GMRT 333-MHz observations of six nearby normal galaxies

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1 INTRODUCTION

The radio continuum emission from normal galaxies originates from two emission processes: thermal free–free emission from H II regions predominantly seen at recent star formation sites and the non-thermal synchrotron emission (hereafter referred to as non-thermal emission) due to acceleration of cosmic ray electrons (CRe) in the ambient galactic magnetic field. A typical galactic magnetic field strength of few microgauss (1–15 µG) and CRe in the energy range 1–10 GeV give rise to radio non-thermal emission between 0.1 and 10 GHz. However, only at frequencies below 1 GHz does the thermal fraction of the emission reduce significantly, and hence low-frequency studies are direct probes of non-thermal emission in galaxies.

It is now abundantly clear that CRe in normal galaxies are accelerated in supernova remnant (SNR) shock fronts (with a typical linear size of <1 pc) of Type II and Type Ib supernovae produced by short-lived (<10^7 yr) massive stars. Subsequently, the CRe diffuse away from their sites of origin and lose their energy primarily via synchrotron and inverse Compton radiation in about 10^8 yr (see Condon 1992 for a review). In turbulent magnetic fields, such as those encountered in the spiral arms, the CRe diffusion speed is the Alfvén speed (∼100 km s^{-1}), and hence the CRe can expand to a volume of radius ∼1 kpc without losing much energy, thus increasing the observed extent of the non-thermal emitting source. Note that the CRe would occupy a larger volume when observed at lower frequencies, since lower energy electrons suffer lesser energy loss and hence can diffuse farther. The CRe generated at the shock front have steep electron energy spectra which results in a non-thermal synchrotron spectrum, well represented by a power law, S_{ν,nt} ∝ ν^{-α}, where S_{ν,nt} is the non-thermal radio flux density at a frequency ν and α_{nt} is the non-thermal spectral index. The effects of CRe generation and propagation will cause α_{nt} to vary from point to point in the galaxy. At the acceleration sites one expects α_{nt} ∼ −0.5 to −0.7 (Bell 1978; Bogdan & Volk 1983; Biermann & Strom 1993), getting steeper due to various losses as the CRe diffuse away.

To confirm the aforementioned scenarios, a host of studies have been performed in the past (see e.g. van der Kruit, Allen & Rots 1977; Segalovitz 1977a,b; Beck & Grave 1982; Klein et al. 1982; Klein, Grave & Wielebinski 1983; Carilli et al. 1992; Niklas & Beck 1997; Berkhuijsen, Beck & Hoernes 2003; Beck et al. 2005; Murgia et al. 2005; Paladino, Murgia & Orrù 2009). However, due to the presence of thermal free–free emission, α_{nt} is contaminated, making the measured value flatter than the true value. This is because the thermal emission has a spectral index of ∼−0.1, while the non-thermal emission is significantly steeper (α_{nt} < −0.5). At frequencies below 1 GHz, the non-thermal emission is expected to dominate. Niklas, Klein & Wielebinski (1997) have shown for a sample of 74 galaxies, about 8 per cent of the emission at 1 GHz is thermal in origin. At even lower frequencies, the contribution of thermal free–free emission to the observed extent of the non-thermal emitting source is significant.
thermal fraction reduces significantly, although there can be considerable local variation between e.g. arms, inter-arms and giant H\textsc{ii} regions, so as to make the separation of the thermal emission important. Previous studies at low frequencies probed linear scales larger than 1 kpc, and hence small-scale structures were lost. These considerations emphasize the importance of high-resolution, low-frequency observations.

In this paper we report the 333-MHz interferometric observation of six nearby galaxies, NGC 1097, NGC 3034, NGC 4736, NGC 5055, NGC 5236 and NGC 6946, using the Giant Metrewave Radio Telescope (GMRT). The galaxies have angular size $\sim 10$ arcmin in the optical and the GMRT observations have a resolution better than 20 arcsec, probing linear scales of 0.4–1 kpc. The typical noise in the maps is $\sim 300 \mu$Jy beam$^{-1}$ (except for NGC 3034), making them 10 times more sensitive than previous studies at similar frequency of other nearby galaxies (Sukumar, Klein & Grave 1987; Heesen et al. 2009; Paladino, Murgia & Orrù 2009). All our maps have a dynamic range $>1000$, which allows us to reliably determine the flux densities in regions near strong emission sites, mainly the nuclear region. We also use the technique developed by Tabatabaei et al. (2007), using archival H\textsc{z} maps, for spatially separating thermal and non-thermal emission as discussed in Section 4. However, we emphasize that by using this robust technique, the resolution is limited by much coarser (40 arcsec) far-infrared maps (discussed in Section 4). In Section 2 we define the sample and discuss the observation and analysis procedure in Section 3. Section 4 discusses the procedure to estimate $\alpha_{\text{uv}}$. Results on individual galaxies are presented in Section 5. We summarize the results in Section 6. The thermal–non-thermal emission separation procedure using H\textsc{z} and infrared data is discussed in Appendix A.

## 2 Sample Definition

Our sample (see Table 1) includes six nearby spiral galaxies, with clearly demarcated arm and inter-arm regions as seen both in the optical and radio continuum. The optical size of these galaxies is typically 9–12 arcmin and the GMRT synthesized beam (typically $\sim 15$ arcsec) at 333 MHz can resolve the arm inter-arm regions.

All the galaxies have 1.4-GHz integrated continuum flux density greater than 200 mJy (as measured in NRAO VLA Sky Survey (NVSS) data; Condon et al. 1998), which is necessary to ensure detection of low surface brightness diffuse emission across the galaxy. High-resolution infrared and H\textsc{z} data (see Table 1) are also used. The infrared data were all taken from the Spitzer Infrared Nearby Galaxy Survey (SINGS; Kennicutt et al. 2003) using Multi-band Imaging Photometer (MIPS; Rieke et al. 2004) on the Spitzer Space Telescope at $\lambda 70 \mu m$ and $\lambda 160 \mu m$, while the H\textsc{z} images were obtained from the ancillary data sets of the SINGS and other public data sets, as described in Appendix A. For five galaxies, the data could be used for thermal–non-thermal separation; however, in the case of NGC 3034, the $\lambda 160-\mu$m MIPS image was not usable due to non-linearity and streaking effects. Finally, higher frequency, near 1.4 GHz, archival continuum interferometric data/maps were used to find the spectral index with 333 MHz (see Table 1).

An interferometer with the shortest baseline $D_{\text{min}}$ can detect all the flux from angular scales less than $\sim 0.61/D_{\text{min}}$, provided the uv-plane is densely sampled at the shortest spacings. The galaxies in our sample have an optical angular size of less than 12 arcmin. For face-on galaxies, the optical and radio continuum sizes are comparable; however, for highly inclined galaxies, the sizes may differ slightly. In GMRT, $D_{\text{min}} \sim 100$ m at 333 MHz allows us to detect all the flux from angular scales less than 18 arcmin. Given that all the galaxies in our sample are less than 12 arcmin, the uv-plane is well sampled (see Fig. 1) and hence we do not expect any missing flux density. This is a concern for the archival higher frequency data, which is discussed below along with a short description of the sample galaxies.

**NGC 1097** is a spectacular barred spiral galaxy in the optical with prominent dust lanes in the bar. The central bar extends to about...
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20 kpc and then continues into the two optical spiral arms. The galaxy has an active Seyfert nucleus and a circumnuclear ring of about 1.5 kpc diameter. Amongst the major radio continuum studies of this galaxy, Ondrechen & van der Hulst (1983) reported radio emission at 1465 MHz coincident with the narrow dust lanes in the bar. Recently, Beck et al. (2005) obtained a spectral index map for this galaxy from observations at 4.8 and 8.4 MHz, which revealed a relatively steep spectral index of $-1$ in the inner ridge of the bar and becomes shallower to $-0.7$ as one moves towards the outer ridge.

