Chapter 4

Resolved low-frequency radio images of nearby dwarf galaxies

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4.1 Introduction

Within the hierarchical structure formation scenario, present-day starburst dwarf galaxies are thought to be the closest analogues to the first galaxies that were bubbling with star formation (Kanekar et al. 2009, 2014; Buitrago et al. 2013; Alavi et al. 2016). For example, the rest frame UV spectrum of the nearby dwarf galaxy NGC 4214 strongly resembles starforming galaxies at redshift $z \geq 3$ (Steidel et al. 1996). Dwarf galaxies are also considered to be the progenitors of the normal spiral galaxies we see in the local universe (see White & Frenk 1991; Baugh 2006). Therefore, understanding the physical processes that take place in the interstellar media of nearby dwarf galaxies is crucial for formulating a consistent picture of the evolution of galaxies within the cosmological context.

Compared to normal spiral galaxies, dwarf galaxies differ in key global properties such as morphology, metallicity, dust content and star formation rate. In contrast to normal spiral galaxies, star formation in dwarf galaxies is episodic/stochastic (Lequeux et al. 1979; Gerola et al. 1980; Stinson et al. 2007) and occurs without the influence of spiral density waves (Hunter et al. 1998). Due to their low star formation rates, dwarf galaxies tend to be fainter in radio continuum than normal spiral galaxies.

Unlike normal spiral galaxies, dwarf galaxies have relatively low rotational velocities (Begum et al. 2008; Oh et al. 2008; Ott et al. 2012; McNichols et al. 2016) implying that the classical $\alpha - \Omega$ dynamo mechanism might not be strong enough to amplify the magnetic fields in them. However strong magnetic field strengths have been detected in nearby dwarf galaxies (Chyży et al. 2000; Kepley et al. 2010). For example, Chyży et al. (2000) detected a 14 $\mu$G total field strength in the nearby dwarf galaxy NGC 4449 which is similar to total field strengths observed in normal spiral galaxies. Detection of magnetic field strengths that are equal in strength compared to normal spiral galaxies indicates that turbulent gas motion, driven by mechanical feedback from supernova explosions, could result in an efficient fluctuating dynamo mechanism. Thus, radio continuum studies of nearby dwarf galaxies can provide a wealth of information about the magnetised interstellar media in these objects and help understanding the physical conditions of the interstellar medium in these cosmological building blocks.

Most of the studies of dwarf galaxies published in the literature have been based on integrated radio continuum properties which can at times be severely affected by background source confusion (see for example Klein 1986). However, resolved radio continuum observations of dwarf galaxies have been few and far between. Only a handful of studies (in the literature) have been based on resolved radio continuum and spectral index observations of dwarf galaxies (for example see Lisenfeld et al. 2004; Kepley et al. 2011; Chyży et al. 2011; Heesen et al. 2011; Basu et al. 2017). Roychowdhury & Chengalur (2012) performed a stacking analysis of NVSS images of 57 dwarf galaxies to study the typical magnetic fields in faint dwarf galaxies. To date, there has not been a systematic resolved study of dwarf galaxies in radio continuum. An attempt was made by Chyży et al. (2011) to map the total and polarized radio continuum emission in dwarf galaxies in the local group using the Effelsberg telescope at 2.64 GHz but they were able
to detect only three of the 12 targeted galaxies. Furthermore resolved studies of
dwarf galaxies have never been carried out at frequencies below 300 MHz.

This picture is about to change with the advent of new low-frequency radio
telescopes like LOFAR and MWA which have significantly improved survey speeds
compared to traditional radio telescopes due to their large fields of view. For
example, the LOFAR Two-metre Sky Survey (LoTSS; Shimwell et al. 2017) is
an ongoing 120 – 168 MHz survey that aims to image the entire northern sky with
a sensitivity of 100 \( \mu \)Jy/beam at an angular resolution of 5”. The LoTSS survey
aims to make calibrated, science-ready images public with the first data release
scheduled to be released in 2018. To prepare for science-ready images from the
LoTSS survey, we have carried out a pilot radio continuum observing campaign
of four nearby dwarf irregular galaxies (NGC 1569, NGC 4214, NGC 2366,
and DDO 50) at 120–168 MHz using the LOFAR High Band Antenna (HBA).
These four galaxies were chosen because of their radio brightness at higher
radio frequencies using data from the Local Irregulars That Trace Luminosity
Extremes - The H\textsuperscript{i} Nearby Galaxy Survey (LITTLE-THINGS; Hunter et al.
2012) and availability of complementary data at other wavelengths. The physical
parameters of the four dwarf galaxies studied in this work are listed in Table 4.1.

This chapter is structured as follows: We present our LOFAR HBA obser-
vations and the data reduction procedure in Section 4.2. In Section 4.3, we
present our total intensity radio continuum maps and we discuss the observed
morphology of the galaxies in detail in comparison with other higher frequency
observations. In Sections 4.4 through 4.6, we estimate the thermal contribution to
the observed total continuum emission and use the non-thermal maps to estimate
the equipartition magnetic field strengths. In section 4.7, we present details of our
search for polarized emission from the dwarf galaxies and from other extragalactic
radio sources within our field of view. Finally, we summarize our conclusions in
Section 4.9. Throughout this work, we define spectral index through
\[ S_\nu \propto \nu^{-\alpha}, \]
where \( S_\nu \) is the flux density at frequency \( \nu \), and \( \alpha \) is the spectral index.

## 4.2 LOFAR observations and data reduction

### 4.2.1 Observational setup and preprocessing

We observed the targets listed in Table 4.1 for eight hours each with the
International LOFAR Telescope (ILT, van Haarlem et al. 2013) using its HBA.
All four galaxies were observed with identical instrumental setup and imaged
following the same calibration scheme. All Dutch and international LOFAR
stations were used during observation, and the stations were operated under the
HBA_Dual.Inner mode. In the HBA_Dual.Inner mode, all core LOFAR stations
are split in two and data from only the 24 inner tiles are used. This operating
mode was chosen to ensure that all LOFAR stations have the same field of view.

Each eight-hour continuous scan on the target was bracketed with a ten-
minute scan on the nearest flux density calibrator (either 3C 295 or 3C 196). All
four polarisation products in the linear basis (XX, XY, YX, YY) were recorded.
The target and the calibrators were observed with identical time and frequency
Table 4.1 – Physical parameters of the observed dwarf galaxies.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Distance [Mpc]</th>
<th>$M_V$ (mag)</th>
<th>Inclination [°]</th>
<th>PA [°]</th>
<th>$\log_{10} \Sigma_{\text{SFR}}$(FUV) $\text{M}_\odot \text{yr}^{-1} \text{kpc}^{-2}$</th>
<th>$R_H$ (arcmin)</th>
<th>$M_{\text{HI}}$ $(10^8 \text{M}_\odot)$</th>
<th>$W_{50}$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1569</td>
<td>3.36 [G08]</td>
<td>-18.2</td>
<td>69 [O15]</td>
<td>123 [O15]</td>
<td>$-0.01 \pm 0.01$</td>
<td>–</td>
<td>0.75</td>
<td>100.8</td>
</tr>
<tr>
<td>NGC 2366</td>
<td>3.44 [T95]</td>
<td>-16.8</td>
<td>65</td>
<td>40 [O08]</td>
<td>$-1.66 \pm 0.01$</td>
<td>4.72</td>
<td>6.49</td>
<td>101.2</td>
</tr>
<tr>
<td>NGC 4214</td>
<td>2.9 [D09]</td>
<td>-17.6</td>
<td>38</td>
<td>65</td>
<td>$-1.08 \pm 0.01$</td>
<td>4.67</td>
<td>4.08</td>
<td>69.8</td>
</tr>
<tr>
<td>DDO 50</td>
<td>3.4 [D09]</td>
<td>-16.6</td>
<td>31</td>
<td>177 [P92]</td>
<td>$-1.55 \pm 0.01$</td>
<td>3.97</td>
<td>5.95</td>
<td>57.4</td>
</tr>
</tbody>
</table>

Notes. Comments on columns: (1) galaxy name; (2) distances in Mpc; (3) $V$-band magnitude from Hunter & Elmegreen (2006); (4) inclination angle from de Blok et al. (2008); (5) position angle; (6) star formation rate density estimated using GALEX FUV flux (Hunter et al. 2010) over the area $\pi R_D^2$ where $R_D$ is the disk scale length (Hunter & Elmegreen 2004); (7) Holmberg radius from Hunter & Elmegreen (2006); (8) H$\text{I}$ mass taken from Walter et al. (2008); (9) H$\text{I}$ profile width at 50% of the peak intensity from Walter et al. (2008);

References. G08: Grocholski et al. (2008); O15: Oh et al. (2015); O08: Oh et al. (2008); P92: Puche et al. (1992); T95: Tolstoy et al. (1995); D09: Dalcanton et al. (2009);
setup. We used 243 non-contiguous sub-bands (SBs) to span the frequency range from 120 MHz to 182 MHz with a total bandwidth of 47.4 MHz. Each SB is 195.3125 kHz wide and is further sub-divided into 64 channels. The visibilities were correlated using a 1s integration time. Relevant observational parameters are listed in Tables 4.2 and 4.3.

