A multifrequency radio continuum study of the Magellanic Clouds – I. Overall structure and star formation rates


Affiliations are listed at the end of the paper

Accepted 2018 July 15. Received 2018 June 27; in original form 2018 January 7

ABSTRACT

We present the first low-frequency Murchison Widefield Array (MWA) radio continuum maps of the Magellanic Clouds (MCs), using mosaics from the GaLactic Extragalactic All-Sky MWA (GLEAM) survey. In this paper, we discuss the overall radio continuum morphology between 76 and 227 MHz and compare them with neutral hydrogen maps, 1.4 GHz continuum maps and optical images. Variation of diffuse emission is noticeable across the Large Magellanic Cloud (LMC) but absent across the bar of the Small Magellanic Cloud (SMC). We also measure the integrated flux densities and derive the spectral indices for the MCs. A double power-law model with fixed $\alpha_1 = -0.1$ fit between 19.7 MHz and 8.55 GHz yields $\alpha_0 = -0.66 \pm 0.08$ for the LMC. A power-law model yields $\alpha_{85.5\text{MHz}} = -0.82 \pm 0.03$ for the SMC. The radio spectral index maps reveal distinctive flat and steep spectral indices for the H II regions and supernova remnants, respectively. We find strong correlation between H II regions and H$\alpha$ emission. Using a new 150 MHz–H$\alpha$ relation as a star formation rate indicator, we estimate global star formation rates of 0.068–0.161 M$\odot$ yr$^{-1}$ and 0.021–0.050 M$\odot$ yr$^{-1}$ for the LMC and SMC, respectively. Images in 20 frequency bands, and wideband averages are made available via the GLEAM virtual observatory server.

Key words: radiation mechanisms: non-thermal – radiation mechanisms: thermal – Magellanic Clouds – radio continuum: galaxies.

1 INTRODUCTION

The Large and Small Magellanic Clouds (LMC and SMC) lie at a distance of about 50 and 60 kpc (Hilditch, Howarth & Harries 2005; Pietrzyński et al. 2013), respectively, and are among the closest extragalactic neighbours of our Galaxy. The close proximity of the Magellanic Clouds (MCs) provides an ideal laboratory for us to probe different physical mechanisms in great detail. Pioneering studies of the MCs in radio continuum emission date back to the 1950s (see e.g. Mills 1955; Shain 1959). Subsequent studies have been carried out to either focus on individual objects (e.g. supernova 1987A; Zanardo et al. 2010 and references therein) or large-scale radio structure and total radio spectrum of the MCs (Haynes et al. 1991 and references therein; Hughes et al. 2007). Aside from radio continuum studies, there have been many other comprehensive multiwavelength studies to date (see e.g. Jameson et al. 2016). Yet, there is more to learn about these nearby galaxies.

E-mail: biqing.for@uwa.edu.au

© 2018 The Author(s)
Published by Oxford University Press on behalf of the Royal Astronomical Society
Radio continuum studies probe two main astrophysical properties: non-thermal synchrotron emission that is generated by relativistic charged particles accelerated in magnetic fields; and thermal free–free emission from ionized hydrogen clouds (Hi regions; Liskenfeld & Völk 2000). The former partly originates from discrete supernova remnants (SNRs). However, studies have shown that only about 10 per cent of the non-thermal synchrotron emission is originated from SNRs (Lisenfeld & Völk 2000) and about 90 per cent probably due to the propagation of cosmic ray electrons and relativistic charged particles accelerated in magnetic fields; and thermal free–free emission from ionized hydrogen clouds (Hi regions; Liskenfeld & Völk 2000).

The intensity of thermal free–free emission is directly proportional to the total number of Lyman continuum photons. In the optically thin regime, the spectrum of a galaxy can generally be described by a power-law function, \( S = \alpha \nu^\beta \), where \( S \) is the radio flux density at a given frequency, \( \nu \), and \( \alpha \) is the spectral index (or power-law slope). The spectrum is “flat” when \( \alpha \approx -0.1 \). Steep spectra with \( \alpha \approx -0.8 \) are commonly observed in star-forming galaxies (see Marvil, Owen & Eilek 2015 and references therein). Low-frequency turnover occurs when the optical depth changes from optically thin to optically thick due to absorption process.

