpc, where the magnetic filament exists with a maximum regular field of \( \approx 6.6 \mu G \). Strong turbulent magnetic fields (\( > 7 \mu G \)) were found in the extended central region and the arms IS.

Comparing the south and north of M33, we found an excess of depolarization due to differential Faraday rotation in the south of M33. Furthermore, the main southern arm IS is highly depolarized due to dispersion in Faraday rotation. These may lead to the wavelength-dependent north-south asymmetry in polarization (or depolarization).

Strong variations in \( RM_i \) in the south of M33, where there is no correlation with PI and also with \( n_e \), may indicate that the regular magnetic field in M33 is not confined to the disk. This may be linked to the warp in this galaxy. Furthermore, there are indications of strong magnetic fields \( B_\parallel \) in the eastern and western edges of the minor axis with opposite directions.

For a better understanding of the magnetic field configuration in M33, it is required to synthesis RM at as many wavelengths as possible (Brentjens & de Bruyn 2005) using multi-channel polarimeters at future high-sensitivity radio telescopes, e.g. the low frequency array (LOFAR).
6 Conclusions

M33’s proximity and favorable inclination make it excellently suited for detailed studies of various astrophysical aspects. Although several studies have been carried out mainly in the optical regime, great efforts are required to explore the structure of the interstellar medium and different components that shape it, and to understand the energy balance of the interstellar medium as a function of galactic environment. These motivates high-resolution observations using different windows of the electromagnetic radiation.

A multi-wavelength study of the IR and radio emission from M33 using highly improved data is presented in this thesis. As the main topics, we investigate the energy sources of the IR emission and correlation with the radio emission, the variation in the spectral index of the synchrotron emission across the galaxy, the linearly polarized emission and magnetism. Previously, our knowledge was restricted to the poor resolution and low sensitivity data in both radio and IR regimes. New receivers of the 100-m Effelsberg telescope enabled us to achieve high-sensitivity and -resolution radio maps in total power and linearly polarized intensity at 3.6 and 6.2 cm. These maps with those at 20 cm observed with the VLA provided our radio continuum window to M33. High resolution and sensitivity IR maps (at 24, 70, and 160 \( \mu \text{m} \)) were also achieved using the Multiband Imaging Photometer on board Spitzer satellite observatory. In this chapter, I present a brief summary of the work and highlight the main results and conclusions.

Radio continuum emission from M33

M33 was observed using the 3.6 cm dual channel and the 6.2 cm four-channel receivers of the 100–m Effelsberg telescope along with the L-band VLA D–array at 20 cm. These observations allowed to study the exponential scale length of the total radio emission, the spectral index distribution, and the linear radio polarization.

We detected considerable extended radio continuum emission, not only from the main spiral arms IS and IN, but also from the weaker arms. M33 belongs to those galaxies showing a sudden drop in their radial surface brightness profile in the optical regime. This break also exists in our radio profiles at \( R \approx 4 \text{kpc} \), where the warp starts, resulting in a larger exponential scale length inside than outside \( R=4 \text{kpc} \). In contrast, the ring mean spectral index versus radius increases faster beyond \( R=4 \text{kpc} \). We found a mean total spectral index of \( \approx 0.7 \) for the whole M33. The most important conclusions are as follows.

- At \( R < 4 \text{kpc} \), a spatial correlation between cosmic rays, magnetic fields, and star-forming regions exists.
Conclusions

- There is a north-south asymmetry in polarization that is frequency-dependent, indicating an asymmetry in Faraday depolarization.

- The total spectral index becomes slightly flatter at longer wavelengths that indicates a free-free absorption of the nonthermal emission in this galaxy.

More details are presented in Chapter 2, see also Tabatabaei et al. (2007c).

Thermal and nonthermal emission from M33

We developed a new method to separate thermal and nonthermal components of the radio continuum emission from M33 without the assumption of a constant nonthermal spectral index. Using the Spitzer FIR data at 70 and 160 µm and a standard dust model, we de-reddened the Hα emission. The extinction corrected Hα emission served as a template for the thermal free-free radio emission. Subtracting from the observed 3.6 cm and 20 cm emission this free-free emission, we obtained the nonthermal maps. A constant electron temperature used to obtain the thermal radio intensity seems appropriate for M33 which, unlike the Milky Way, has a shallow metallicity gradient. On the other hand, the standard assumption of a constant nonthermal spectral index assumption imposes more uncertainty in the thermal/nonthermal distribution than a constant electron temperature. It is interesting that the obtained thermal fractions for the whole M33 at different wavelengths agree with those obtained from the standard method within the errors. This indicates that the assumption of a constant nonthermal spectral index (if known) is proper for global studies.