To find the spectral index with GMRT 333 MHz, we analysed the archival 1465-MHz data observed using a CD array from the VLA\(^3\). The map has an angular resolution of $40 \times 40$ arcsec\(^2\), and the shortest measured baseline is $\sim 150\lambda$, which can detect angular scales up to $\sim 14$ arcmin. However, the \textit{uv}-coverage is sparse for angular scales above 8 arcmin (see Fig. 1). Since the size of the galaxy is about 9 arcmin, we expect missing flux density at large angular scales in these data.

\textit{NGC 3034 (M82) is a prototypical, starburst, edge-on galaxy. The galaxy was initially classified as irregular; however, recently, Mayya, Carrasco & Luna (2005) have reported the discovery of two symmetric spiral arms in the near-infrared. The galaxy is bright in the radio continuum and has a synchrotron-emitting halo extending up to a diameter of about 8 kpc. Based on a low-frequency spectral index study of the whole galaxy from 330 to 4835 MHz, Seaquist & Odegard (1991) found a spectral index of $-0.4$ in the nuclear region, steepening to $-1$ at a radius of 1 kpc due to transport of CRe from the disk by galactic winds.}

We used the archival 1490-MHz VLA map [obtained from the NASA/IPAC Extragalactic Database (NED); Condon 1987] at a resolution of $60 \times 60$ arcsec\(^2\)\(^3\) to obtain the spectral index with 333 MHz. The 1490-MHz observations were made with the VLA D configuration with the shortest baseline length of $\sim 170\lambda$, and are sensitive to angular sizes less than $\sim 12$ arcmin. This should be sufficient to detect the galaxy, which has an optical size ($D_{25}$) of $\sim 11$ arcmin. However, due to very bright emission from the core, the high-resolution radio continuum map is dynamic range limited.

\textit{NGC 4736 (M94) is the nearest large spiral galaxy, which has a double-ringed morphology. The inner ring is mainly made of recent star-forming H\textsc{ii} regions, showing bremsstrahlung spectra (Duric & Dittmar 1988) and is distinctly visible in Hz. The outer ring however is a low-surface brightness feature in the optical. The rings were suggested to be caused by inner and outer Lindblad resonances (Schommer & Sullivan 1976). The radio continuum study by de Bruyn (1977) between 610 and 1415 MHz reported spectral index maps with the spectral index being $-0.5$ towards the centre of the galaxy and steepening towards the outer parts of the galaxy.}

We used the archival Westerbork Synthesis Radio Telescope (WSRT\(^4\)) 1374.5-MHz map taken from the Westerbork SINGS sample (Braun et al. 2007) at a resolution of $19 \times 12.5$ arcsec\(^2\) after smoothing to $20 \times 20$ arcsec\(^2\) to obtain the spectral index. The observations were made using the ‘maxi-short’ array configuration of the WSRT where the shortest east–west baseline was $\sim 170\lambda$, $250\lambda$, and $330\lambda$. (36, 54 and 72 m, respectively), and are sensitive to angular scales less than $\sim 12$ arcmin. NGC 4736, having an angular size of $\sim 6$ arcmin in the radio, has good sampling of the \textit{uv}-plane and thus this map is not affected by the lack of short spacing measurements.

\textit{NGC 5055 (M63) is a nearby flocculent spiral which has short multiple arms. Although this galaxy lacks organized spiral arms in the optical, polarization observation at 10.55 GHz shows regular, spiral magnetic fields with radial component due to dynamo action (Knapik et al. 2000). Radio continuum spectral index maps between 610 and 1417 MHz by Hummel & Bosma (1982) showed a spectral index of about $-0.6$ in the central regions of the galaxy, which steepens to $-1$ towards the outer parts. The galaxy appears featureless in the above study as well as in the high-frequency 10.7-GHz map of Klein & Emerson (1981).}

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\(^{4}\) The WSRT is operated by the Netherlands Foundation for Research in Astronomy (NFRA) with financial support from the Netherlands Organization for scientific research (NWO).
The archival 18.5 \times 12.5 \text{arcsec}^2 1696-MHz map from the Westerbork SINGS (Braun et al. 2007), after smoothing to 20 \times 20 \text{arcsec}^2 was used for obtaining the spectral index with 333 MHz. The ‘maxi-short’ configuration of the WSRT at 1695 MHz allows us to image angular scales up to 10 arcmin. However, the uv-coverage is too sparse to detect flux from structures above \sim 7 arcmin. NGC 5055 has an angular extent of \geq 8 arcmin, and thus we believe this map has missing flux density.

NGC 5236 (M83) is a large barred spiral galaxy and is seen almost face-on. The central bar extends up to 3 arcmin (\sim 4 kpc), showing clear dust lanes. The galaxy is bright in radio continuum and the central bar and the disk are in the 1465- and 4885-MHz observations of Ondrechen (1985). Sukumar et al. (1987) found the total and non-thermal integrated spectral index to be \sim 0.75 and \sim 0.8, respectively, obtained between 327, 1465 and 4750 MHz and a thermal fraction of 20 per cent at 4750 MHz.

The archival data at the 1452-MHz VLA CD array (project code: AS325) were downloaded and analysed to produce a 26 \times 14 \text{arcsec}^2 map, which was used for obtaining spectral index with our 333-MHz observations. The 1452-MHz data set had the shortest baseline of \sim 150\lambda, which is sensitive to a maximum angular size of \sim 14 arcmin. The uv-coverage is sparse for structures above \sim 10 arcmin. NGC 5236 is about 11 arcmin in size and hence there may be a small amount of missing flux density in this observation.

NGC 6946 is a large spiral galaxy with multiple arms. The galaxy has well-separated arm and inter-arm regions and has been the subject of several studies in the radio continuum. There are several star-forming regions in the galaxy and one of them shows the first likely detection of ‘anomalous’ dust emission, due to spinning dust, outside of the Milky Way (Murphy et al. 2010). Observations at 610 MHz, 1415 MHz and 5 GHz by van der Kruit et al. (1977) revealed a bright radio disk of non-thermal origin. Klein et al. (1982), based on observations at 10.7 GHz, estimated a thermal fraction of 19 \pm 10 per cent. The spectral index study by Beck (2007) between 1465 MHz and 8.5 GHz clearly shows a flatter spectral index of \sim 0.5 in the arms, which steepens to about \sim 1 in the inter-arm regions.

Table 2. Observational summary of 333-MHz observations of our sample galaxies. Time spent on the source excludes calibration overheads. Column 5 gives the synthesized beam achieved and column 6 gives the map rms (\sigma_{\text{map}}). Column 7 gives the integrated flux of the source inside the 4\sigma_{\text{map}} contour.

| Name         | Obs. date | Time on source (hr) | Calibrators used | Synthesized beam (arcsec\(^2\)) | \sigma_{\text{map}} (\mu Jy beam\(^{-1}\)) | Integrated flux (Jy) |
|--------------|-----------|---------------------|------------------|----------------------------------|---------------------------------------------|-----------------------|
| NGC 1097     | 29-Oct-09 | 6                   | Flux cal: 3C 48, 3C 286 | 16 \times 11                     | 300  \pm 0.14                              | 2.0  \pm 0.14          |
| NGC 3034 (M82)| 31-Oct-09 | 4.5                 | Phase cal: 0116–208, 0409–179 | 22 \times 15                     | 3000 \pm 1                                        | 14  \pm 1               |
| NGC 4736 (M94)| 04-Jul-09 | 7                   | Flux cal: 3C 48, 3C 286 | 13 \times 12                     | 250  \pm 0.06                                | 0.9  \pm 0.06           |
| NGC 5055 (M63)| 02-Nov-09 | 3                   | Phase cal: 3C 286, 3C 286 | 17 \times 10                     | 240  \pm 0.2                                   | 2.3  \pm 0.2            |
| NGC 5236 (M83)| 31-Oct-09 | 5                   | Flux cal: 3C 286, 3C 286 | 16 \times 12                     | 500  \pm 0.5                                  | 7.4  \pm 0.5            |
| NGC 6946     | 29-Jul-09 | 6.5                 | Phase cal: 1459+716, 2350+646 | 12 \times 11                     | 300  \pm 0.24                                | 4.3  \pm 0.24           |

For obtaining the spectral index with 333 MHz, we used an archival 15 \times 15 arcsec\(^2\) VLA map at 1465 MHz. The VLA map was made by combining interferometric data from C (Beck 2007) and D configurations (Beck 1991). Beck (2007) noted the integrated flux density from the VLA map and single-dish Effelsberg measurement had similar values, and there was no indication of missing large angular scale structures.