After correlation, the recorded visibility data were flagged for Radio Frequency Interference (RFI) using the AOFlagger (Offringa et al. 2010, 2012) software package. The flagged data were then averaged down to four channels per SB and 4s time resolution. Only the averaged visibility data were stored on the LOFAR Long Term Archive (LTA)\(^1\) and the raw data were deleted.

### 4.2.2 Calibration

We followed the new direction dependent facet calibration procedure (van Weeren et al. 2016; Williams et al. 2016) to calibrate and image our LOFAR HBA data. Here, only the Dutch baselines (including core and remote stations) were used for calibration and imaging. Analysis of the sub-arcsec resolution maps of the compact H\(_\text{II}\) regions in the dwarf galaxies using international LOFAR baselines will be presented in a future study. The calibration procedure was carried out in two stages: a direction-independent step where we first applied flux calibration and a correction for station clock offsets followed by a direction-dependent step where we corrected for direction-dependent effects due to the ionosphere and due to our insufficient knowledge of the LOFAR beam.

In the direction-independent step, we first derived calibration solutions for the diagonal gain terms (\(G_{xx}\) and \(G_{yy}\)) using either 3C 295 or 3C 196. For 3C 295, we assumed a two-point source model using the flux scale defined in Scaife & Heald (2012) while we used a four-component model 3C 196 characterised using a second order spectral curvature (Pandey, private communication). The modelled total flux density of 3C 196 differs from the Scaife & Heald (2012) flux scale by a factor of \(1.074 \pm 0.024\) (Williams et al. 2016). We return to this in section 4.2.3. In addition to the gain terms, we also solved for a rotation angle term that accounts for differential Faraday rotation. We derived gain solutions for each subband separately with a 4s solution interval. Using these gain solutions, we estimated the station clock offsets and the phase offset between the X and the Y dipoles of each station using the “clock-TEC” separation method described in van Weeren et al. (2016). The correction for clock offset is required because the core and the remote LOFAR stations are not connected to the same clock, and hence synchronisation errors can lead to clock offsets of the order of 100ns. We transferred the derived gain amplitude, clock offset and phase offset solutions to the target data using the NDPPP software.

At low radio frequencies, the ionospheric Faraday rotation has to be calibrated out to prevent depolarisation due to the ionosphere. We determined the corrections using the publicly available RMExtract\(^2\) software package. RMExtract uses the model of the Earth’s magnetic field (Finlay et al. 2010) and the Total

\(^1\)http://lofar.target.rug.nl/

\(^2\)https://github.com/maaijke/RMextract/
Table 4.2 – LOFAR HBA telescope setup

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integration time</td>
<td>1 s</td>
</tr>
<tr>
<td>Total on-source time</td>
<td>8.0 hr</td>
</tr>
<tr>
<td>Correlations</td>
<td>XX, XY, YX, YY</td>
</tr>
<tr>
<td>Frequency range</td>
<td>120 – 182 MHz</td>
</tr>
<tr>
<td>Total bandwidth</td>
<td>47.4 MHz</td>
</tr>
<tr>
<td>Subbands (SBs)</td>
<td>243</td>
</tr>
<tr>
<td>Bandwidth per SB</td>
<td>195.3125 KHz</td>
</tr>
<tr>
<td>Channels per SB</td>
<td>64</td>
</tr>
<tr>
<td>LOFAR Array Mode</td>
<td>HBA Dual Inner</td>
</tr>
<tr>
<td>Stations</td>
<td>72⁢a total</td>
</tr>
<tr>
<td></td>
<td>23 core (each split in two)</td>
</tr>
<tr>
<td></td>
<td>14 remote</td>
</tr>
<tr>
<td></td>
<td>12 international</td>
</tr>
</tbody>
</table>

Notes. (a) Some LOFAR HBA stations were flagged either during observation or during calibration. Stations CS004HBA0 and CS031HBA0 were flagged in the NGC 4214 dataset. Station RS409HBA was flagged in the DDO 50 dataset. Station RS210HBA was flagged while observing NGC 1569 due to hardware issues related to oscillating dipoles.

Electron Content maps from the Center for Orbit Determination in Europe (CODE) to estimate the required ionospheric Rotation Measure (RM) correction. The applied ionospheric RM corrections ranged from 0.09 rad m$^{-2}$ to 0.79 rad m$^{-2}$.

After transferring the calibrator solutions to the target and correcting for ionospheric Faraday rotation, we merged the target measurement sets into blocks of 10 SBs such that each block has a bandwidth of 2 MHz. Phase calibration was applied to the SB blocks using a 6° × 6° model of the sky extracted from the 150 MHz Giant Metrewave Radio Telescope (GMRT) Sky Survey Alternate Data Release (Intema et al. 2017, TGSS ADR). Phase solutions were derived for and applied to each SB block separately with an 8s solution interval.

The aim of the direction-dependent calibration step is to allow the recovery of weak, diffuse radio continuum emission by minimising calibration artefacts around bright point sources within the LOFAR field of view. To achieve this, we divided the region within the primary beam into facets using Voronoi tessellation such that each facet has at least one point source, or facet calibrator, brighter than 0.4 Jy/beam. We processed the facets individually in decreasing order of the total flux in each facet. For each facet, we performed self-calibration to improve the skymodel and to derive good gain solutions for that facet. After deriving direction-dependent solutions, we corrected the visibility dataset corresponding to each target using solutions derived from the nearest facet calibrator. The list of facet calibrators used and their distances from the corresponding target galaxies is shown in Table 4.3.
Figure 4.1 – Facet layout for NGC 2366


<table>
<thead>
<tr>
<th>Parameter</th>
<th>NGC 1569</th>
<th>NGC 2366</th>
<th>DDO 50</th>
<th>NGC 4214</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pointing center</td>
<td>04h30m49.2s</td>
<td>07h28m54.6s</td>
<td>08h19m05.0s</td>
<td>12h15m39.2s</td>
</tr>
<tr>
<td></td>
<td>+64d50m52.5s</td>
<td>+69d12m57s</td>
<td>+70d43m12s</td>
<td>+36d19m37s</td>
</tr>
<tr>
<td>Flux density calibrators</td>
<td>3C 196</td>
<td>3C 196</td>
<td>3C 196</td>
<td>3C 295</td>
</tr>
<tr>
<td>Observation ID</td>
<td>557200</td>
<td>560195</td>
<td>570739</td>
<td>582785</td>
</tr>
<tr>
<td>Observation date</td>
<td>Nov 03, 2016</td>
<td>Nov 30, 2016</td>
<td>March 02, 2017</td>
<td>April 05, 2017</td>
</tr>
<tr>
<td>Direction-dependent facet calibrator</td>
<td>J042932+645627</td>
<td>J072753+685256</td>
<td>J082216+705308</td>
<td>J121420.7+361426</td>
</tr>
<tr>
<td>Distance from facet calibrator</td>
<td>9′.87</td>
<td>20′.75</td>
<td>18′.60</td>
<td>16′.63</td>
</tr>
<tr>
<td>High resolution:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robust parameter</td>
<td>-0.7</td>
<td>-0.7</td>
<td>-0.7</td>
<td>-0.7</td>
</tr>
<tr>
<td>Gaussian taper (″)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Beam (″)</td>
<td>14.8 × 11.4</td>
<td>15.1 × 11.5</td>
<td>15.6 × 11.9</td>
<td>16.2 × 11.1</td>
</tr>
<tr>
<td>Noise (μJy beam⁻¹)</td>
<td>138</td>
<td>216</td>
<td>198</td>
<td>185</td>
</tr>
<tr>
<td>Low resolution:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robust parameter</td>
<td>-0.7</td>
<td>-0.7</td>
<td>-0.7</td>
<td>-0.7</td>
</tr>
<tr>
<td>Gaussian taper (″)</td>
<td>30</td>
<td>20</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Beam (″)</td>
<td>33.7 × 30.1</td>
<td>24.6 × 21.5</td>
<td>24.8 × 21.8</td>
<td>34.7 × 32.0</td>
</tr>
<tr>
<td>Noise (μJy beam⁻¹)</td>
<td>315</td>
<td>561</td>
<td>495</td>
<td>356</td>
</tr>
<tr>
<td>Integrated flux density at 143 MHz (mJy)</td>
<td>899.0 ± 92.0</td>
<td>32.5 ± 3.3</td>
<td>124.0 ± 12.4</td>
<td>275.7 ± 27.6</td>
</tr>
<tr>
<td>Thermal contribution at 143 MHz (mJy)</td>
<td>114.3</td>
<td>15.0</td>
<td>6.2</td>
<td>26.5</td>
</tr>
</tbody>
</table>
4.2.3 Final imaging