As expected, the nonthermal emission is distributed more smoothly than the thermal emission across M33, showing that the cosmic ray electrons diffuse to large scales, spiral around magnetic fields, and emit synchrotron emission. On the other hand, strong nonthermal emission is detected from giant star-forming regions and spiral arms, providing a spatial correlation between the thermal and nonthermal emissions, confirming our prediction in (Tabatabaei et al. 2007c). The most significant results are as follows.

- The mean extinction in rings in the galactic plane exhibits a shallow radial gradient.

- The wavelet transform of the nonthermal maps revealed that the nonthermal emission is smoother at 20 cm than at 3.6 cm, indicating that high-energy cosmic ray electrons experience more energy losses, and hence diffuse less than low-energy CR electrons.

- Assuming equipartition between the magnetic field and CRs, the scale length of the CR electrons and of the magnetic field estimated are \( l_{cr} \simeq 12 \text{ kpc} \) and \( l_B \simeq 24 \text{ kpc} \) in this galaxy.

In Chapter 4, we explain this method and compare it with the standard method in different aspects, see also Tabatabaei et al. (2007b).
Variations in the synchrotron spectral index across M33

Constraints on the origin and propagation of cosmic rays can be achieved by studying the variation in the spectral index of the synchrotron emission across external galaxies. For the first time, we determined variations in the nonthermal spectral index across a galaxy, M33. In the spiral arms, $\alpha_n = 0.6 \pm 0.1$, the typical spectral index of supernova remnants. The nonthermal spectrum in the interarm regions and the outer parts of the galaxy is steeper than that within the arms. This indicates energy-loss of the relativistic electrons when they diffuse from their origin in star-forming regions towards interarm regions and the outer parts of the galaxy. The main conclusions drawn by the nonthermal spectral index map are as follows.

- At $R < 4$ kpc, the ring-mean nonthermal spectral index varies between 0.65 and 0.9, indicating that cosmic ray electrons are injected by sources related to massive stars and diffused suffering a mixture of both leakage and synchrotron (and inverse-Compton) losses. At $R > 4.5$ kpc, synchrotron (and inverse-Compton) is the dominant energy loss mechanism as $\alpha_n \approx 1$ on average.

- The nonthermal spectral index smaller than 0.5, found in some HII complexes like NGC604 and NGC592, indicates that ionization and free-free losses are dominant in these regions.

- Globally, the nonthermal emission from the southern half of the galaxy seems to have a steeper spectrum than that from the northern half, indicating a more important role of synchrotron and leakage losses in the southern half (that is possibly related to the vertical fields in the halo, see below).

Further details are presented in Chapter 4 (see also Tabatabaei et al. 2007b).

IR emission: energy sources and correlation with radio emission

In this study, we used the wavelet transform of the IR and radio maps to a) separate the diffuse emission components from compact sources, b) compare the emission at different wavelengths, and c) study the radio–IR correlation at various spatial scales. We also used the H$\alpha$ map as a tracer of the star forming regions. We found that the bright HII regions affect the wavelet spectra causing dominant small scales or decreasing trends towards the larger scales. The dominant scale of the 70 $\mu$m emission is larger than that of the 24 $\mu$m emission, while the 160 $\mu$m emission shows a smooth wavelet spectrum. The radio and H$\alpha$ maps are well correlated with all 3 MIPS maps, although their correlations with the 160 $\mu$m map are weaker. After subtracting the bright HII regions, the 24 and 70 $\mu$m maps show weaker correlations with the 20 cm map than with the 3.6 cm map at most scales. We also found a strong correlation between the 3.6 cm and H$\alpha$ emission at all scales. The most important conclusions concerning the scales smaller than 4 kpc are listed in the followings.
• The role of young, massive stars is more significant in heating the dust than that of a diffuse radiation field. The IR emission is influenced by O/B stars increasingly with decreasing wavelength from 160 to 24 \( \mu \text{m} \).