We emphasize that the GMRT 333-MHz images of the galaxies do not suffer from missing flux density, while some of the higher frequency maps (especially NGC 1097 and NGC 5055) may have missing flux density from large angular-size structures. Thus, the true spectral index, particularly in the outer parts of the galaxies, is flatter than that determined in this study.

3 OBSERVATIONS AND ANALYSIS

We conducted interferometric observations at 333 MHz for the six galaxies in our sample with the GMRT located near Pune, India (Swarup et al. 1991). Data with 16-MHz bandwidth (corresponding to \nu_{\text{RF}} of 325–341 MHz, and a centre \nu_{\text{RF}} of 333 MHz), divided into 128 channels, were recorded following the usual protocol of observing flux and phase calibrator interlaced with observation on the source. At the beginning and end of the observing run, one of the flux calibrators 3C 48, 3C 286 or 3C 147 was observed for about 10–20 min. Phase calibrators were observed every \sim 30–35 min for \sim 4–5 min. Calibrators chosen for each of the observed sources are listed in Table 2.

Data reduction was done using the Astronomical Image Processing System (AIPS) following standard procedure. After editing the data for strong radio frequency interference (RFI), standard flux and phase calibration were applied to the source. The Baars et al. (1977) absolute flux density scale was used to determine flux densities of the flux calibrators and then were applied to the phase calibrator and the source.
The task 'FLGIT' was used to remove low-level RFI at the 4–6σ level across the frequency channels. Even lower level RFI was subsequentely removed using the tasks 'TVFLG', 'WIPER' and/or 'SPELGL'. The procedure was iteratively done by obtaining the gain solutions after every RFI removal stage. The final gain solution that was applied to the target source when the closure errors were less than 1 per cent on the phase calibrators.

The calibrated data were then used to obtain the deconvolved images using the task 'IMAGR'. Prior to this, the data were condensed in frequency by vector averaging six adjacent channels of 125 kHz each (resulting in channel width of 750 kHz) using the task 'SPLAT'. This ensured that bandwidth smearing was less than the size of one synthesized beam at 333 MHz. To account for wide-field imaging with non-coplanar baselines, polyhedron imaging was used in IMAGR (Cornwell & Perley 1992), where the field of view is subdivided into a number of smaller fields (facets). For our purpose, we used 7 × 7 = 49 facets covering the primary beam up to the half-power beamwidth (HPBW, ~1.5°). Strong sources outside the HPBW, if present, were included in additional facets.

Several rounds of phase-only self-calibration were performed iteratively, by choosing point sources such that the flux density within one synthesized beam is more than 8σ. Any stripe present in the map due to bad data were removed using a Fourier-transform method. In the last iteration, one round of amplitude and phase self-calibration was carried out. Final maps were made from the full UV-coverage and the UV-data were weighted using Briggs robust weighting of 0 (Briggs 1995). To clean the extended diffuse emission from the galaxies, we used the SDI CLEAN algorithm (Steer, Dewdney & Ito 1984). The final full-resolution images obtained are shown in Fig. 2 and their corresponding synthesized beams are listed in column 6 of Table 2.

The integrated flux density of all the six galaxies was obtained by integrating within the 4σmap (where σmap is the map noise) contour and is given in Table 2. We compared the flux density obtained for each of our sample galaxies with measurements performed at other radio frequencies by other researchers, as given in Table 3. Fig. 4 shows the integrated broad-band spectrum for our sample galaxies. Our flux density measurements are in good agreement with the interpolated flux densities from higher and lower radio frequency observations reported in earlier studies.

The uncertainties in the estimated flux density (Ssource) depend on the rms noise in the map as well as on errors associated with uncalibrated system temperature (Tsys) variations, which is about 5 per cent (Roy & Rao 2004) at 333 MHz for the GMRT. The flux density error (δSsource) can be calculated as

\[ \delta S_{\text{source}} = \sqrt{\left(\frac{\delta T_{\text{sys}}}{T_{\text{sys}}} \times S_{\text{source}}\right)^2 + \sigma_{\text{map}}^2}. \]

The flux density also has a systematic error of about 8 per cent associated with the absolute flux scale error at 333 MHz.

4 NON-THERMAL SPECTRAL INDEX (αnt)

The non-thermal spectral index αnt is the main parameter of interest because it is used to model CR electron generation and propagation. However, it is not possible to measure it directly. The quantity which is measured is the total spectral index α, which is contaminated by thermal free–free emission. This contamination is significant for spatially resolved regions of the galaxy where the thermal fraction6 (henceforth fth) is high. In this section, we assess the effect of fth on αnt obtained between 333 MHz and near 1.4 GHz in spatially resolved regions of the galaxy. To achieve this, we use the method of thermal–non-thermal separation developed by Tabatabaei et al. (2007) and apply it to five of our galaxies (except NGC 3034). The method uses dust extinction-corrected Hz maps to obtain a template for the free–free emission across the galaxy and extrapolates it to the desired radio frequency to obtain spatially resolved thermal radio emission maps. The extinction correction is achieved by estimating dust temperature and optical depth using the far-infrared maps at λ70 and λ160 μm (see Appendix A for details). The far-infrared λ160-μm map has an angular resolution of 40 × 40 arcsec2, and hence the final non-thermal spectral index maps have this angular resolution, which is significantly coarser than the total spectral index (hereafter α) maps. The usefulness of this method lies in the fact that it can be used in spatially resolved parts of the galaxy. Furthermore, Tabatabaei et al. (2007) demonstrate the robustness of their method over several other existing thermal–non-thermal separation techniques (see references therein and Gioia, Gregorini & Klein 1982; Hummel & Bosma 1982; Broadbent, Osborne & Haslam 1989).

The mean fth for all our sample galaxies was found to be less than 5 per cent at 333 MHz, although the value can go up to 10 per cent in some specific bright H II regions and in the spiral arms. Applying the same method to the available higher frequency data at or close to 1.4 GHz, we found the mean fth to be less than 12 per cent. The distribution of fth at 333 MHz and near 1.4 GHz for five galaxies is shown in Fig. A1.

The non-thermal 333-MHz and higher frequency maps were further used to obtain αnt variation for the five galaxies. The left-hand panels of Fig. 4 show the α maps and the right-hand panels show the αnt maps. Fig. 5 shows the variation of α and αnt with radius for the galaxies. Here, the spectral index was estimated by azimuthally averaging over annuli of one beamwidth. The radial profiles clearly reveal that the non-thermal spectral index is nominally steeper than the uncorrected values, and further steepens towards the outer parts of the galaxy. However, we note that towards the outer parts of the galaxies, the steepening of both the total and non-thermal spectral indices may be caused due to ‘missing flux density’ problems.