After correcting the visibilities with the direction-dependent gain solutions, we imaged the facets containing the target galaxies using the WSClean\(^3\) imager (Offringa et al. 2014) making use of its Wideband Deconvolution algorithm\(^4\) which accounts for spectral curvature within the bandpass. We weighted the visibilities using the Briggs weighting scheme (Briggs 1995) with \texttt{robust}=-0.7 and a Gaussian taper. We deconvolved the dirty maps down to 1\(\sigma\) threshold using a CLEAN mask to minimize CLEAN bias (Becker et al. 1995; Cohen et al. 2007).

During imaging, a combination of a more uniform visibility weighting and a Gaussian taper was needed to suppress PSF sidelobes in our final total intensity maps while enhancing the diffuse emission by down-weighting the long baselines. Figures 4.2 and 4.3 show the shape of the PSF for three different visibility weighting schemes. As can be seen from Figures 4.2 and 4.3, the first sidelobe of the PSFs are as high as 40 and 20\% when imaging the LOFAR HBA data with Briggs weighting using \texttt{robust} parameters 0.0 and 0.5.

We followed the procedure explained above to image the calibrated visibilities at two different resolutions to highlight the diffuse and high-resolution morphological features in the galaxies. Different resolutions were achieved using different Gaussian tapering values while keeping all other imaging parameters the same. The relevant imaging parameters used to make the high and low resolution total intensity maps are listed in Table 4.3.

![Figure 4.2](https://sourceforge.net/p/wsclean/wiki/Home/)\(^3\) ![Figure 4.3](https://sourceforge.net/p/wsclean/wiki/WidebandDeconvolution/)\(^4\)

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\(^3\)https://sourceforge.net/p/wsclean/wiki/Home/
\(^4\)https://sourceforge.net/p/wsclean/wiki/WidebandDeconvolution/
**Figure 4.3** – Point Spread Functions for a typical LOFAR HBA observation including all Dutch baselines and imaged using different visibility weighting schemes. Two dimensional slices along the minor axis of all three PSFs are shown in Figure 4.2.
4.3. TOTAL INTENSITY MAPS

Primary beam correction was not applied to the final images as all the diffuse emission from the dwarf galaxies is within the 99.5% level of the primary beam. While the point source models used to calibrate the visibility data have $\leq 4\%$ intrinsic flux uncertainty within our observational bandwidth (see Figure 3 in Scaife & Heald 2012), we assume a conservative 10% uncertainty on the measured flux densities for all our subsequent analysis.

Note that the total flux included in the model for 3C 196 used to calibrate the LOFAR dataset deviates from the Scaife & Heald (2012) flux scale by a factor of $1.074 \pm 0.024$. Final total intensity images that were calibrated using 3C 196 were scaled by this factor so that the maps are consistent with the Scaife & Heald (2012) flux scale.

4.3 Total intensity maps

We detect radio continuum emission at 143 MHz from all four dwarf galaxies. Figures 4.4 and 4.5 show the high and low resolution LOFAR HBA total intensity contour lines overlayed on the corresponding H$\alpha$ (Hunter & Elmegreen 2004) and Digitized Sky Survey (DSS) maps. In the following sub-sections, we provide comments on the individual galaxies.

4.3.1 NGC 1569

The LOFAR total intensity radio continuum contours of NGC 1569 overlayed on an H$\alpha$ and optical DSS image are shown in Figures 4.4 and 4.5. The overall radio morphology of the diffuse radio continuum emission in NGC 1569 seen at 143 MHz is consistent with the 20 cm radio continuum morphology presented in the literature (see for example Kepley et al. 2010).

Contour lines drawn in Figure 4.4 reveal that the isocontour shape of the galaxy changes from being oval in the inner regions of the galaxy to a boxy-shape in the outer parts. Comparing the morphology of the galaxy at 3, 6, 13 and 20 cm, Kepley et al. (2010) also noticed that the morphology changes from oval-shaped to box-shaped as one moves towards low radio frequencies. We see a continuation of the same morphological effect with our new LOFAR data.

Figures 4.4, 4.5, 4.6, and 4.7 show the LOFAR radio contour lines overlayed on H$\alpha$, optical DSS, GALEX NUV, and neutral hydrogen column density images of NGC 1569. Comparing the radio continuum morphology of NGC 1569 with images from higher frequency observations, we find interesting correspondences between radio emission and features seen at other frequencies.

Comparing the GALEX NUV image and the LOFAR radio image of NGC 1569 (see Figure 4.6), we see that the peak radio emission is coincident with the site of intense star formation in the western part of the galactic disk. It is also interesting to note that while most intense star formation is occurring in the north-eastern part of the disk, it is the south-western part of the radio halo that shows the most extended vertical structure in our maps. Comparing our 143 MHz radio image with those presented in (Kepley et al. 2010, see their Figure 1), it is interesting to note that the south-western part of the radio halo
Figure 4.4 – LOFAR high resolution total intensity contours overlayed on Hα maps (Hunter & Elmegreen 2004). Contour levels are drawn at $2 \times \sigma I \times 1.5^n$ where $n = 0, 1, 2, 3, \ldots$. Broken contour lines in the maps are drawn at $-2\sigma$ level. The LOFAR maps were generated using a $10''$ Gaussian taper and the resolutions of the LOFAR maps are listed in Table 4.3. The size of the LOFAR beam is shown in the lower left corner of each image.
Figure 4.5 – LOFAR low resolution total intensity contours overlayed on optical DSS maps. Contour levels are drawn at $2 \times \sigma_1 \times 1.5^n$ where $n = 0, 1, 2, 3,...$. Broken contour lines in the maps are drawn at $-2\sigma$ level. The LOFAR maps were generated using a 30'' Gaussian taper and the resolutions of the LOFAR maps are listed in Table 4.3. The size of the LOFAR beam is shown in the lower left corner of each image.
increases in size only at frequencies below 2.27 GHz. In fact, the north-eastern halo appears to be more extended at 3, 6, and 13 cm. Only in radio maps with wavelengths longer than 20 cm do we see more extended emission in the south-east.

Notice that the Hα image in figure 4.4 shows the presence of an arm-like structure protruding from the western end of the galactic disk. While this extended Hα filament is usually referred to as the “western arm” (see Klein & Graeve 1986, and references therein), the Hα emission from the filament originates from the limb of a bubble. The radio continuum contours shown in Figures 4.4 trace the “western arm” quite clearly in the south-western part of the galaxy.

The low resolution LOFAR contours overlayed on a neutral hydrogen column density map of NGC 1569 in Figure 4.7 shows that the peak radio continuum emission, which is coincident with the site of intense star formation, is coincident with a region that shows a lack of H I emission compared to its surroundings.