• The radio–IR correlations indicate that the warm dust–thermal radio correlation is stronger than the cold dust–nonthermal radio correlation.

• A perfect 3.6 cm–H\( \alpha \) correlation indicates small extinction of the H\( \alpha \) emission by dust in M33 (this was also shown in Chapter 4, as \( \tau_{\text{H}\alpha} < 1 \) everywhere).

The radio–IR correlation described in Chapter 3 and published in Tabatabaei et al. (2007a), was re-investigated after the thermal/nonthermal separation (in Chapter 4), confirming a stronger warm dust–thermal than the cold dust–nonthermal radio correlation, and giving more results as follows.

• There is a characteristic scale range of 0.8 kpc-2 kpc where the IR–nonthermal radio correlation is maximum. This scale range includes the sizes of the giant molecular clouds, giant star forming regions, spiral arms, and the central extended region of M33.

• The better correlation of the cold dust with the thermal than with the nonthermal emission indicates that the role of UV photons from O/B stars is larger than that of the cosmic ray electrons in heating the cold dust at scales smaller than 4 kpc.

• The nonthermal 3.6 cm emission is better correlated with the warm dust than with the cold dust emission. This can be explained by the correlation of the nonthermal emission with the thermal emission e.g. because of strong magnetic fields and/or high densities of cosmic ray electrons in or nearby star-forming regions.

Magnetic fields in M33

We determined the distribution of the Faraday rotation measures across M33 at an angular resolution of \( 3' \) (0.7 kpc), indicating more variations in the south than in the north of the galaxy. In the south and also eastern and western minor axis, high values of the intrinsic rotation measure were found, where no dense medium of thermal electrons exists. Hence, in these regions, the regular magnetic field has strong components along the line of sight. These could be related to the M33’s warp making the disk not a simple plane. This explains why single dynamo modes of ASS and BSS do not fit to the azimuthal behavior of the rotation measure. It is interesting that, in southern M33, there is a coincidence between the steeper nonthermal emission and stronger magnetic field along the line of sight which increases the effect of synchrotron losses. For the whole galaxy, we estimated the strengths of the total and regular magnetic fields as \( \simeq 6.4 \mu \text{G} \) and \( \simeq 2.5 \mu \text{G} \). Other highlights are as follows.

• The large-scale magnetic field exhibits a well ordered spiral structure with almost the same orientation as that of the optical spiral arms. However, there is no general structural correlation or anti-correlation between the magnetic and optical arms.
Conclusions

- The regular magnetic field in the south is not as confined to the disk as that in the north of the galaxy.

- High degree of polarization of the synchrotron emission (> 20%) and strong regular magnetic field in the sky plane (∼ 6.6 µG) are found in the northern magnetic filament.

- An excess of differential Faraday rotation in the southern half together with strong Faraday dispersion in the main southern arm IS seem to be responsible for the north-south asymmetry in the observed depolarization (which is wavelength dependent).

Details are presented in Chapter 5. More studies about the magnetic field structure and depolarization are in process. This work is going to be submitted to Astronomy & Astrophysics journal.

M33 versus other nearby galaxies

Most of the nearby spiral galaxies host a super massive black hole in their center that was made by merging with other galaxies, according to the galaxy formation scenarios. However, M33, with its small bulge and no satellite, is a rare example of a spiral galaxy that has not probably experienced merging in its formation history. On the other hand, it has a ten times more massive neighbor, M31, only 200 kpc away. Despite its much smaller mass, M33 has a star-formation rate comparable to that of M31. This provides a more efficient role of UV photons in heating the dust in M33 than in M31. While the total magnetic field strength are about the same in M33 and M31 (∼ 7 µG), the ordered magnetic field strength in M33 is about half of that in M31 (∼ 4 µG). M33’s stronger depolarization and higher turbulence due to star-formation activities can explain this difference. In M31, the large-scale magnetic field is confined to the disk (toroidal) and follows the ASS dynamo model (Fletcher et al. 2004), in contrast to M33.