With new state-of-the-art low-frequency telescopes, such as the Murchison Widefield Array (MWA; Lonsdale et al. 2009; Bowman et al. 2013; Tingay et al. 2013), it is feasible to carry out new continuum surveys with fast survey speeds to probe astrophysical processes at these frequencies. In this paper, we present a multifrequency study of the MCs using data from the GaLactic Extragalactic All-sky MWA (GLEAM) survey (Wayth et al. 2015; Hurley-Walker et al. 2017), the Parkes single-dish radio telescope and radio interferometer data from the Australia Telescope Compact Array (ATCA). In Section 2, we describe the GLEAM observations and data reduction. We show the radio continuum maps of the MCs and discuss their morphology in comparison with the integrated neutral hydrogen (HI) maps and optical images in Section 3. Our analysis and results are presented in Section 4. In Section 5, we derive the global star formation rates. Our investigation of spatial variation of the spectral index among H II regions, a possible turnover frequency study of the MCs using data from the GaLactic Extragalactic All-sky MWA (GLEAM) survey (Wayth et al. 2015; Hurley-Walker et al. 2017), the Parkes single-dish radio telescope and radio interferometer data from the Australia Telescope Compact Array (ATCA). In Section 2, we describe the GLEAM observations and data reduction. We show the radio continuum maps of the MCs and discuss their morphology in comparison with the integrated neutral hydrogen (HI) maps and optical images in Section 3. Our analysis and results are presented in Section 4. In Section 5, we derive the global star formation rates. Our investigation of spatial variation of the spectral index among H II regions, a possible turnover frequency

The overall radio continuum morphology of the LMC shows a distinct asymmetry, with the eastern side being brighter and compressed. This asymmetry is also visible in the combined single-dish (Parkes) and interferometer (ATCA) HI map (Kim et al. 2003; Staveley-Smith et al. 2003) and 4.75 GHz (Haynes et al. 1991) radio continuum maps, are also visible in the GLEAM sub-bands images.

The "arm" structures as seen in the HI map, as well as the 1.4 GHz (Feitzinger et al. 1987) and 4.75 GHz (Haynes et al. 1991) radio continuum maps, are also visible in the GLEAM sub-bands images.

The most noticeable concentration of radio continuum emission is at the largest HI region, 30 Doradus, where the HI column density is high enough to fuel star formation. The lesser explored star-forming complex, N79, in the south-west region of the LMC has recently been reported to possess more than twice the star formation efficiency of 30 Doradus (Ochsendorf et al. 2017). Interestingly, for both N11 and N79 which are among the largest star-forming regions in the LMC, the radio continuum is relatively weak in all GLEAM sub-bands. Other patches of strong emission are also consistent

2 OBSERVATIONS AND DATA REDUCTION

The MWA is a low-frequency radio interferometer operating between 70 and 300 MHz. It was designed to have a wide field of view (15°–50°) and a short-medium baseline distance suitable for detecting the faint redshifted 21-cm spectral line emission from the Epoch of Reionization (EoR), as well as supporting a wide range of other astrophysics applications (Bowman et al. 2013). Phase 1 of the MWA consisted of 128 32-dipole antenna tiles that spread across an area of ~3 km in diameter. We refer the reader to Tingay et al. (2013) for technical details.

The GaLactic Extragalactic All-sky MWA (GLEAM) survey is the main MWA continuum survey that covers the sky south of declination +30° with a frequency range of 72–231 MHz split into five separated sub-bands (Wayth et al. 2015). The data were collected in nightly drift scans, where all frequencies for a single declination strip were observed each night. The data reduction process is described in detail in Wayth et al. (2015) and Hurley-Walker et al. (2017). To summarize, raw visibility data were processed using COTTER (Offringa et al. 2015), which performs flagging and averaging of the visibility data to a time resolution of 4 s and a frequency resolution of 40 kHz. Subsequent calibration involved the creation of a sky model for each observation, “peeling” to minimize sidelobes from the bright sources, and astrometric correction for ionospheric effects. Lastly, a single mosaic per sub-band is obtained by combining all declination strips from each week of observations. A slight apparent blurring of the point spread function (PSF) is noted due to slightly different ionospheric conditions in the 20–40 observations per pixel. To take this into account, PSF maps are created for each mosaic as a function of position on the sky, with three channels whose pixels represented the major axis, minor axis, and position angle.

We employ the final flux calibrated mosaic imaged with robust weighting of 0 (Briggs 1995) for this study because the theoretical noise is lower than standard GLEAM data reduction, and the brightness sensitivity is higher. Uncertainty in the flux density scale mainly arises from the declination-dependent flux density correction. The systematic uncertainty (\( \sigma_{\text{scale}} \)) is derived as the standard deviation of a Gaussian fit to the residual variation in the ratio of predicted to measured source flux densities. The systematic uncertainties for the studied regions are 8.5 per cent (LMC) and 13 per cent (SMC) (Hurley-Walker et al. 2017).