Figure 4.6 – LOFAR total intensity radio continuum contours overlayed on GALEX NUV image of NGC 1569. The contour lines are drawn at $10 \times \sigma \times 1.5^n$ where $n = 1, 2, 3...$ and $\sigma = 210$ mJy/b. The image shows that the peak radio continuum emission in NGC 1569 coincides with a site of intense star formation in the western part of the disk.
In comparison with the sensitive 20cm total intensity map from Kepley et al. (2011), we find that the radio continuum emission at 143 MHz appears extended perpendicular to the inner disk while no noticeable extended emission is seen along the major axis. In our low-resolution LOFAR map, we can trace the diffuse radio continuum emission out to a distance of 4′.18 from the kinematic center (4:30:48.600,+64:50:57.89). Assuming a distance of 2.96 ± 0.22 Mpc, this corresponds to a projected linear size of 3.60 ± 0.27 kpc. Similar vertical extensions have also been seen at low radio frequencies in NGC 253 (Kapińska et al. 2017) and in NGC 5775 (Heald et al in prep). Given that NGC 1569 is a post-starburst galaxy, this extension perpendicular to the disk probably indicates the presence of a galactic wind. Hα kinematics of the outer parts of the halo indicate the presence of a large-scale outflow of ionised gas (Tomita et al. 1994; Heckman et al. 1995; Martin 1998; Westmoquette et al. 2007a,b, 2008). Modelling the propagation of cosmic ray electrons with tools like SPINNAKER (Heesen et al. 2016) using our LOFAR HBA data and future observations with LOFAR low band antenna (LBA) will allow us to study the nature of cosmic-ray transport from the galactic disk to the halo (advection- or diffusion-dominated) and measure the outflow wind speed.

We measure the integrated flux density from NGC 1569, after masking out a few background point sources, to be 0.965±0.096 Jy. As discussed in section 4.2.2, the model for the flux density calibrator that was used to calibrate the NGC 1569 LOFAR data deviates from the Scaife & Heald (2012) flux scale by a factor of 1.074 ± 0.024. Thus, the integrated flux density from NGC 1569 needs to be rescaled resulting in an integrated flux of 0.899 ± 0.092 Jy in the Scaife & Heald (2012) flux scale. The integrated LOFAR flux density is consistent with flux density estimates from the 6C survey (Hales et al. 1993). Fitting a power-law (see fig 4.8), we find that the integrated spectral index for NGC 1569 is 0.46±0.02.

### 4.3.2 NGC 4214

The radio morphology of NGC 4214 shown in Figures 4.4 and 4.5 is composed of two bright radio emission components in the inner regions of the galaxy superimposed on a weaker diffuse component. In addition to these two components, the radio images also show several point-like sources (labelled as ‘RS4’, ‘RS5’, ‘RS6’, and ‘H’). The nature of these sources is discussed below.

Comparing the distribution of radio emission and Hα emission from ionised gas in NGC 4214, we see that the peak in radio and Hα emission coincide quite well. The two bright radio-emitting regions (with associated bright Hα emitting regions) correspond to the H II regions: NGC 4214-I and NGC 4214-II. The radio continuum morphology of NGC 4214 at 143 MHz is consistent with the 1.4 GHz WSRT radio image of NGC 4214 published by Kepley et al. (2011) but shows more extended emission.

Figure 4.9 shows the comparison between the radio continuum morphology of NGC 4214 and the distribution of neutral hydrogen in the galaxy. Unlike NGC 1569, the neutral hydrogen distribution in NGC 4214 is more extended.
Figure 4.7 – Low resolution LOFAR contours on the THINGS H\textsubscript{i} column density map (Walter et al. 2008) of NGC 1569. The column density sensitivity of the THINGS map is $4 \times 10^{19}$ cm$^{-2}$. The contour lines are drawn at the same level as in Figure 4.5. The $33'' \times 30''.1$ resolution of the LOFAR map is indicated as a filled circle in the lower left corner.
Figure 4.8 – Integrated spectral index for NGC 1569.
than the low frequency radio continuum emission as is often seen in normal spiral galaxies. The radio continuum emission at 143 MHz traces two arm-like features (containing the background radio sources ‘RS4’ and ‘RS6’) seen in H\textsc{i}. These arm-like features also trace two inter-arm regions one to the south of ‘RS4’ and the other to the south-east of ‘RS6’.

Before estimating the integrated flux density of NGC 4214, it is imperative to understand the nature of the point sources seen towards NGC 4214. The point-like radio sources marked H and RS4 in both Figures 4.4 and 4.5 are detected in the 1.4 GHz radio continuum maps published in Kepley et al. (2011). In the high resolution LOFAR image (7\arcsec.3 × 4\arcsec.8) shown in Figure 4.10, the source RS4 gets resolved into a double-lobed radio source. This is consistent with the conclusions of Kepley et al. (2011) who also classify the source RS4 to be background AGN based on its resolved structure in the FIRST maps, hard X-ray emission detected by Hartwell et al. (2004), and steep spectral index between 6 and 3cm. Comparing the radio continuum map with the optical and H\textalpha maps, Kepley et al. (2011) argue that the source marked H is part of NGC 4214. While the source ‘H’ looks like a point source in the 1.4 GHz WSRT radio image of Kepley et al. (2011), the high resolution image shown in Figure 4.10 resolves source ‘H’ into a bright core surrounded by diffuse radio emission. The morphology of this source at high resolution looks similar to the radio morphology of sources like Fornax A (for example, see Fomalont et al. 1989) or the remnant radio galaxy discovered by Brienza et al. (2016). Source ‘H’ also appears to have a steep spectral index (see Figure 4.13) For these reasons, we consider the source marked ‘H’ to be a background radio galaxy. The nature of sources marked ‘RS5’ and ‘RS6’ is uncertain due to the lack of emission at other wavelengths and we assume them to be background radio sources.

After masking out RS4, RS5, and RS6, we estimated the integrated flux density from NGC 4214 to be 275.7 ± 27.6 at 143 MHz. The total spectral index is $\alpha = 0.65 ± 0.06$.

### 4.3.3 NGC 2366

The low frequency radio continuum morphology of NGC 2366 is consistent with previous L-band and higher frequency observations (for example, see Thuan et al. 2004; Kitchener 2016). The radio continuum emission from NGC 2366 is dominated by two prominent H\textsc{ii} regions in the southern part of the galaxy: the Giant Extragalactic H\textsc{ii} Region (GEHR) NGC 2363 (= Mrk 71) and the Western H\textsc{ii} region (labelled NGC 2366-III in Drissen et al. 2000). In both H\textsc{ii} regions, the peak of the radio continuum emission is offset from the peak of the H\alpha emission. A similar positional offset is also seen between the H\alpha emission and the H\textsc{i} intensity map (van Eymeren et al. 2009). Positional offsets are also seen between H\alpha and H\textsc{i} intensity maps in other dwarf galaxies such as Sextans A (Hodge et al. 1994) and IC 10(Hodge et al. 1990), and can be explained as the consequence of sequential star formation (Elmegreen & Lada 1977).

Optical and H\alpha maps resolve the GEHR NGC 2363 (= Mrk 71) into two superstar clusters: NGC 2366-I and NGC 2366-II. NGC 2366-I dominates the
Figure 4.9 – Low resolution total intensity LOFAR contours of NGC 4214 overlayed on the integrated intensity H\textsc{i} map from THINGS (Walter et al. 2008). The column density sensitivity of the THINGS map is $4 \times 10^{19}$ cm$^{-2}$. The $34'' \times 32''$ LOFAR beam is indicated in the lower left corner of the image. The contour lines are drawn at the same level as in Figure 4.5.
Figure 4.10 – A high resolution blow-up of the northern part of NGC 4214 showing the sources ‘RS4’ and ‘H’ marked in Figure 4.5. The rms noise in this map is 112µJy/beam and the contour levels are drawn at $2 \times \sigma \times 1.5^{n}$ where $n = 0, 1, 2, ...$. The 7′′.3 $\times$ 4′′.8 beam is shown in the lower left corner of the map.