We are now in a position to quantify the importance of thermal–non-thermal separation, for robust estimates of αnt between 333 MHz and near 1 GHz. The uncertainty in αnt can be estimated by propagating the various sources of errors in obtaining the non-thermal maps. Three primary sources of error affect the αnt measurement, namely the rms in the two radio maps (σv,map), the error associated with the uncalibrated system temperature of the instrument σv,Tsys, and the error in thermal fraction, σT. Note that σv,Tsys is about 5 per cent at 333 MHz for the GMRT and assumed to be about 2 per cent for VLA and WSRT near or at 1.4-GHz maps. Tabatabaei et al. (2007) estimated the error σT to be about 10 per cent at these frequencies (also see Appendix A). Incorporating these errors, we have computed the ratio α/αnt in regions by dividing the galaxy into rectangular grids of size of approximately 40 arcsec.

6 Thermal fraction is defined as fth = Sν,th/Sν,Br, where Sν,th is the flux density of the thermal emission. In the text, we express fth as percentages.

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Figure 2. The contour maps show GMRT 333-MHz observations of the sample galaxies which are overlaid on the optical Digitized Sky Survey (DSS) image in grey-scale. The contour levels start from $4\sigma$, increasing in multiples of $\sqrt{2}$. The grey contours show $(-2, -3, -4) \times \sigma$.

1.4 GHz. Within the error bars the ratio is consistent with unity for thermal fraction less than 10 per cent. For higher thermal fraction (predominantly in the arms or H II regions) the ratio drops below unity, and to obtain $\alpha_{nt}$, correction to $\alpha$ could be as high as 20 per cent. The thermal–non-thermal separation is even more important for $\alpha_{nt}$ calculated between higher frequency pairs like 1.4 and 4.8 GHz. The ratio $\alpha/\alpha_{nt}$ for NGC 6946 obtained between 1465 and 4860 MHz (using the archival map downloaded from the NED;
Table 3. Multi-frequency integrated flux density for our sample galaxies.

| Source  | Frequency (GHz) | Flux density (Jy) | Reference |
|---------|----------------|------------------|-----------|
| NGC 1097 | 0.333          | 2.1 ± 0.14       | This paper |
|         | 1.365          | 0.350 ± 0.025    | 1         |
|         | 1.465          | 0.42 ± 0.02      | VLA CD array |
|         | 1.665          | 0.262 ± 0.030    | 1         |
|         | 4.850          | 0.142 ± 0.012    | 1         |
|         | 8.450          | 0.094 ± 0.018    | 1         |
| NGC 3034 | 0.038          | 23 ± 3           | 2         |
|         | 0.178          | 14.6 ± 0.7       | 2         |
|         | 0.333          | 14 ± 1           | This paper |
|         | 0.750          | 10.7 ± 0.5       | 2         |
|         | 1.415          | 8.0 ± 0.4        | 3         |
|         | 2.695          | 5.7 ± 0.3        | 2         |
|         | 5.0            | 3.9 ± 0.2        | 2         |
|         | 10.7           | 2.25 ± 0.06      | 4         |
|         | 14.7           | 1.79 ± 0.04      | 4         |
| NGC 4736 | 0.333          | 9.0 ± 0.06       | This paper |
|         | 0.408          | 0.539±--         | 5         |
|         | 0.610          | 0.435±0.026      | 7         |
|         | 1.365          | 0.320±0.01       | 6         |
|         | 1.415          | 0.276±0.02       | 7         |
|         | 4.995          | 0.111±0.01       | 7         |
|         | 10.7           | 0.096±0.018      | 8         |
|         | 15             | 0.017±--         | 9         |
| NGC 5055 | 0.333          | 2.3 ± 0.13       | This paper |
|         | 0.408          | 1.16 ± 0.022     | 5         |
|         | 0.610          | 0.83 ± 0.04      | 10        |
|         | 0.750          | 0.88 ± --        | 11        |
|         | 1.417          | 0.409±0.02       | 10        |
|         | 1.696          | 0.285±0.02       | WSRT      |
|         | 2.295          | 0.26±0.02        | 12        |
|         | 3.7            | 0.254±--         | 13        |
|         | 10.7           | 0.117±0.026      | 14        |
| NGC 5236 | 0.327          | 6.86±0.62        | 15        |
|         | 0.333          | 7.3±0.4          | This paper |
|         | 1.452          | 2.3±0.15         | VLA CD array |
|         | 1.465          | 2.2±0.11         | 15        |
|         | 2.7            | 1.24±--          | 16        |
|         | 4.75           | 0.97±0.13        | 15        |
| NGC 6946 | 0.158          | 7.54±1.40        | 17        |
|         | 0.178          | 5.88±0.44        | 18        |
|         | 0.333          | 4.6±0.24         | This paper |
|         | 0.408          | 3.95             | 5         |
|         | 0.601          | 2.34             | 19        |
|         | 1.415          | 1.54±0.10        | 19        |
|         | 1.465          | 1.41±0.08        | VLA C+D array |
|         | 2.695          | 0.83±0.03        | 20        |
|         | 4.86           | 0.54±0.05        | VLA+Effelsberg |
|         | 8.50           | 0.45±0.05        | 21        |
|         | 10.70          | 0.359±0.042      | 8         |

1. Beck et al. (2002); 2. Kellerman, Pauliny-Toth & Williams (1969); 3. Hummel (1980); 4. Klein, Wiebelius & Morsi (1988); 5. Gioia & Gregorini (1980); 6. Braun et al. (2007); 7. de Bruyn (1977); 8. Klein & Emerson (1981); 9. Nagar, Falcke & Wilson (2005); 10. Hummel & Bosma (1982); 11. de Jong (1966); 12. Arp (1973); 13. Kuril’chik, Onishchenko & Turyvskii (1967); 14. Klein & Emerson (1981); 15. Sukumar et al. (1987); 16. Wright et al. (1990); 17. Brown & Hazard (1961); 18. Caswell & Wills (1967); 19. van der Kruit et al. (1977); 20. de Jong (1967); 21. Kuril’chik et al. (1970).

Beck 2007) is plotted in red in Fig. 6, where we clearly see that the ratio is significantly below unity for the entire range of thermal fractions. Note that since there is also a systematic uncertainty associated with the absolute calibration scale for calibrating radio flux densities, the absolute value of the spectral index can vary by about 10 per cent.

5 DISCUSSION ON INDIVIDUAL GALAXIES

NGC 1097. Our 333-MHz map (see Fig. 2) has an angular resolution of $16 \times 11$ arcsec$^2$, which corresponds to a spatial resolution of $\sim 1.1$ kpc, if the galaxy is at a distance of 14 Mpc. The only other low-frequency radio continuum study of this galaxy was done by Ondrechen & van der Hulst (1983) and Ondrechen, van der Hulst & Hummel (1989) at 1465 MHz. They reported strong radio emission coincident with the nuclear region, and, as expected, prominent shock fronts are visible on the leading side of the bar with respect to the sense of rotation. The $f_n$ in the bar region at 333 MHz is estimated to be $< 1$ per cent; hence, the radio emission at this frequency is entirely non-thermal in origin. These observations fit well with the explanation that the radio emission from the bar results due to shock compression of gas, dust and magnetic field, as concluded by Ondrechen & van der Hulst (1983). The total emission from the bar and the central component (the region shown in Fig. 7) is $835 \pm 57$ mJy, out of which $750 \pm 52$ mJy arises from the central compact region ($25 \times 21$ arcsec$^2$). For a similar-size central region, Ondrechen & van der Hulst (1983) quote a flux density of 260 mJy at 1465 MHz, based on which we obtain an $\alpha$ of $\sim 0.75$. The $\alpha_n$ is $-0.85 \pm 0.1$ within a 40–arcsec region based on our analysis. Close to the nuclear region, this $\alpha_n$ is steeper when compared with other galaxies in our sample. This indicates the possibility of radiative cooling by inverse Compton/synchrotron processes.