3 RADIO CONTINUUM MAPS OF THE MAGELLANIC CLOUDS

We present a series of selected GLEAM images of the MCs in Fig. 1. Due to varying PSF across the large area of the MCs images, we derive the synthesized beam sizes by averaging the values of the corresponding PSF map of each band for the analysed area. The typical PSF variation across each field is 15–20 per cent. A summary of the observed central frequency, synthesized beam, pixel area, and average noise level (RMS) for the 20 GLEAM sub-bands images is given in Table 1. We present combined three colour composite images of the LMC and SMC in Fig. 2. Optically thick HI regions appear to be bluer due to their positive steep spectral index (\( \alpha \approx 2 \); Condon 1992).

The overall radio continuum morphology of the LMC shows a distinct asymmetry, with the eastern side being brighter and compressed. This asymmetry is also visible in the combined single-dish (Parkes) and interferometer (ATCA) HI map (Kim et al. 2003; Staveley-Smith et al. 2003) as shown by the contours in Fig. 3. We note that the compressed side of the LMC is facing the direction of proper motion of the LMC (Kallivayalil et al. 2013; van der Marel & Kallivayalil 2014) and leading the trailing Magellanic Stream. The “arm” structures as seen in the HI map, as well as the 1.4 GHz (Feitzinger et al. 1987) and 4.75 GHz (Haynes et al. 1991) radio continuum maps, are also visible in the GLEAM images.

The most noticeable concentration of radio continuum emission is at the largest HI region, 30 Doradus, where the HI column density is high enough to fuel star formation. The lesser explored star-forming complex, N79, in the south-west region of the LMC has recently been reported to possess more than twice the star formation efficiency of 30 Doradus (Ochsendorf et al. 2017). Interestingly, for both N11 and N79 which are among the largest star-forming regions in the LMC, the radio continuum is relatively weak in all GLEAM sub-bands. Other patches of strong emission are also consistent
Figure 1. Selected radio images of the LMC and SMC from the GLEAM survey. From top left to bottom right are images centred at 92, 115, 143, 166, 189, and 212 MHz. The grey scale is in units of Jy beam$^{-1}$. 

A radio continuum study of the MCs
Table 1. Basic information for the GLEAM images in this study. \( \nu \) represents the central frequency of the observed sub-band. \( \sigma \) is the average rms of three selected emission free regions. Synthesized beams are derived from the associated PSF map (Section 2).

<table>
<thead>
<tr>
<th>( \nu ) (MHz)</th>
<th>FWHMLMC (arcsec)</th>
<th>FWHMSMC (arcsec)</th>
<th>Pixel Size (arcsec)</th>
<th>( \sigma_{\text{LMC}} ) (Jy beam(^{-1}))</th>
<th>( \sigma_{\text{SMC}} ) (Jy beam(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>76</td>
<td>471.5 \times 411.6</td>
<td>495.4 \times 455.6</td>
<td>61.2</td>
<td>0.092</td>
<td>0.079</td>
</tr>
<tr>
<td>84</td>
<td>423.5 \times 370.5</td>
<td>443.0 \times 410.2</td>
<td>61.2</td>
<td>0.056</td>
<td>0.059</td>
</tr>
<tr>
<td>92</td>
<td>390.4 \times 343.1</td>
<td>407.2 \times 378.2</td>
<td>61.2</td>
<td>0.056</td>
<td>0.063</td>
</tr>
<tr>
<td>99</td>
<td>367.6 \times 319.6</td>
<td>380.4 \times 353.9</td>
<td>61.2</td>
<td>0.068</td>
<td>0.055</td>
</tr>
<tr>
<td>107</td>
<td>334.5 \times 294.5</td>
<td>356.8 \times 333.0</td>
<td>45.4</td>
<td>0.041</td>
<td>0.041</td>
</tr>
<tr>
<td>115</td>
<td>307.3 \times 272.5</td>
<td>328.0 \times 306.4</td>
<td>45.4</td>
<td>0.036</td>
<td>0.036</td>
</tr>
<tr>
<td>123</td>
<td>289.3 \times 256.8</td>
<td>309.8 \times 288.2</td>
<td>45.4</td>
<td>0.029</td>
<td>0.032</td>
</tr>
<tr>
<td>130</td>
<td>279.6 \times 246.6</td>
<td>293.4 \times 276.2</td>
<td>45.4</td>
<td>0.030</td>
<td>0.032</td>
</tr>
<tr>
<td>143</td>
<td>255.2 \times 220.9</td>
<td>271.8 \times 255.9</td>
<td>34.9</td>
<td>0.022</td>
<td>0.029</td>
</tr>
<tr>
<td>150</td>
<td>240.0 \times 208.3</td>
<td>254.4 \times 239.5</td>
<td>34.9</td>
<td>0.020</td>
<td>0.025</td>
</tr>
<tr>
<td>158</td>
<td>229.3 \times 198.8</td>
<td>242.6 \times 229.3</td>
<td>34.9</td>
<td>0.019</td>
<td>0.026</td>
</tr>
<tr>
<td>166</td>
<td>220.4 \times 190.8</td>
<td>234.5 \times 222.6</td>
<td>34.9</td>
<td>0.018</td>
<td>0.024</td>
</tr>
<tr>
<td>174</td>
<td>212.6 \times 184.7</td>
<td>224.5 \times 212.6</td>
<td>29.1</td>
<td>0.020</td>
<td>0.025</td>
</tr>
<tr>
<td>181</td>
<td>202.4 \times 177.2</td>
<td>214.4 \times 203.4</td>
<td>29.1</td>
<td>0.018</td>
<td>0.021</td>
</tr>
<tr>
<td>189</td>
<td>193.4 \times 168.6</td>
<td>208.1 \times 196.4</td>
<td>29.1</td>
<td>0.020</td>
<td>0.021</td>
</tr>
<tr>
<td>197</td>
<td>188.1 \times 163.9</td>
<td>202.1 \times 189.4</td>
<td>29.1</td>
<td>0.019</td>
<td>0.020</td>
</tr>
<tr>
<td>204</td>
<td>182.0 \times 157.9</td>
<td>197.2 \times 184.5</td>
<td>25.0</td>
<td>0.018</td>
<td>0.019</td>
</tr>
<tr>
<td>212</td>
<td>173.4 \times 150.9</td>
<td>189.2 \times 176.6</td>
<td>25.0</td>
<td>0.017</td>
<td>0.019</td>
</tr>
<tr>
<td>219</td>
<td>169.5 \times 147.0</td>
<td>183.4 \times 170.4</td>
<td>25.0</td>
<td>0.018</td>
<td>0.019</td>
</tr>
<tr>
<td>227</td>
<td>164.8 \times 142.9</td>
<td>178.9 \times 165.6</td>
<td>25.0</td>
<td>0.017</td>
<td>0.019</td>
</tr>
</tbody>
</table>