Like M33, spiral structure of the large-scale magnetic field has been found in M51, M81, IC342 as well, with different degrees of regularity. The spiral pattern of the magnetic field is generally linked to the αΩ-dynamo action. In these galaxies, but M51, the regular magnetic field can be explained by a dominant single dynamo mode. The magnetic field in M51 is not confined to the disk and is extended to the halo (a magneto-ionic halo) with a structure different from that in the disk (Berkhuijsen et al. 1997). A similarity between M33 and M51 is that their magnetic fields are neither axisymmetric nor bisymmetric. This situation in M51 is perhaps due to the interaction with its companion, NGC5195, and in M33 possibly due to the warp in this galaxy (although the warp may also be linked or affected by a tidal interaction with M31).
A Ionization and recombination Processes

Some of absorption, emission, ionization, recombination, excitation, and de-excitation processes are described below. All these processes can occur when an incoming photon or electron interacts with an atom or ion.

1. **Induced absorption**: An incoming photon can excite an electron in an atom to a higher energy state $\epsilon_n = \epsilon_m + h\nu$. This process occurs with a probability that is proportional to the occupation number $N_m$ in state $m$ and the energy density $U_\nu$ of the radiation field, where the transition probabilities are specified by the Einstein coefficients $B_{mn}$, giving a transition rate $R = U_\nu B_{mn}N_m$.

2. **Stimulated emission**: An electron in an excited atom at energy state $\epsilon_n$ is stimulated by a passing photon $\nu$ from the ambient radiation field and falls back into a lower state $\epsilon_m$, emitting during this process a second photon with energy $h\nu = \epsilon_n - \epsilon_m$. The probability of this process is also proportional to the energy density $U_\nu$ of the radiation field, as for induced absorption (i.e., with a rate of $R = U_\nu B_{nm}N_n$). This process is relevant to laser emission.

3. **Spontaneous emission**: In contrast to stimulated emission, no incoming photon is needed. An electron spontaneously falls from a higher energy state $\epsilon_n$ to a lower state $\epsilon_m$ by emission of a photon with $h\nu = \epsilon_n - \epsilon_m$. The probability is given by the Einstein coefficients $A_{nm}$, so the rate is $R = N_{nm}A_{nm}$.

4. **Photo-ionization**: This is a *bound-free transition*, where the incoming photon has a higher energy than the ionization energy (i.e., $> 13.6$ eV for hydrogen), so that the bound electron escapes from the atom. The wavelength of the incoming photon is $\lambda = hc/\Delta\epsilon$, with $\Delta\epsilon = \epsilon_j + 1/2m_ev_e^2$, where $\epsilon_j$ is the ionization energy of the atom from the bound state $\epsilon_j$ of the electron, and $1/2m_ev_e^2$ is the kinetic energy of the free electron after escape.

5. **Radiative (or 2-body) recombination**: Recombination (also called *free-bound transition*) can occur by several processes, such as radiative recombination, collisional recombination, or dielectronic recombination. In radiative recombination a free electron is captured by an ion into one of the available energy states $\epsilon_i$, while the excess energy is removed by emission of a photon with energy $h\nu = 1/4m_ev_e^2 - \epsilon_i$, just as the time-reverse process of photo-ionization. This type of *bound-free transition* produces series limit continua such as the Balmer (3646 Å) and Lyman continua (912 Å) of hydrogen. These wavelengths correspond to the ionization energies
of $\epsilon_1 = 13.6$ eV from the ground state level $n = 1$ and $\epsilon_2 = 3.6$ eV from the first excited state $n = 2$.

6. **Dielectronic recombination:** The term *dielectronic recombination* indicates that two electrons are involved in this process. A free electron $e^{-}_1$ is captured by an ion, resulting in a double excitation of the ion: (1) the original free electron lands in an excited state, and (2) a bound electron of the ion also becomes excited. Dielectronic recombination is accomplished when the highly unstable doubly excited configuration subsequently stabilizes, with one or both excited electrons falling back into vacancies of the lowest available states.

7. **Auto-ionization:** An ion is initially in a doubly excited state $Z''$ and auto-ionizes (i.e., it spontaneously ionizes without induced particle or photon) to $Z^+ + e^-$, thus leaving an ion and a free electron. If an electron from a lower energy state is knocked off, an electron from a higher energy level has to fall back to the emptied lower state to stabilize the ion. This process is also called *auto-ionization*.