Table 4.4 – Integrated radio continuum flux density for NGC 4214

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Flux density (mJy)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.14</td>
<td>275.7 ± 27.6</td>
<td>7</td>
</tr>
<tr>
<td>1.40</td>
<td>51.5 ± 10.3</td>
<td>6</td>
</tr>
<tr>
<td>1.40</td>
<td>38.3 ± 7.7</td>
<td>5</td>
</tr>
<tr>
<td>2.38</td>
<td>36.0 ± 3.0</td>
<td>4</td>
</tr>
<tr>
<td>4.86</td>
<td>34.0 ± 6.8</td>
<td>6</td>
</tr>
<tr>
<td>4.85</td>
<td>30.0 ± 4.5</td>
<td>2</td>
</tr>
<tr>
<td>4.85</td>
<td>30.0 ± 7.0</td>
<td>3</td>
</tr>
<tr>
<td>8.46</td>
<td>20.5 ± 0.5</td>
<td>1</td>
</tr>
<tr>
<td>8.46</td>
<td>24.2 ± 4.8</td>
<td>6</td>
</tr>
</tbody>
</table>

References. (1) Schmitt et al. (2006); (2) Becker et al. (1991); (3) Gregory & Condon (1991); (4) Dressel & Condon (1978); (5) Condon et al. (2002); (6) Kepley et al. (2011); (7) this work.
Figure 4.11 – Integrated spectral index for NGC 4214.
Table 4.5 – Integrated radio continuum flux density for NGC 2366.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Flux density (mJy)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.143</td>
<td>32.5 ± 3.3</td>
<td>1</td>
</tr>
<tr>
<td>1.400</td>
<td>11.7</td>
<td>2</td>
</tr>
<tr>
<td>1.400</td>
<td>19.9</td>
<td>3</td>
</tr>
<tr>
<td>4.750</td>
<td>10.0 ± 1.0</td>
<td>4</td>
</tr>
</tbody>
</table>

References. (1) this work; (2) Thuan et al. (2004); (3) Condon et al. (2002); (4) Klein & Graeve (1986)

Radio continuum emission from this region. While we see an extension towards NGC 2366-II, we do not see a second continuum peak associated with this superstar cluster. We estimate the combined radio continuum flux density from the superstar clusters NGC 2366-I and -II to be $8.75 \pm 0.90$ mJy/beam at 143 MHz. Comparing the estimated integrated flux density from Mrk 71 at 143 MHz with higher frequency measurements from Thuan et al. (2004) and Klein et al. (1984), it appears that Mrk 71 shows a spectral turnover ($\alpha < 0$).

The source marked RS3 is resolved into a double-lobed structure in the 3″ resolution C-band radio continuum map of Kitchener (2016). Thuan et al. (2004) misidentify this source as radio emission from an H\textsubscript{II} region in the galaxy. Also, due to low resolution of the single dish Effelsberg map, the 4.75 GHz integrated flux density reported by Klein & Graeve (1986) is an overestimate as it confuses the double-lobed structure with NGC 2366. This is likely to be the cause for the mismatch between the 1.4 GHz flux densities reported by Condon et al. (2002) and Thuan et al. (2004). While there is H\alpha emission coincident with the source marked RS2, it is not clear if it is part of the galaxy or if it is a background radio source.

Apart from these, low-level diffuse radio continuum emission is seen in the northern part of the galaxy and to the south-west of the Western H\textsubscript{II} region. Assuming that the source ‘RS2’ and ‘RS3’ are not related to NGC 2366, we estimate the total radio continuum flux density at 143 MHz to be $32.2 \pm 3.3$ mJy. The power-law spectral index between 0.143 GHz and 4.750 GHz is 0.34 ± 0.10.

4.3.4 DDO 50

The low frequency radio continuum emission from DDO 50 shown in Figure 4.4 appears to be very clumpy. We also find that the radio continuum morphology is strongly correlated with the distribution of H\alpha emission in the galaxy. DDO 50 was also observed at 20 cm using the Westerbork Synthesis Radio Telescope as part of the WSRT-SINGS survey (Braun et al. 2007). Braun et al. (2007) found that most of the radio continuum emission is confined to the prominent H\textsubscript{II} regions in DDO 50. The radio continuum morphology of DDO 50 in our LOFAR HBA image shown in Figure 4.5 is consistent with the 20cm map from Braun et al. (2007).
Table 4.6 – Integrated Radio continuum flux density for DDO 50.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Flux density (mJy)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.143</td>
<td>124.0 ± 12.4</td>
<td>1</td>
</tr>
<tr>
<td>0.335</td>
<td>52.0 ± 5.0</td>
<td>2</td>
</tr>
<tr>
<td>1.365</td>
<td>27.0 ± 1.0</td>
<td>3</td>
</tr>
<tr>
<td>1.465</td>
<td>18.9 ± 0.2</td>
<td>2</td>
</tr>
<tr>
<td>4.860</td>
<td>11.7 ± 0.1</td>
<td>2</td>
</tr>
</tbody>
</table>

References. (1) this work; (2) Tongue & Westpfahl (1995); (3) Heessen et al. (2014)

In Figures 4.4 and 4.5, we have marked a few regions of interest (A – G and RS1) following the same naming scheme used by Tongue & Westpfahl (1995). In our high resolution image shown in Figure 4.4, we detect radio continuum emission from all discrete radio sources identified by Tongue & Westpfahl (1995) except source ‘A’. Based on the spectral indices of source ‘E’, ‘F’, and ‘G’, Tongue & Westpfahl (1995) suggest that these sources could be supernova remnants near or associated with the underlying star-forming regions visible in Hα. Radio emission labelled ‘RS1’ (or radio source one) has no counterpart in the optical or Hα and is considered to be a background point source.

In addition to clumpy radio emission associated with the above-mentioned sources, the low resolution image in Figure 4.5 shows low-level diffuse emission surrounding regions with relatively high radio surface brightness. Tongue & Westpfahl (1995) argue that the low-level radio continuum emission seen around the prominent HII regions could be due to local enhancement of cosmic ray electron population injected by supernovae associated with the HII regions and/or due to local enhancements of magnetic field strength as a result of compression. We estimate the integrated flux density from DDO 50 to be 124.0 ± 12.4 mJy/beam after masking out the point source RS1. Table 4.6 shows a list of integrated flux densities from DDO 50 reported in the literature. A power-law fit to the integrated flux densities result in a spectral index of $\alpha = 0.62 \pm 0.11$.

### 4.4 Estimating thermal fraction

Thermal contribution to total intensity radio continuum emission can be estimated using the following equation from Hunt et al. (2004):

$$
\frac{F_\nu}{\text{mJy}} = 1.16 \left(1 + \frac{n(\text{He}^+)}{n(\text{H}^+)}\right) \left(\frac{T}{10^4 \text{ K}}\right)^{0.617} \times \left(\frac{\nu}{\text{GHz}}\right)^{-0.1} \left(\frac{F_{\text{H}\alpha, \text{corr}}}{10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}}\right).
$$

(4.1)

In the above relation, $F_\nu$ is the estimated radio flux due to thermal emission at frequency $\nu$ and $F_{\text{H}\alpha, \text{corr}}$ is the extinction-corrected Hα flux. $T$ is the electron
temperature within the emitting region and is assumed to be 10^4 K. We have also assumed that the ratio of the number density of ionised helium to that of ionised hydrogen \( n(\text{He}^+)/n(\text{H}^+) \) is 0.087 (Martin & Kennicutt 1997).

We estimated the thermal emission at 143 MHz for all four of our galaxies using the publicly available flux-calibrated and continuum-subtracted H\(\alpha\) maps published by Hunter & Elmegreen (2004). All H\(\alpha\) maps were observed using the Perkins 1.8-m telescope at the Lowell observatory and have a resolution of 2\(^\prime\).2 x 2\(^\prime\).2.

While H\(\alpha\) is a good tracer of the thermal component, the measured H\(\alpha\) flux is always lower than the true H\(\alpha\) flux due to interstellar extinction by the Milky Way foreground and in the host galaxy. We correct for interstellar extinction in the host galaxy using the relation (Kennicutt et al. 2009)

\[
F_{\text{H\(\alpha\),corr}} = F_{\text{H\(\alpha\)}} 10^{A_{\text{H\(\alpha\)}}/2.5} + 0.02 F_{24\mu m} \tag{4.2}
\]

where \(F_{\text{H\(\alpha\),corr}}\) is the extinction-corrected H\(\alpha\) flux, \(F_{\text{H\(\alpha\)}}\) is the observed H\(\alpha\) flux, and \(F_{24\mu m}\) is the observed 24\(\mu\)m flux. Since NGC 1569 is at a relatively low galactic latitude (\(b \sim 11\) deg), we first corrected for the foreground dust extinction using a value of \(A_{\text{H\(\alpha\)}} = 1.26\) (Relaño et al. 2006) instead of using the value from Schlegel et al. (1998). For the remaining galaxies, the Galactic foreground extinction was determined using the standard dust extinction maps from Schlegel et al. (1998).