The south-eastern (SE) side of the bar has a flux density of 50 ± 4 mJy and the north-western (NW) side has a flux density of 30 ± 2 mJy, measured within the 2 mJy closed contours. The red lines in Fig. 7 show the SE and NW bars. In the optical, the bar region continues into two prominent arms; however, the radio emission is highly diffuse. We find the thermal fraction of the inter-arm region at 333 and 1465 MHz to be 0.2 and 2.5 per cent, respectively, whereas in the spiral arm regions it is 1 and 4.5 per cent, respectively. In the arm regions, $(\alpha_n)$ is $-1.4 \pm 0.09$, while it becomes significantly steeper ($-1.8 \pm 0.12$) in the inter-arm regions, which may be caused due to missing flux density problems. The radial profile of $\alpha$ and $\alpha_n$ in Fig. 5 becomes steeper towards the outer parts of the galaxy, possibly due to missing flux density. We emphasize that the overall thermal fraction in this galaxy is very low, with $(f_n)$ of $\sim 0.6$ per cent at 333 MHz and $\sim 4.8$ per cent at 1465 MHz (see Fig. A1).

At 333 MHz, we detect the radio galaxy discovered by Beck et al. (2005), located $\sim 90$ arcsec from the nucleus of NGC 1097 towards the south-west at a position angle of $-110^\circ$ (see Fig. 7). The radio galaxy has a total flux density of 9.5 ± 0.5 mJy, with 4.8 ± 0.25 mJy in the northern component [RA = 02h46m12s7 and Dec. = $-30^\circ17^\prime01^\prime$ (J2000)] and 3.8 ± 0.2 mJy in the southern component [RA = 02h46m12s5 and Dec. = $-30^\circ17^\prime26^\prime6$ (J2000)].

NGC 3034 (M82). The 333-MHz map (see Fig. 2) of this galaxy has an angular resolution of $22 \times 15$ arcsec$^2$, corresponding to a spatial resolution of about 0.5 kpc for a distance of 3.9 Mpc. We find the integrated flux density at 333 MHz to be 14 Jy, which is consistent
Figure 3. Integrated flux density as a function of frequency. The black circles represent the integrated flux densities without the thermal–non-thermal emission separation (see Table 3), while the red triangles represent the non-thermal flux densities of the galaxies. The blue square for NGC 5055 is the flux density measured within $6.7 \times 3.2$ arcmin$^2$ (see Section 4).

with flux densities measured at other frequencies. The rms of the image, which is $3 \text{ mJy beam}^{-1}$, is dynamic range limited since the peak flux density in the galaxy is $3 \text{ Jy beam}^{-1}$. Morphologically, the galaxy is featureless at our resolution, although the northern extension (RA = 09$^h$55$^m$56$^s$ and Dec. = +69$^\circ$41$'$48$''$) is coincident with the base of the H$\alpha$/optical horn (see Fig. 2), which is likely due to synchrotron emitting particles convected outwards by the nuclear wind, tracing the H$\alpha$ horns. The galaxy was observed between 330 and 4835 MHz by Seaquist & Odegard (1991), and a similar horn was seen at $\sim 1515$ MHz. Their study also revealed a non-thermal radio halo surrounding the galaxy; however, our observations do not show this due to dynamic range limitations.

For this galaxy, the thermal–non-thermal separation was not possible, but we have computed the $\alpha$ map and radial profile as shown in Figs 4 and 5. The 333-MHz GMRT map was convolved to the resolution of the VLA map at 60 arcsec. This is a good approximation for $\alpha_{nt}$ index variation across the galaxy since the thermal fraction of this galaxy has been estimated to be 15 per cent at 32 GHz (Klein et al. 1988), corresponding to $\sim 3$ and 2 per cent at 1.4 GHz and 333 MHz, respectively. The spectral index is seen to be very flat with $\alpha = -0.35 \pm 0.03$ towards the centre and steepens to $-1 \pm 0.2$ at a distance of $\sim 2$ kpc from the centre. Similar radial variation of the spectral index was also reported by Seaquist & Odegard (1991).

**NGC 4736 (M94).** The 333-MHz map (see Fig. 2) of this galaxy has an angular resolution of $13 \times 12$ arcsec$^2$, corresponding to a spatial scale of about 0.3 kpc for a distance of 4.7 Mpc. The other low-frequency study of this galaxy exists at 610 MHz (de Bruyn 1977), observed with a much lower angular resolution of $56 \times 85$ arcsec$^2$. At our angular resolution, we clearly detect emission from the inner star-forming circumnuclear ring of the galaxy as shown in Fig. 8 overlaid on the H$\alpha$ map. The ring is located at about 50 arcsec (major axis), corresponding to 1.1 kpc, from the centre, and is $\sim 19$ arcsec (420 pc) wide (up to the half-power) having a flux density of $240 \pm 13$ mJy. The estimated thermal fraction of the ring at 333 and 1374.5 MHz is $5 \pm 1$ and $10 \pm 4$ per cent, respectively, and hence the ring at 333 MHz is largely non-thermal in origin. The ring is seen to be coincident with the H$\alpha$ ring, which is shown in Fig. 8 after convolving to the same radio resolution.
Figure 4. Left column: the total spectral index ($\alpha$) maps between GMRT 333 MHz and near 1 GHz. The top row shows NGC 1097, middle row shows NGC 3034 and the bottom row shows NGC 4736. The $\alpha$ maps for NGC 1097, NGC 3034 and NGC 4736 have a resolution of 40 $\times$ 40 arcsec$^2$, 60 $\times$ 60 arcsec$^2$ and 20 $\times$ 20 arcsec$^2$, respectively. Right column: the non-thermal spectral index ($\alpha_{nt}$) between 333 MHz and near 1 GHz at a resolution of 40 arcsec. Overlaid are the 333-MHz contours. Contour levels are indicated below each figure.
GMRT 333-MHz observations

Figure 4. – continued Left column: the total spectral index ($\alpha$) maps between GMRT 333 MHz and near 1 GHz. The top row shows NGC 5055, middle row shows NGC 5236 and the bottom row shows NGC 6946. The $\alpha$ maps for NGC 5055, NGC 5236 and NGC 6946 have a resolution of 20 × 20 arcsec$^2$, 26 × 14 arcsec$^2$ and 15 × 15 arcsec$^2$, respectively. Right column: the non-thermal spectral index ($\alpha_{nt}$) between 333 MHz and near 1 GHz at a resolution of 40 arcsec. Overlaid are the 333 MHz contours. Contour levels are indicated below each figure.
Figure 5. Azimuthally averaged spectral index determined within annuli of one beamwidth. The black circles are the total spectral index ($\alpha$), while the red triangles are the non-thermal spectral index ($\alpha_{nt}$). The top x-axis shows the angular distance from the centre in arcmin. For NGC 3034, the averaging was done for half the synthesized beam and therefore adjacent points are not independent.

Figure 6. The bottom panel of the plot shows the ratio $\alpha/\alpha_{nt}$ as a function of $f_{\text{th}}$ at 1465 MHz for NGC 6946 obtained at spatially resolved regions of the galaxy. The black circles correspond to $\alpha/\alpha_{nt}$ between 333 and 1465 MHz, while the red triangles show $\alpha/\alpha_{nt}$ between 1465 and 4860 MHz. The top panel shows the flux density normalized to the peak value at 333 MHz (in black) and 1465 MHz (in red), respectively. Note that generally higher flux density regions have high thermal fractions.