8. **Thomson scattering:** It is the scattering of photons by free electrons which is independent of photon energy. The scattering rate is proportional to the electron density.

9. **Free-free emission:** This process is also called *bremsstrahlung*. Electrons are non-elastically scattered off ions and emit photons that have energies corresponding to the energy difference of the incoming and outcoming electron (i.e., $h\nu = \epsilon' - \epsilon$).

10. **Collisional ionization:** This occurs by collisions of ions with free electrons, when an orbiting electron of the ion (generally the outermost) is removed, and the ion is left in the next higher ionization state. This process is much more important than photo-ionization (when a photon incident on an ion results in removal of an orbiting electron).
B Wavelets as a tool for scaling analysis

The term wavelet means literally ‘little wave’, originated in the early 1980’s in its French version ‘ondelette’ in the work of Morlet and some seismologists. As an prototypical example, we consider Haar wavelet

\[ h(x) = \begin{cases} 
1, & 0 \leq x < \frac{1}{2} \\
-1, & \frac{1}{2} \leq x < 1 \\
0, & \text{elsewhere.} 
\end{cases} \] (B.1)

Here, the ‘wavelet’ property is simply shown by the fact that \( h \) has average zero i.e,

\[ \int_{-\infty}^{\infty} h(x) \, dx = \int_{0}^{1} h(x) \, dx = 0. \]

So, Haar wavelet has some oscillation but unlike such periodic functions as sine and cosine it has compact support: it lives on the interval \([0, 1)\) and does not oscillate everywhere on \((-\infty, \infty)\).

Wavelet analysis is based on a space-scale decomposition using the convolution of the data with a family of self-similar basic functions that depend on two parameters, scale and

![Figure B.1: Haar wavelet.](image)
Figure B.2: The sinusoids have infinity support but the wavelets (here db10) have compact (or interval) support.

Figure B.3: An input signal decomposed by the fourier transform.

Figure B.4: An input signal decomposed by a wavelet transform.
Wavelets as a tool for scaling analysis

location. It can be considered as a generalization of the Fourier transformation, which uses harmonic functions as a one-parametric functional basis, characterized by frequency, or in the case of a space function, by the wavevector $k$. The wavelet transformation also uses oscillatory functions, but in contrast to the Fourier transform these functions rapidly decay towards infinity. The family of functions is generated by dilations and translations of the mother function, called the analysing wavelet. This procedure provides self-similarity, which distinguishes the wavelet technique from the windowed Fourier transformation, where the frequency, the width of the window and its position are independent parameters.

We consider the continuous wavelet transform, which in the two-dimensional case can be written in the form

$$W(a, x) = \frac{1}{a^2} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} f(x') \psi^* \left( \frac{x' - x}{a} \right) dx'. \quad (B.2)$$

Here $x = (x, y)$, $f(x)$ is a two-dimensional function, for which the Fourier transform exists (i.e. square integrated), $\psi(x)$ is the analysing wavelet (real or complex, * indicates the complex conjugation), $a$ is the scale parameter, and $\kappa$ is a normalization parameter which will be discussed below.

For later considerations the relation between the wavelet and the Fourier decomposition will be useful. The 2-D Fourier transform $\hat{f}(k)$ of the function $f(x)$ is defined as

$$\hat{f}(k) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} f(x)e^{-ikx} dx, \quad (B.3)$$

where $k = (k_x, k_y)$ is the wavevector. Then the inverse Fourier transform is

$$f(x) = \frac{1}{4\pi^2} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \hat{f}(k)e^{ikx} dk. \quad (B.4)$$

and the wavelet coefficients (B.2) can be expressed as

$$W(a, x) = a^2 - \kappa \frac{1}{4\pi^2} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \hat{f}(k)\psi^*(ak)e^{iak} dk. \quad (B.5)$$

The choice of the wavelet function depends on the data and on the goals of the analysis. For spectral analysis wavelets with good spectral resolution (i.e. well localized in Fourier space, or having many oscillations) are preferable, for local structure recognition a function, well localized in the physical space, is preferable. (Note that the spectral resolution $\Delta k$ and the space resolution $\Delta x$ are strongly related and are restricted by the uncertainty relation $\Delta x \Delta k \geq 2\pi$.) An obligatory property of the wavelet is the zero mean value $\int \int \psi(x, y) dx dy = 0$. An isotropic wavelet is an axisymmetric function $\psi = \psi(\rho), \rho = \sqrt{x^2 + y^2}$.