To correct for intrinsic extinction, we used the publicly available 24\(\mu\)m maps observed with the MIPS instrument onboard the Spitzer space telescope. DDO 50 was observed as part of the SINGS survey Kennicutt et al. (2003) while the remaining three galaxies were published by Bendo et al. (2012). The pixels in all the 24\(\mu\)m maps have units ‘MJy/sr’ and we scaled the pixel values by 958.772 to have units of \(\mu\)Jy/beam assuming a resolution of 6\(\prime\).5 x 6\(\prime\).5. The H\(\alpha\), 24\(\mu\)m and the radio continuum maps were first convolved to a 16\(\prime\).5 resolution and regridded to a common coordinate grid. After correcting for extinction due to the Galactic foreground and intrinsic dust extinction using equation 4.2, we estimated the thermal contribution on a pixel by pixel basis using equation 4.1.

The integrated thermal flux density at 143 MHz estimated for each galaxy is shown in Table 4.3. The galaxy-wide integrated thermal fraction at 143 MHz is less than 15% for all galaxies except NGC 2366. In the case of NGC 2366, the overall thermal fraction is about 50%. Such a high value even at low radio frequencies is not surprising given that the radio continuum morphology of NGC 2366 is dominated by two large H\(\Pi\) regions. The thermal fraction maps for all four galaxies are shown in Figure 4.12.

In NGC 1569, the peak in thermal fraction (\(~ 30\%) is at the north-western part of the optical disk which is a site of intense star formation. Within the rest of the optical disk, the thermal fraction is on average about 15%. Immediately above and below the optical disk, the thermal fraction drops below 10% except in the extraplanar H\(\alpha\) filaments like the “western H\(\alpha\) arm” where the thermal

\[^6\]http://www2.lowell.edu/users/dah/littlethings/

\[^7\]Thermal fraction \(f_{\text{th}}\) is defined as \(f_{\text{th}} = F_{\text{th}}/F_{\text{tot}}\) where \(F_{\text{th}}\) is the estimated thermal emission and \(F_{\text{tot}}\) is the observed radio continuum emission.
4.4. ESTIMATING THERMAL FRACTION

Figure 4.12 – Thermal fraction map estimated at 143 MHz for all four dwarf galaxies. The 16''.5 beam is shown in the lower left corner of each image. LOFAR total intensity contours overlayed on the thermal fraction estimates are drawn at the same level as in Figure 4.5. The colour bar at the top of each panel gives the thermal fraction scale.
fraction is similar to that of the optical disk. In NGC 4214, the two H\textsc{ii} regions - NGC 4214-I and NGC 4214-II - show the highest thermal fraction of about 30 and 50 per cent respectively. Beyond the inner region of NGC 4214, the rest of the radio continuum disk shows low ($S_{th} < 10\%$) thermal fraction including the region ‘H’. In the case of NGC 2366, the Giant H\textsc{ii} region NGC 2363 (Mrk 71) appears to be entirely thermal which is consistent with the spectral turnover inferred in Section 4.3.3. Apart from this giant H\textsc{ii} region, the thermal fraction in the other parts of NGC 2366 is about 10\% on average. In DDO 50, the peak thermal fraction of about 20 – 60 \% is seen around the H\textsc{ii} marked ‘C’ in the total intensity maps. For the rest of the galaxy including the regions around the supernova remnants E, F, and G, the thermal fraction is lower than 10\%.

4.5 Non-thermal spectral index maps

Figure 4.13 shows the non-thermal spectral index maps of NGC 1569 and NGC 4214 computed using our 143 MHz LOFAR HBA and archival 1.4 GHz radio images from Kepley et al. (2010) and Kepley et al. (2011) respectively. Before computing the spectral index, we first subtracted the estimated thermal contribution at 143 MHz and 1.4 GHz from the total intensity radio images. Non-thermal spectral index was computed on a pixel-by-pixel basis using the thermal emission subtracted images. Uncertainty on the computed spectral index values was determined based on the relation

$$\alpha_{\text{err}} = \frac{1}{\log(\nu_1/\nu_2)} \sqrt{\left(\frac{S_{1,\text{err}}}{S_1}\right)^2 + \left(\frac{S_{2,\text{err}}}{S_2}\right)^2}$$

(4.3)

where $S_1$ and $S_2$ are the pixel values in the radio continuum maps at frequencies $\nu_1$ and $\nu_2$ and $S_{1,\text{err}}$ and $S_{2,\text{err}}$ are the corresponding uncertainties on the pixel values. All pixels in the spectral index maps corresponding to a spectral index error greater than 0.2 were blanked. Histograms of the spectral index distribution in NGC 1569 and NGC 4214 are shown in Figure 4.14.

Spectral index values in NGC 4214 vary between about -0.2 to 1.2. A steeper spectral index of about 1.7 is seen towards the source marked as ‘H’ in Figure 4.5. The H\textsc{ii} region NGC 4214-II shows a flat spectrum with spectral index $\alpha \sim 0$.

In NGC 1569, we see spectral index variations between $\alpha \sim 0.2 - 1.3$ with flatter spectral index seen in the north-western part of the galactic disk which is also the site of intense star formation.

4.6 Equipartition magnetic field strength

The strength of the total magnetic field can be estimated from the total intensity radio continuum image assuming energy equipartition between cosmic rays and magnetic fields (Beck & Krause 2005). The observed synchrotron intensity $I_{\text{syn}}$ is related to the strength of the total magnetic field perpendicular to the line of sight ($B_{\text{tot},\perp}$) as

$$B_{\text{tot},\perp} \propto I_{\text{syn}}^{1/(3+\alpha)}$$

(4.4)
Figure 4.13 – Non-thermal spectral index maps of NGC 4214 and NGC 1569 estimated between 0.143 and 1400 MHz. The 16'' beam is shown in the lower left corner of both maps and the contour levels are drawn at the same levels as in Figure 4.5. The colour bar to the right of each panel gives the spectral index scale.

Figure 4.14 – Histograms of non-thermal spectral index distribution in NGC 1569 and NGC 4214. Background radio sources RS4, RS5, RS6, and H were masked before generating the histograms. The mean and the standard deviations of the spectral indices are also indicated.
Figure 4.15 – Total magnetic field strength of NGC 1569 and NGC 4214 estimated assuming energy equipartition. Pixels with high thermal fraction have been masked. Pixels corresponding to background radio sources have also been masked. The 16′′ resolution of the non-thermal radio map used to compute the magnetic field strength is indicated in the lower left corner of each image. The LOFAR total intensity contour lines are drawn at the same level as in Figure 4.5.

where $\alpha$ is the non-thermal spectral index. Further assumptions, like path length through the synchrotron emitting media and the ratio of proton-to-electron number density, are needed to compute the equipartition magnetic field strength from the total intensity map.

The equipartition magnetic field strength maps of NGC 1569 and NGC 4214 shown in Figure 4.15 were computed using maps of non-thermal emission that were estimated in section 4.5. We did not compute the equipartition magnetic field maps for DDO 50 and NGC 2366 since they do not show significant diffuse radio emission as seen in NGC 1569 and in NGC 4214. While computing the magnetic field strengths, we assumed that the synchrotron path length is 1 kpc and that the ratio of the proton-to-electron number density is 100 (Bell 1978). Note that these assumptions do not affect the resulting magnetic field strengths significantly. Varying the path length and proton-to-electron number density by a factor of two results in less than a 20% change in the value of $B_{\text{tot}}$.

The mean equipartition magnetic field strength in the optical disk of NGC 1569 is about 32 $\mu$G. The mean magnetic field strength drops to about 16 $\mu$G in the halo. In the case of NGC 4214, the mean magnetic field strength is about 11.5 $\mu$G. Our estimates of equipartition magnetic field strength in NGC 1569 and in NGC 4214 confirm the values estimated by Kepley et al. (2010) and Kepley et al. (2011).