Radio emission from the ring is also seen in the higher frequency 8.46-GHz observations made by Chyży & Buta (2008); however, at these frequencies the emission is a mixture of thermal and non-thermal components. The ring has a relatively high thermal fraction which leads to a noticeable change in the spectral index (see Fig. 5): $\langle \alpha \rangle = -0.45 \pm 0.02$, while $\langle \alpha_{nt} \rangle = -0.6 \pm 0.1$. The ring has massive ongoing star formation (Smith et al. 1991) and the $\alpha_{nt}$ value indicates that both CRe generation and escape happen on time-scales shorter than the radiative time-scale. The compact nucleus lies within the central 0.5 kpc (25 $\times$ 22 arcsec$^2$) with an integrated flux density of 110 $\pm$ 6 mJy and a peak flux of 45 mJy beam$^{-1}$ and $\alpha_{nt} = -0.6 \pm 0.05$. Outside the ring extending to the edge of the galaxy, there is no thermal emission observed leading to $\alpha_{nt} \sim \alpha$.

NGC 5055 (M63). The 333-MHz observation (see Fig. 2) has an angular resolution of 17 $\times$ 10 arcsec$^2$ corresponding to a spatial...
The star-forming inner circumnuclear ring in NGC 4736. The contours are the high-resolution 333-MHz GMRT map with a synthesized beam of 10.8 × 9.9 arcsec² and the grey-scale shows the Hα image (in erg s⁻¹ cm⁻²) from the Jacobi Kapteyn Telescope with the 6570-Å filter (Knapik et al. 2004), smoothed to the same resolution as the 333-MHz map. The lowest contour is at 3 mJy, increasing in steps of 1 mJy.

Note that Hummel & Bosma (1982) using observations at 610 and 1410 MHz at the much lower angular resolution of 58 × 87 arcsec², the galaxy appears featureless, which is also the case in our higher resolution 333-MHz map. However, 10.55-GHz polarization observations by Knapik et al. (2000) show a regular spiral structure. The overall radio emission at 333 MHz at a level of 4σ is ~8.6 × 5.3 arcmin² in extent, which has an integrated flux density of 2.3 ± 0.13 Jy. This value is higher than that would be obtained using a spectral index of −0.78 estimated between 610 and 1417 MHz (Hummel & Bosma 1982). The reason for this is that Hummel & Bosma (1982) estimate the integrated flux density within a region 6.7 × 3.2 arcmin² at 610 MHz, which is smaller than our detected size at 333 MHz. However, if a region of similar size is considered, we obtain a flux density of 1.4 ± 0.1 Jy, which is consistent with a spectral index of −0.78 as seen in Fig. 3(d). NGC 5055 is highly inclined, with inclination angle, i = 59°, and the extended low-frequency radio emission can result due to escape of low-energy (<2 GeV) CRe from the disc which travels larger distances (~4.5 kpc) into the galactic halo.

The mean thermal fraction (f_θn) at 1696 MHz (λ = 18 cm) and 333 MHz is 12 and 1.3 per cent, respectively. The α_π in the central region is ~−1, which steepens to −1.7 towards the outer parts of the galaxy⁷ (see Fig. 5). This result supports the conclusion drawn by Hummel & Bosma (1982) that the spectral index steepening is mainly due to energy losses of CRe and decrease in number of relativistic electrons with increasing galactic radius.

NGC 5236 (M83). The 333-MHz observation (see Fig. 2) has an angular resolution of 16 × 12 arcsec², which corresponds to a linear scale of about 0.4 kpc at a distance of 4.2 Mpc. An early study of this galaxy by Sukumar et al. (1987) at 327 MHz using the Ooty Synthesis Radio Telescope (OSRT) quotes an integrated flux density of 6.86 ± 0.62 Jy at a resolution of 53 × 33 arcsec², while our GMRT observations have a slightly higher integrated flux density of 7.4 ± 0.4 Jy.

Ondrechen (1985) has reported several point sources in this galaxy. To verify the presence of these sources at 333 MHz, we made a high-resolution image of 13 × 10 arcsec² as shown in Fig. 9. Comparing this with Ondrechen (1985), we detect the central bar (shown in red lines) and the H II regions named as A, F, H and L, and non-thermal polarized point sources D, G and X. Note that source G is identified as a background galaxy by Maddox et al. (2006). The region E was identified as a shocked region in the arm and has a flux density of 33 ± 2 mJy, while the point source Q is an H II region and has a flux density of 5 mJy beam⁻¹. However, we were unable to detect point sources B and C. The flux densities of the point sources are given in Fig. 9. In addition to this, we see an extended radio arm which runs along the faint narrow dust lane visible in the infrared λ70-μm map.

The galaxy has a low mean thermal fraction of about 3 per cent at 333 MHz and about 7 per cent at 1452 MHz, and hence α_π ~ α as seen in the radial spectral index profile of the galaxy in Fig. 5. In the arms, at 333 MHz, the thermal fraction is estimated to be 8—10 per cent, where α ranges from −0.3 ± 0.04 to −0.5 ± 0.05, which gets modified to α_π as −0.4 ± 0.05 to −0.65 ± 0.05. Note that α_π along the arms is seen to change significantly from −0.4 within the central 3 kpc to −0.65 beyond 3 kpc. Thermal fraction at 333 MHz in the inter-arm regions is 1—4 per cent and beyond the central 4.5 kpc it is less than 1 per cent, indicating purely non-thermal emission. In the inter-arm regions, α_π values lie in the range of −0.7 ± 0.06 to −1.2 ± 0.09.

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⁷ Note that Hummel & Bosma (1982) using observations at 610 and 1417 MHz quote a spectral index variation of −0.6 to −1 between the central and outer parts of the galaxy, while we find much steeper values. The WSRT 1696-MHz map has a flux density of 284 mJy within the same region of 6.7 × 3.2 arcmin², which when extrapolated using a spectral index of −0.78 has a much lower value (see Fig. 3d). This may be due to missing flux density issues as discussed in Section 2. Thus, the true spectral index should be flatter than that observed by us.
NGC 6946. The 333-MHz observation (see Fig. 2) has an angular resolution of $12 \times 11$ arcsec$^2$ which corresponds to a spatial resolution of 0.4 kpc at a galaxy distance of 6.8 Mpc. The integrated flux density at 333 MHz is 4.5 $\pm$ 0.24 Jy. Using our 333-MHz and archival 1465-MHz VLA maps, we estimate the mean thermal fraction to be about 4.3 and 11 per cent, respectively.

Spectral index study by Klein et al. (1982) between 610 MHz and 10.7 GHz showed variation in spectral index from about $-0.55$ near the centre to about $-0.9$ towards the edge. The spectral index between the GMRT 333-MHz map and the VLA 1465-MHz map shows a similar trend, with a spectral index of $-0.45$ at the centre and $-1$ towards the edge. Recently, Beck (2007) studied the spectral index between 4860 and 1465 MHz, which showed a flatter spectral index in the arm than the inter-arm due to higher thermal fraction. In our studies, thermal fraction is higher in the arm (5–10 per cent) than in the inter-arm (1–5 per cent). In the arm, $\alpha$ lies in the range of $-0.55$ to $-0.65$, while $\alpha_{\text{nt}}$ is steeper $-0.7$ to $-0.85$. In the inter-arm regions the average spectral index is steeper with $\langle \alpha \rangle = -0.9 \pm 0.06$, while $\alpha_{\text{nt}}$ does not change significantly, $\langle \alpha_{\text{nt}} \rangle = -0.95 \pm 0.11$.