A simple real isotropic wavelet with a minimal number of oscillations is known as the Mexican Hat (MH),

$$\psi(\rho) = (2 - \rho^2)e^{-\rho^2/2}. \quad (B.6)$$

For a better separation of scales (to analyse spectra and to find the scale of dominant structures) another isotropic wavelet is used which is defined in Fourier space by the formula

$$\hat{\psi}(k) = \begin{cases} \cos^2 \left( \frac{\pi}{2} \log_2 \left( \frac{|k|}{2\pi} \right) \right) & : \pi < |k| < 4\pi \\ 0 & : |k| < \pi, |k| > 4\pi. \quad (B.7) \end{cases}$$
Wavelets as a tool for scaling analysis

Figure B.5: Two isotropic wavelet functions: the MH wavelet (thin line) and the PH wavelet (thick line).

The function is localized in Fourier space in a ring with a median radius $2\pi$ and vanishes for $|k| < \pi$ and $|k| > 4\pi$. This wavelet definition provides a relatively good spectral resolution, it is referred to Pet Hat (PH) (Frick et al. 2001). In physical space the PH wavelet is obtained by numerical integration of (B.7). Both wavelets MH and PH are shown in Fig. B.5

The wavelet transform (B.2) is unique and reversible which means that the analyzed function $f(x, y)$ can be reconstructed from its wavelet decomposition. An extended description of continuum wavelet transform can be found in e.g. Holschneider (1995) and Torresani (1995).

Wavelet energy spectrum In the studies of scaling properties of turbulence a commonly used characteristic of a turbulent field is the spectral energy density $E(k)$ which includes the energy $F(k) = |\hat{f}(k)|^2$ of all Fourier harmonics with wavenumbers $k$, for which $|k| = k$

$$E(k) = \int_{|k|=k} F(k) dk. \quad (B.8)$$

The spectral energy is related to the autocorrelation function

$$C(l) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} f(x)f(l-x)dx \quad (B.9)$$

by its Fourier transform

$$F(k) = \hat{C}(k) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} C(l)e^{-ikl} dl. \quad (B.10)$$
Wavelets as a tool for scaling analysis

The vector \( l \) defines the shift of the image in the convolution (B.9) and is the scale parameter. In the important case of isotropic turbulence the autocorrelation function depends only on the distance between two points \( C(l) = C(l) \), and the spectral energy depends only on the modulus of the wavevector \( F(k) = F(k) \). Then these two functions are related by the Hankel transform

\[
F(k) = 2\pi \int_{0}^{\infty} C(l) J_0(kl) \,dl , \tag{B.11}
\]

where \( J_0 \) is the Bessel function and \( E(k) = 2\pi k F(k) \).

Another often used characteristic for scaling studies is the structure function defined for arbitrary order \( q \) as

\[
S_q(l) = \langle (f(x) - f(x - l))^q \rangle_{|l|=l} , \tag{B.12}
\]

where the brackets \( \langle ... \rangle \) mean the average value. Calculation of high-order structure functions requires a high accuracy of the initial data. In the case of maps of external galaxies, where a relatively small number of grid points is available and the noise is significant, only the second-order function \( S_2 \), corresponding to the energy spectrum (B.8), can be discussed.

In the wavelet representation the scale distribution of the energy can be characterized by the wavelet spectrum, defined as the energy of the wavelet coefficients of scale \( a \) of the whole physical plane

\[
M(a) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} |W(a, x)|^2 \,dx . \tag{B.13}
\]

The wavelet spectrum can be related to the Fourier spectrum. Using (B.5) one can easily rewrite (B.13) in the form

\[
M(a) = \frac{a^{4-2\kappa}}{16\pi^4} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} |\hat{f}(k)|^2 |\hat{\psi}(ak)|^2 \,dk . \tag{B.14}
\]

This relation shows that the wavelet spectrum is a smoothed version of the Fourier spectrum. In the isotropic case (B.14) has a more simple form

\[
M(a) = \frac{a^{4-2\kappa}}{8\pi^3} \int_{0}^{\infty} E(k)|\hat{\psi}(ak)|^2 \,dk . \tag{B.15}
\]
C Effective optical depth