4.7 Search for polarized emission

We used the rotation measure (RM) synthesis technique (Brentjens & de Bruyn 2005) to search for polarized emission in our LOFAR data (see chapter 5 for more information on RM synthesis). For our observational setup, we have
4.7. SEARCH FOR POLARIZED EMISSION

Table 4.7 – Polarization imaging parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low resolution</th>
<th>High resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>250''</td>
<td>26''</td>
</tr>
<tr>
<td>Channel width</td>
<td>48.8 kHz</td>
<td>48.8 kHz</td>
</tr>
<tr>
<td># of channels</td>
<td>850</td>
<td>849</td>
</tr>
<tr>
<td>$\lambda_{\text{min}}$</td>
<td>1.805 m ($\nu = 166.087$ MHz)</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{\text{max}}$</td>
<td>2.493 m ($\nu = 120.238$ MHz)</td>
<td></td>
</tr>
<tr>
<td>UV limit</td>
<td>10 – 800$\lambda$</td>
<td>80 – 10000$\lambda$</td>
</tr>
<tr>
<td>robust value</td>
<td>1.0</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

$\lambda_{\text{min}} = 1.805$ m and $\lambda_{\text{max}} = 2.493$ m resulting in a resolution of FWHM = 1.172 rad m$^{-2}$ and the largest detectable scale $\phi_{\text{max}} = 0.964$ rad m$^{-2}$. Any magnetised structure wider than 0.964 rad m$^{-2}$ will be depolarized. Also note that RM synthesis rotates all instrumentally polarized emission to Faraday depth $\phi \approx 0$ rad m$^{-2}$. However, the ionospheric RM corrections applied in Section 4.2 smear the instrumentally polarized emission in Faraday depth space. The ionospheric RM corrections that we applied during calibration varies from 0.12 rad m$^{-2}$ to 0.25 rad m$^{-2}$. This implies polarized emission that appears between Faraday depths -1.052 rad m$^{-2}$ and 1.422 rad m$^{-2}$ is dominated by instrumental polarization.

Before making the Stokes Q and U channel maps, we flagged all ear-to-ear baselines in the LOFAR core to avoid cross-talk which is known to occur within the station cabinet electronics. We imaged our calibrated visibilities at two different resolutions: 30'' and 250''. The low resolution channel maps were used to detect weak, diffuse polarized emission from the Galactic foreground while the higher resolution maps were used to search for polarized emission from NGC 1569. The channel maps were made using the AWImager (Tasse et al. 2013) and the imaging parameters used to make channel maps at the two different resolutions are listed in Table 4.7. AWImager estimates the time- and frequency-dependent LOFAR beam and applies the corrections during the visibility gridding and degridding steps. Due to low signal-to-noise in the individual channel maps, we did not perform deconvolution and used the “dirty” channel maps for RM synthesis. Since we did not deconvolve our channel maps, the data products produced by RM synthesis will not be affected by artefacts described in Pratley & Johnston-Hollitt (2016).

Inspecting the polarization cubes, we do not find any polarized emission towards any of the four dwarf galaxies in our sample. However, we do detect linearly polarized emission from the Galactic foreground and from a few extragalactic radio sources. While a detailed analysis of polarized emission at low radio frequencies from the Galaxy and from background radio sources is beyond the scope of this thesis, we present some preliminary results to demonstrate the quality of the polarization data.
4.7.1 Polarized Galactic foreground

Figure 4.16 shows diffuse polarized emission from the Galactic foreground at four different Faraday depths. Polarized intensity in the maps are displayed in brightness temperature units using the conversion factor of 1 Jy/beam = 949.84 K estimated close to the center of the band at 143.5 MHz using equation 9-25 from Wrobel & Walker (1999).

The maps shown in Figure 4.16 are at Faraday depth 4.6, 5.6, 6.9, and 7.9 rad m$^{-2}$ and correspond to the LOFAR field of view centered on NGC 1569. The images show a filamentary structure extending from the bottom left corner of the field to the top right corner as one advances in Faraday depth. An interesting aspect of the linear feature seen in Figure 4.16 is that it can be traced in the LOFAR polarized intensity maps towards the nearby spiral galaxy IC 342 published by Van Eck et al. (2017)\textsuperscript{8}. Note that IC 342 is about 5° away from NGC 1569. The orientation and morphology of the filamentary structure visible in our Faraday depth cube is similar to that seen by Van Eck et al. (2017) (see their figures 5 and 7) suggesting that the polarized emission from the Galactic foreground is caused by a single magnetised structure which spans a few degrees in angular extent.

Similar linear features in polarized intensity have been using a variety of radio telescopes (Wieringa et al. 1993; Duncan et al. 1999; Jelić et al. 2014, 2015; Lenc et al. 2016) and some have also noticed striking similarities between H I filaments and the polarized structures (see Clark et al. 2014, and references therein). While the origin of such filamentary structures in the ISM is still unclear, polarized intensity images like the ones shown in Figure 4.16 indicate that the physical mechanism giving rise to them span a large angular distances in the sky consistent with MWA results over large sky area (Lenc et al. 2016).

4.7.2 Polarized emission from a giant radio galaxy

The inverse relationship between the field of view of a radio telescope and the observing frequency implies that observations at low radio frequencies will have larger fields of view compared to their high frequency counterparts. Furthermore, modern radio telescopes like LOFAR are constructed using fixed dipoles (instead of steerable dishes) whose sensitivity pattern on the sky results in large fields of view. Consequently, low frequency observations tend to contain other interesting radio sources in addition to the primary science target and the LOFAR datasets discussed in this chapter are no exception.

While hunting for interesting radio sources other than the primary science target, we identified an extended (about 7.7 in angular extent) double-lobed source in the DDO 50 dataset about 1.5 degrees away from the pointing center. The total intensity image of the radio source is shown in the left panel of Figure 4.17. Cross-matching the source with the NASA/IPAC Extragalactic Database, the extended radio source turned out to be the known giant radio galaxy 8C 0821+695 (Lacy et al. 1993). Located at a redshift of $z = 0.538$, an

\textsuperscript{8}The top right corner of the field of view shown in Fig 4.16 coincides with the bottom-left corner of the field of view published in Fig 5 of Van Eck et al. (2017).
Figure 4.16 – Diffuse polarized emission from the Galactic foreground at four different Faraday depths.
angular extent of 7.7' corresponds to a projected linear size of about 2.65 Mpc. Also, notice that the northern lobe shows a tail-like structure near its base which is a canonical sign of gas backflow interacting with a density gradient in the surrounding medium (Leahy & Williams 1984).

VLA observations at 1.4 GHz reveal linearly polarized emission from both the northern and the southern lobes with a mean polarization fraction of 23 and 26% respectively (Lara et al. 2000). Inspecting the Faraday depth cube for any polarization feature towards the giant radio galaxy, we identified polarized emission from the northern lobe corresponding to a Faraday depth of -22 rad m$^{-2}$. The Faraday depth spectrum towards the northern lobe of the giant radio galaxy is shown in the right panel of Figure 4.17. We do not detect any polarized emission from the southern lobe.

In addition to the giant radio galaxy, visual inspection of the Faraday depth cubes revealed the presence of several other polarized extragalactic sources within the field of view of all four LOFAR HBA datasets discussed in this chapter. However, catalogues obtained through visual inspection of large datasets like these tend not to be complete and are prone to selection biases. Recently, a number of automated polarization source detection and characterisation pipelines have been developed (Farnes et al. 2017; Van Eck et al. 2018, and Neld et al., submitted) within the LOFAR Magnetism Key Science Project (Beck et al. 2013). We aim to re-process the polarization data products using these automated pipelines and publish a catalogue of polarized extragalactic sources elsewhere.

### 4.8 Discussion

In this chapter, we present sensitive low-frequency radio continuum images of four nearby dwarf galaxies. Comparing the total integrated flux density measured at 143 MHz with flux density values measured at higher frequencies reported in the literature, we find that the integrated flux densities of all four galaxies can be best fitted using a single power-law implying none of the observed dwarf galaxies show any sign of spectral flattening at low radio frequencies. However, we observe non-thermal spectral index consistent with $\alpha \sim 0$ towards multiple star-forming regions. Relativistic cosmic ray electrons that produce synchrotron emission are thought to be injected into the interstellar medium by supernova remnants. When a population of relativistic cosmic ray electron with an energy spectrum $Q(E) \propto E^p$ is accelerated in a magnetic field, they emit synchrotron emission. The spectral index of the energy spectrum $p$ is related to the spectral index of the emitted synchrotron $\alpha$ through the relation $\alpha = (1 - p)/2$. Observations of supernova remnants in the Galaxy (Kothes et al. 2006; Green 2009) and models of shock acceleration in supernova remnants Bell (1978) indicate that $p \sim -2$ implying that the injection spectral index of cosmic ray electrons in galaxies is $\alpha \sim 0.5$. The observed non-thermal spectral index flatter than the injection index in sites of intense star formation in NGC 1569 and in NGC 4214 suggest that synchrotron emission from these regions undergo free-free absorption.
Figure 4.17 – Left: LOFAR HBA total intensity image of the giant radio galaxy 8C 0821+695 located at redshift $z = 0.53$. The LOFAR contour lines are drawn at $7 \times 2^n$ mJy/beam where $n = 1, 2, 3, \ldots$. The location where the polarization emission is detected is indicated using a ‘+’ symbol.