The 333-MHz map prominently shows the giant H$\alpha$ regions identified by van der Kruit et al. (1977). The H$\alpha$ region at RA = 20$^h$35$^m$06$^s$ and Dec. = $+60^\circ$10'56" (J2000) (region C in van der Kruit et al. 1977) is about 35 arcsec (1.2 kpc) in size, and can be seen in the 40 arcsec low-resolution non-thermal maps. This region is a suitable candidate to investigate the CRe injection near high star-forming sites. We find the thermal fraction to be 10 $\pm$ 3 per cent at 333 MHz and 15 $\pm$ 4 per cent at 1465 MHz. The $\alpha_{\text{nt}}$ in this region is $-0.6 \pm 0.08$, whereas before the separation the spectral index is $-0.4 \pm 0.05$.

The central 35-arcsec region [at RA = 20$^h$34$^m$52$^s$ and Dec. = $+60^\circ$09'14" (J2000)] has a flux density of 226 $\pm$ 13 mJy at 333 MHz, while at 1465 MHz the same region has a flux density of 117 $\pm$ 6 mJy. This corresponds to an $\alpha$ of $-0.44 \pm 0.05$ at a resolution of 15 $\times$ 15 arcsec$^2$. However, after the separation, a similar region has an $\alpha_{\text{nt}}$ of $-0.54 \pm 0.1$ (see Fig. 4). In the nuclear region, about 15 per cent of the total emission is due to thermal emission at 333 MHz, higher than the rest of the galaxy, where the thermal emission lies within 10 per cent.

6 SUMMARY

The 333-MHz GMRT observations of six nearby galaxies (greater than 10 arcmin in size) presented in this paper are by far the highest angular resolution maps for these galaxies at this frequency, which are sensitive to both small ($\lesssim$0.5 kpc) and large ($\gtrsim$10 kpc) scale structures. The hybrid array of the GMRT enables us to recover emission from both the diffuse and small-scale emission in these sources, which we have adequately verified by comparing our estimated integrated flux densities with those available in the literature. Our observations have comparable resolution as that attained at higher frequencies, and probe linear scales of about 0.4–1 kpc.

At 333 MHz, the galaxies appear smoother than at higher frequencies, where spiral arms are often discernible. The thermal emission (which is primarily associated with ionized structures observed in H$\alpha$ maps) for all the galaxies was found to be less than 5 per cent of the total emission, and hence at these frequencies, the emission is essentially non-thermal. The smooth appearance is consistent with the conjecture that non-thermal emission at 333 MHz primarily results from a population of old (>10$^7$ yr) CRe, which diffuses away from their formation sites filling up a volume of radius $\gtrsim$1 kpc, without losing much energy. This scale is larger than the width of the gaseous spiral arms and comparable to the width of the inter-arm region (see e.g. Condon 1992), hence reducing any contrast in intensity across the galaxy. The prominent radio structures observed at higher frequencies (>1 GHz) are visible solely due to the increased thermal fraction.

We have determined robust estimates of spatially resolved $\alpha_{\text{nt}}$ (see Section 3) for five galaxies in our sample, with a resolution of 40 arcsec, corresponding to a linear scale of 1–3 kpc, which also corresponds to the diffusion scale of the CRe. The observed $\alpha_{\text{nt}}$ ranges from $-0.3$ to $-1.8$ in various regions of the galaxies. Generally CRe are thought to be accelerated at SNR where both the theoretical prediction (Bell 1978) and observation based on Galactic SNR suggest mean $\alpha_{\text{nt}} \sim -0.5$ (Green 2009; Kothes et al. 2006). The SNR are short-lived ($\sim 10^3$ yr), while the CRe diffuse away from their acceleration sites, losing their energy through several physical mechanisms for typically $10^3$ yr, and hence their initial energy spectrum gets distorted, leading to a change in $\alpha_{\text{nt}}$. If the energy losses are due to ionization, $\alpha_{\text{nt}}$ flattens (Longair 2011). Synchrotron radiation and inverse Compton scattering loss leads to a steepening of the spectra, while adiabatic cooling and bremsstrahlung keep the spectra unchanged. To assess the behaviour of $\alpha_{\text{nt}}$ in spatially resolved parts of the galaxy, we plot the $\alpha_{\text{nt}}$ distribution (as shown in Fig. 10) for two regimes of thermal fraction: $f_{\text{th}}^{1.4\text{GHz}} > 10$ per cent (filled grey histogram) and $f_{\text{th}}^{1.4\text{GHz}} < 10$ per cent (unfilled histogram), using data from four galaxies.8 To do this, we have computed $\alpha_{\text{nt}}$ by dividing the galaxy in rectangular grids of 40 arcsec. The histograms are binned with step size 0.05 in $\alpha_{\text{nt}}$. The high thermal fraction corresponds to bright regions in H$\alpha$ which traces gas ionized by massive OB stars in star-forming regions. These regions host the CRe generation and acceleration sites. The distribution of $\alpha_{\text{nt}}$ for such high thermal fraction regions has a Gaussian shape, with mean $\alpha_{\text{nt}} \sim -0.78$ and narrow spread of 0.16. It is interesting that this narrow distribution arises from multiple spatially resolved regions from an assorted set of galaxies with very different star formation histories. This is clearly indicative of a generic process of energy loss of CRe by synchrotron radiation and inverse Compton scattering as they propagate from their acceleration sites. The flatter

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8 We did not use NGC 5055, since we think that there is a missing flux density problem at 1690 MHz and hence the derived $\alpha$ and $\alpha_{\text{nt}}$ might be steeper than the actual value.
part of \( \alpha_{\text{int}} \) (\( \sim -0.55 \)) primarily arises from NGC 5236, indicating that ionization losses are dominant (Longair 2011). Niklas et al. (1997), based on the integrated flux density of 74 galaxies, found the average \( \alpha_{\text{int}} \sim -0.83 \), which is comparable to the \( \alpha_{\text{int}} \) value that we have obtained. The galaxy’s integrated spectral index is an average over tens of kpc where the flux density is highly dominated by bright regions which are mostly spiral arms or H II regions. A number of earlier studies have noted that the average \( \alpha_{\text{int}} \) obtained using VLA observations at 325 MHz and near 1.4 GHz is flatter for infrared bright regions. This is similar to that we observed in a region of 40 arcsec, which for all these galaxies corresponds to \( \sim 1-3 \) kpc, and hence the flatter part of the \( \alpha_{\text{int}} \) distribution may be affected due to bright regions. As mentioned earlier, the absolute value of \( \alpha_{\text{int}} \) can change by \( \sim 10 \) per cent due to uncertainty in the flux scale at 333 MHz. A recent study by Paladino et al. (2009) for NGC 628, NGC 3627 and NGC 7331, using infrared emission (\( \lambda > 1 \) \mu m) as a tracer of star-forming regions, found that \( \alpha_{\text{int}} \) obtained using VLA observations at 325 MHz and near 1.4 GHz is flatter for infrared bright regions. This is similar to that we observe in our set of galaxies. The high angular resolution 333-MHz observations presented in this paper can be used to study in detail the spatially resolved far-infrared–radio and CO–far-infrared correlations, which will be reported in a future paper.