The general radiative transfer equation for a medium in case of both absorption and emission can be written as

$$\frac{dI}{d\tau} = S - I, \tag{C.1}$$

from which the integral form of the transfer equation follows formally,

$$I = I_0 e^{-\tau} + \int_0^{\tau} S(\tau') e^{-(\tau-\tau')} d\tau', \tag{C.2}$$

with $\tau$ the optical depth of the medium, $I_0$ the intensity of an incoming emission from background, and $S$ the so called source function (the ratio of the emissivity to the absorption factor).

Considering a homogeneous mixing of emitting (sources) and absorbing media, (C. 2) is converted to

$$I = S_0 (1 - e^{-\tau}), \tag{C.3}$$

(Rybicki & Lightman 1979) with $S_0$ the total intrinsic intensity and neglecting the background emission.

Now, a question is assuming this medium is occupied only by a homogeneous distribution of the emitters, what would be the effective thickness of an only absorbing medium in front of this emission to give the same amount of intensity in (C. 3).

For only emitting medium, the radiative transfer gives

$$I_e = S_0 \tau, \tag{C.4}$$

and for only absorbing medium,

$$I_a = I_e e^{-\tau_{\text{eff}}}, \tag{C.5}$$

or using (C. 4)

$$I_a = S_0 \tau e^{-\tau_{\text{eff}}}. \tag{C.6}$$

$I_a$ should be equivalent to $I$ in (C. 3), thus

$$(1 - e^{-\tau})/\tau = e^{-\tau_{\text{eff}}}. \tag{C.7}$$

Expanding both sides as series,

$$1 - \frac{\tau}{2} + \frac{\tau^2}{6} - ... = 1 - \tau_{\text{eff}} + \frac{(\tau_{\text{eff}})^2}{2} - .... \tag{C.8}$$

Neglecting O(2) in the optically thin condition gives $\tau_{\text{eff}} = \frac{1}{2} \tau$. However, values of $\tau \approx 1$ does not harm the optically thin assumption as $\tau_{\text{eff}} \approx 0.46.$
Bibliography

Altenhoff, W., Mezger, P. G., Wendker, H., & Westerhout, G. 1960, Veroff Sternwarte Bonn, 59, 48


Beck, R. & Krause, M. 2005, Astronomische Nachrichten, 326, 414


Fürst, E., Reich, W., & Sofue, Y. 1987, A&AS, 71, 63
Panagia, N. 1979, Memorie della Societa Astronomica Italiana, 50, 79
Reich, W. 2006, ArXiv Astrophysics e-prints


Sofue, Y. & Reich, W. 1979, A&AS, 38, 251


Tabatabaei, F., Krause, M., & Beck, R. 2005, AN, 326, 532


Torresani, B. 1995, Continuous Wavelet Transform (Savoire, Paris)


Curriculum vitae

Address
Max-Planck-Institut für Radioastronomie
Auf dem Hügel 69
53121 Bonn, Germany
Tel: +49 228 525 324
Fax: +49 228 525 229
Email: tabataba@mpifr-bonn.mpg.de

Personal Details
Gender: Female
Date of birth: 31 August 1974
Place of birth: Tehran, Iran
Marital status: Married

Education
10/1993-07/1997 Undergraduate Student in Physics (Bachelor of science) at the University of Tehran (http://www.ut.ac.ir)

10/1997-01/2000 Graduate student in Physics (Master of Science) at the Institute for Advanced Studies in Basic Sciences (IASBS), Zanjan (http://iasbs.ac.ir)
Specialization: Astrophysics
Thesis title: A Phenomenological Study of Evolution of Galaxies and QSOs Advisor: Dr. Sadollah Nasiri

01/2005-01/2008 PhD student at the Max-Planck-Institut für Radioastronomie, Bonn (http://www.mpifr-bonn.mpg.de)
Thesis title: Thermal and Nonthermal Emission from the Nearby Galaxy M33 Supervisor: Prof. Dr. Uli Klein

Academic Experience


01/2003-07/2003 Teaching in Shahrood University, Shahrood.

Publications

- Tabatabaei, F. S., Krause, M., and Beck, R.