Right: Faraday depth spectrum for the region indicated with a ‘+’ symbol on the image on the left. The Faraday depth spectrum show two peaks near Faraday depth $-22$ rad/m$^2$ and 0 rad/m$^2$. The feature near Faraday depth 0 rad/m$^2$ (enclosed by the two vertical lines) is due to instrumental polarization while the peak near Faraday depth $-22$ rad/m$^2$ corresponds to polarized emission from the giant radio galaxy.
Of the four dwarf galaxies studied in this chapter, NGC 1569 shows the most extended radio continuum emission. Our LOFAR radio images reveal the presence of radio continuum emission in the halo of NGC 1569 up to a distance of \(\sim 4\) kpc from the galactic disk. The extended low frequency radio halo seen around NGC 1569 is morphologically similar to the radio continuum halos detected around normal late-type galaxies like NGC 891 and NGC 5775 where kpc-scale extensions are seen perpendicular to the galactic disk (see for example Ekers & Sancisi 1977; Soida et al. 2011; Mulcahy et al. 2018). In normal edge-on galaxies, the extended radio halo is typically seen only above the star-forming disk (see for example Dahlem et al. 2006) and this vertical extension seen only above the star-forming disk appears to hold in the case of NGC 1569 as well (see Figure 4.7). Furthermore, based on H\(\alpha\) and radio continuum observations of late-type spiral galaxies, Dahlem et al. (2006) reported a direct, linear relationship between the radial extent of radio continuum halos and the sizes of star-forming regions in the disks of the host galaxies (also see Dahlem et al. 1995; Tüllmann et al. 2006a,b). Dahlem et al. (1995) argued that there exists a threshold in energy input to the ISM (through supernova feedback) above which it is possible to launch outflows driving gas and cosmic ray electrons into the halo. They also observed that relatively compact regions of star formation are more likely to produce an extended halo than galaxies with widely spread star formation. This implies that regions with intense star formation are more likely to give rise to the “break out condition” necessary for matter to escape the galactic disk in the form of galactic chimneys (Norman & Ikeuchi 1989). Given the presence of filamentary structure seen in H\(\alpha\) in the halo of NGC 1569, regions with intense star-formation in the galactic disk, and the radial steepening of non-thermal spectral index in the extended radio halo, it is very likely possible that a galaxy-wide wind similar to the disk-halo interaction first defined in Norman & Ikeuchi (1989) is at play in NGC 1569.

The presence of a large-scale wind in dwarf galaxies can be of vital importance to the various models that attempt to explain the magnetization of the intergalactic medium using primeaeval galaxies. Kronberg et al. (1999) proposed that burst-like star formation in the shallow potential wells of the first galaxies can give rise to magnetised outflows which can pollute the immediate vicinity of the first galaxies with seed magnetic fields. Kronberg et al. (1999) showed that acausal diffusion (Hogan 1983) of the seed magnetic field combined with cosmological expansion of the universe can propagate the fields to large-scales within a Hubble time. Hydrodynamic simulations and radio polarimetry observations of superbubbles in nearby spiral galaxies indicate that starburst-driven galactic outflows can transport the ordered magnetic field lines from the inner regions of galaxies to the outer halo (see for example Brandenburg et al. 1995; Chyży et al. 2011; Heald 2012). Furthermore, numerical simulations such as the one carried out by Bertone et al. (2006) do show that a significant fraction of the cosmological volume can be magnetised through seed magnetic fields in the range of \(10^{-12} \lesssim B \lesssim 10^{-8}\) G setup by outflows from the first galaxies (see also Dubois & Teyssier 2010). However, direct observations of the first galaxies to test this scenario are impossible even with the sensitivity of the next generation radio
telescopes like the Square Kilometre Array (SKA). However, nearby star-burst dwarf galaxies like NGC 1569 are considered to be the closest analogues to the first galaxies (see for example Steidel et al. 1996). Thus, a detailed model for the propagation of cosmic rays in the halos of dwarf galaxies and the various physical processes that give rise to outflows is key to figuring out whether the first galaxies could be responsible for magnetizing the early universe.

Finally, as mentioned briefly in the introduction, one of the objectives behind our pilot LOFAR observations of dwarf galaxies discussed in this chapter was to prepare for the upcoming LoTSS data release by getting a sense for the sort of science that can be carried out using sensitive radio continuum images of nearby dwarf galaxies at $\sim 150$ MHz. Observations for our pilot study were carried out using the same observational setup that is employed by the LoTSS survey. The results from our study clearly demonstrate that radio images from the LoTSS survey (with a sensitivity of about $100 \mu$Jy/beam$^9$ at $5''$ resolution) might not be sensitive enough to detect weak, diffuse emission from the radio halos around all nearby dwarf galaxies. From the radio continuum images shown in this chapter, we can see quite clearly that while extended radio emission is detected around the brightest nearby dwarf galaxies like NGC 1569, we do not detect any diffuse emission from even moderately bright galaxies like NGC 2366 and DDO 50. Thus, to be able to detect the diffuse component of the radio continuum emission from nearby dwarf galaxies and to study the propagation of cosmic ray electrons in their halos, deeper observations with both LOFAR LBA and HBA are needed. A brief motivation to pursue this line of research further is provided in chapter 6.

4.9 Summary and conclusions

In this chapter, we have presented a pilot study with the LOFAR High Band Antenna to produce deep, resolved radio continuum images of four nearby dwarf galaxies. The key findings are summarised as follows:

- The low frequency total intensity radio continuum map of NGC 1569 and NGC 4214 show diffuse extended emission as compared to previous sensitive observations at 20cm. In NGC 1569, the diffuse emission is more extended by $\sim 1'$ especially in the northern part of the radio halo.

- The integrated radio continuum spectra of all four dwarf galaxies can be fitted with a single power-law spectral index showing no indications of spectral flattening at low frequencies. However, on small scales, non-thermal spectral indices flatter than the injection spectral index ($\sim 0.5$) are seen towards several star-forming regions in all four dwarf galaxies hinting at the presence of free-free absorption in H$\text{\textsc{ii}}$ regions. Further observations in the $30 - 70$ MHz frequency range using the LOFAR LBA array are required to determine if these regions exhibit spectral turnover.

\footnote{Note that the “true” sensitivity limit in each LoTSS image can deviate from this advertised $100 \mu$Jy/beam limit due to several reasons like changing RFI conditions around the telescope, the presence of bright off-axis sources, and bad ionospheric conditions.}
• Less than 15% of the radio continuum emission observed at 143 MHz appears to be thermal for all galaxies except NGC 2366. About 50% of the radio continuum emission from NGC 2366 at 143 MHz appears to be thermal. This is not surprising given that the two giant H\textsubscript{II} regions dominate the radio continuum morphology of the galaxy.

• Assuming energy equipartition, we estimated the total magnetic field strength in NGC 4214 and NGC 1569. The mean magnetic field strength in NGC 4214 is about 11.5 $\mu$G. In the case of NGC 1569, the mean magnetic field in the inner galaxy is about 32 $\mu$G and falls down to 16 $\mu$G in the halo.

• No linear polarization was detected towards any of the four dwarf galaxies studied in this chapter. However, the Faraday depth cubes reveal linearly polarized emission from the Galactic foreground and several polarized extragalactic radio sources (including one lobe of a giant radio galaxy at a redshift of 0.538).

• Faraday depth images of the Galactic foreground generated using the linearly polarized emission from the NGC 1569 field show filamentary structure spanning several degrees in angular size.

• Imaging products released by the LOFAR Tier-1 Sky Survey (LoTSS) will not be sensitive enough to detect diffuse radio halos around all nearby dwarf galaxies.