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REFERENCES

Arp H., 1973, ApJ, 183, 791
Baars J. W. M., Genzel R., Pauliny-Toth I. I. K., Wintzel A., 1977, A&A, 61, 99
Beck R., 1991, A&A, 251, 15
Beck R., 2007, A&A, 470, 539
Beck R., Grave R., 1982, A&A, 105, 192
Beck R., Shoutenkov V., Ehle E., Harnett J. I., Haynes R. F., Shukurov A., Sokoloff D. D., Thierbach M., 2002, A&A, 391, 83
Beck R., Fletcher A., Shukurov A., Snodin A., Sokoloff D. D., Ehle M., Moss D., Shoutenkov V., 2005, A&A, 444, 739
Bell R., 1978, MNRAS, 182, 443

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APPENDIX A: THERMAL–NON-THERMAL FLUX SEPARATION

The Tabatabaei et al. (2007) method uses an Hα map of the galaxy as a template of thermal emission. Since Hα emission is affected

Figure A1. Left-hand panel: the pixel-wise distribution of the estimated dust temperature ($T_{\text{dust}}$). The bins are at intervals of 0.5 K. Middle panel: the radial profile of the estimated emission measure ($\text{EM} = \int n_e^2 dl \text{ pc cm}^{-6}$). The EM is azimuthally averaged over annuli of one beamwidth, i.e. 40 arcsec. Right-hand panel: the pixel-wise distribution of the thermal fraction ($f_{\text{th}}$) with a bin size of 0.5 per cent. The solid black histograms show the distribution at 333 MHz, while the dashed red histograms show the distribution near 1.4 GHz. The top, middle and bottom rows show NGC 1097, NGC 4736 and NGC 5055, respectively. Each pixel is 10 arcsec in size, corresponding to a physical scale of about 700, 400 and 340 pc, respectively.
by extinction, far-infrared data at $\lambda 70 \mu$m and $\lambda 160 \mu$m are used to obtain a model for extinction, which is then used to correct the $H\alpha$ data. The corrected $H\alpha$ image is then used to predict the thermal emission at radio frequencies of interest (the whole process is described in detail in Sections 3 – 6 of Tabatabaei et al. 2007). In this section, we summarize the various steps and the intermediate results that we obtained in the separation process.

(i) **Data sets.** The far-infrared images at $\lambda 70$ and $\lambda 160 \mu$m were obtained from the publicly available data from the SINGS (Kennicutt et al. 2003). All $\lambda 70-\mu m$ images have a pixel size of 4.5 arcsec and a point spread function (PSF) of about 16 arcsec. At $\lambda 160 \mu m$, each pixel is 9 arcsec in size and has a PSF of 40 arcsec. Both the $\lambda 70-\mu m$ and $\lambda 160-\mu m$ maps are calibrated in surface brightness units of MJy sr$^{-1}$.

The continuum-subtracted $H\alpha$ images for NGC 1097 (1.5-m CTIO, filter: CT6586) and NGC 6946 (KPNO 2-m, filter: KP1563) were obtained from the ancillary data at the SINGS website. The maps were in units of DN s$^{-1}$ pixel$^{-1}$, which was converted into erg s$^{-1}$ cm$^{-2}$ using the calibration provided in the SINGS Fifth Data Delivery documentation.\(^9\)

The continuum-subtracted $H\alpha$ images for NGC 4736, observed with the 1-m Jacobus Kapteyn Telescope (JKT) at La Palma, filter: Ha6570 (Knapen et al. 2004), NGC 5055 observed with the 2.3-m telescope at KPNO, filter: 6580, and NGC 5236 observed with the 0.9-m telescope at CTIO, filter: 6563, were downloaded from the NED.

The counts per second (cps) in these maps were converted into apparent magnitude, $m_{AB}$, using the zero-point given in the FITS file header. The apparent magnitude $m_{AB}$ further was converted into specific intensity, using $f_\nu (\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}) = 10^{-\left(m_{AB} + 48.6 \nu/2.5\right)}$. The flux in units of erg s$^{-1}$ cm$^{-2}$ was computed using, $f = f_\nu (d\lambda/\lambda^2)$.

All the $\lambda 70-\mu m$ and continuum-subtracted $H\alpha$ maps were convolved to the coarser 40-arcsec PSF of $\lambda 160 \mu m$, and pixels were re-gridded to 9 arcsec. All the subsequent calculations were carried out on a pixel-by-pixel basis.

(ii) **Dust temperature and optical depth.** Following Tabatabaei et al. (2007), as a first step for extinction correction of $H\alpha$ maps, we need to estimate the optical depth due to obscuring dust. For this purpose, the colour temperature of the dust ($T_{dust}$) is found by fitting a blackbody spectrum incorporating dust absorption efficiency (see equation 1 of Tabatabaei et al. 2007) to the far-infrared maps at $\lambda 70$ and $\lambda 160 \mu m$. The distribution of the dust temperature for all the five galaxies is shown in the left-hand panel of Fig. A1. The mean temperature estimated for all the galaxies is between 19 and 22 K. Note that a single dust temperature model has been assumed. The optical depth at $160 \mu m$ ($\tau_{160 \mu m}$) was then obtained by using equation (2) of Tabatabaei et al. (2007) using the estimated $T_{dust}$. The $H\alpha$ optical depth was obtained as $\tau_{H\alpha} \sim f_d \times 2200 \times \tau_{160 \mu m}$ (Krügel 2003) with $H\alpha$ filling factor $f_d = 0.33$ (Dickinson, Davies

\(^9\) Available from http://data.spitzer.caltech.edu/popular/sings/20070410_enhanced_v1/Documents/sings_fifth_delivery_v2.pdf
For all the five galaxies, $\tau_{H\alpha}$ lies in the range of 0.03–0.6 at linear scales $>1$ kpc, with the highest values being towards the centre of the galaxies.

(iii) Emission measure. Extinction-corrected H$\alpha$ maps were used to estimate the emission measure ($EM = \int n_e^2 \, dl \, pc \, cm^{-6}$, where $n_e$ is the thermal electron density) using equations (3) and (4) of Tabatabaei et al. (2007) (also see Valls-Gabaud 1998) and assuming an electron temperature of $T_e = 10^4$ K. The emission measure radial profile for all the five galaxies is shown in the middle panel of Fig. A1. The emission measure towards the centre of the galaxy lies in the range of $\sim 10^3$–$10^4$ pc cm$^{-6}$ and falls off to $\sim 10$–$10^2$ pc cm$^{-6}$ towards the edge of the galaxy. These range of emission measure values are consistent with those observed in the Milky Way (see e.g. Berkhuijsen, Mitra & Mueller 2006).

(iv) Thermal emission at radio frequencies. Equations (5) and (6) of Tabatabaei et al. (2007) were used to determine the radio continuum optical depth and the brightness temperature ($T_B$) using the Rayleigh–Jeans approximation. The thermal flux density ($S_{\nu, th}$) at a radio frequency $\nu$ was obtained from $T_B$ using

$$\frac{S_{\nu, th}}{Jy \, beam^{-1}} = 8.18 \times 10^{-7} \left( \frac{\theta_{maj}}{arcsec} \right) \left( \frac{\theta_{min}}{arcsec} \right) \left( \frac{\nu}{GHz} \right)^2 \frac{T_B}{K}. $$

Here, $\theta_{maj}$ and $\theta_{min}$ are the sizes of the restoring beam in the radio map (in this case 40 arcsec).

For all the five galaxies, the pixel-wise distribution of the thermal fraction ($f_{th} = S_{\nu, th}/S_{\nu, tot}$) at 333 MHz and near 1 GHz is shown in the rightmost panel of Fig. A1. The mean $f_{th}$ at 333 MHz and near 1 GHz for all the galaxies was found to be less than 5 and 12 per cent, respectively. However, in certain giant H$\Pi$ regions, the thermal fraction can extend up to 10 per cent at 333 MHz and 30 per cent near 1 GHz. Tabatabaei et al. (2007) pointed out that the primary source of error in the thermal fraction arises from the unknown value of $T_e$. Using similar arguments, we estimate the uncertainty in the thermal fraction at 333 MHz and near 1 GHz to be $\sim 10$ and 15 per cent, respectively.