- Tabatabaei, F. S., Beck, R., Krause, M., Krügel, E., and Berkhuijsen, E. M.
  *Variation of the radio synchrotron spectral index in the interstellar medium of M33*, Astronomiche Nachrichten, 2007, V. 328, p. 636

- Tabatabaei, F., Krause, M. and Beck, R.
  *Spitzer images of M 33: a probe to radio-FIR correlation*, Astronomiche Nachrichten, 2005, V. 326, p. 532

- Tabatabaei, F. S., Krause, M. Beck, and R. Berkhuijsen, E.
  *The radio-F(IR) correlation in M33* in Turbulence in the magnetized interstellar medium, German-Russian Open Workshop, Perm, Russia, September 2006.

- Tabatabaei, F. S., Beck, R., Krügel, E., Krause, M., Berkhuijsen, E. M., Gordon, K. D., Menten, K. M.
  *Variations of the Radio Synchrotron Spectral Index in M33*, in Formation and Evolution of Galaxy Disks, Vatican, October 2007

- Tabatabaei, F. S., Beck, R., Krause, M., and Berkhuijsen, E. M.
  *A Multi-Scale Study of IR and Radio Emission from M33*, in Formation and Evolution of Galaxy Disks, Vatican, October 2007

- Tabatabaei, F. & Nasiri, S.

- Tabatabaei, F. & Nasiri, S.
  *Distribution of the Surface Brightness of QSOs*, proceeding of the ‘Annual Iranian Physics Conference’, Babolsar, August 1999

- Tabatabaei, F. & Nasiri, S.
Research Interests

- Dust emission and absorption in the galaxies’ ISM: The interstellar medium plays a central role in the evolution of galaxies. In order to understand how the energy sources of dust emission (and also extinction) varies as a function of environment and star formation efficiency. Using the wavelet transformation of the MIPS M33 data, we (Tabatabaei et al. 2007a) showed that, depending on the wavelength of the dust emission, heating sources of dust (UV photons from O/B stars or ISRF) varies with scale of emitting structure. In M33, at scales smaller than 0.8 kpc, cold dust is heated mainly by UV photons from massive stars, while an average interstellar field also contribute at larger scales. I also found that stellar photons are more important than cosmic ray electrons in heating the dust up to scales of 2kpc in M33. I plan to investigate these properties in other nearby galaxies like M31, M51 to probe different environmental conditions and starformation efficiencies. I am also interested in very cold dust detection in galaxies as it is important for SED studies globally and high-mass starformation locally. This will be done for M33 using the Hershel space telescope (I am a project member of the Herschel M33 extended Survey), allowing us to accurately determine the amount of dust in M33 and how it is distributed with respect to the stars and the gas. Polarization by dust is another interest as it is important to know how magnetic fields control star formation in galaxies.

- Radio-IR correlation in galaxies: separating the radio continuum emission to its thermal and nonthermal components on one hand and the IR emission to its cold and warm components on the other hand helps to better understanding the origin of this well-known correlation. Furthermore, correlation analysis locally and as a function of spatial scale is possible using the wavelet tool, providing a knowledge about the typical scale where the radio-IR correlation is maximum or, in case of high resolution data, the smallest scale this correlation is still valid.

- Origin and propagation of cosmic rays in galaxies: The map of synchrotron spectral index in M33 by Tabatabaei et al. (2007c) provides, for the first time in an external galaxy, information on the origin and propagation of cosmic ray electrons. I plan to extract these information using this map and through modellings.

- Extragalactic magnetic field: what is the role of magnetic field in energy ballance of interstellar medium, star formation efficiency, and evolution of galaxies? I have studied the magnetic field distribution, depolarization and Faraday effects in M33
using the Effelsberg and VLA radio polarization data and our recent separated map of the synchrotron emission from this galaxy (Tabatabaei et al. in prep). I plan to observe radio continuum emission from this galaxy using the EVLA in order to reach resolutions comparable to that of the Hershel that is important for energy balance studies in M33’s ISM.

- Evolution of galaxies and AGNs: I investigated the specific angular momentum in terms of the specific luminosity of galaxies of various morphological types for my MSc, showing inverse relations between these two parameters. Furthermore, I studied the luminosity function of QSOs using the LBQS data.