Figure 2. Three colour RGB composite images of the Magellanic Clouds using the combination of 123, 181, and 227 MHz images, respectively. Images are reprojected and regridded to a common projection and angular resolution of 123 MHz images prior to combination. Left: Large Magellanic Cloud in a 10\(^{\circ}\) \times \ 10\(^{\circ}\) image, Right: Small Magellanic Cloud in a 6\(^{\circ}\) \times \ 6\(^{\circ}\) image.

with supershell locations, where the shell interaction and expansion could also be triggering star formation.

An asymmetry is also seen in deep optical images of the LMC (Besla et al. 2016), except that the overdensity of the stellar component is located at the opposite side (west) of the radio continuum emission. Since the old stellar population results in this overdensity on the western side of the LMC, detection of radio continuum emission is not expected. The asymmetric feature as shown in both radio and optical has been studied in simulations and concluded to be evidence of tidal interaction between our Milky Way and the MCs and a result of ram-pressure (see Diaz & Bekki 2011; Besla et al. 2016; Mackey et al. 2016).

Fig. 3 (bottom panel) shows the 227 MHz radio continuum image of the SMC overlaid with HI contours (Stanimirovic et al. 1999). The overall morphology of the SMC's radio continuum emission is similar to HI, its stellar distribution, and with the dominant of
bright H II complexes across the bar. There is visible diffuse emission extending out from the bar region toward the south-east side (SMC wing) and the H II complexes (N83/84; Bolatto et al. 2003). The further extensions known as the SMC “tail” (Stanimirovic et al. 1999) and Magellanic bridge (Brüns et al. 2005) are quite distinct in H I. A stellar component has been found in the bridge suggesting stripped material due to tidal interaction (Harris 2007) but the young stellar component also suggests ongoing star formation (Chen et al. 2014).

4 ANALYSIS AND RESULTS

4.1 Integrated flux densities

To obtain the spatially integrated flux densities \(S_\nu\), we extract \(8^\circ \times 8^\circ\) and \(6^\circ \times 6^\circ\) images centred on the LMC and SMC, respectively, from the mosaic in each band. Subsequently, we mask out pixels below 3\(\sigma\) background noise level of the extracted GLEAM images. The background noise level (\(\sigma_{\text{RMS}}\)) is the average of measured values of three selected emission-free regions around the MCs. The same regions are used for all bands. The \(S_\nu\) is then calculated using

\[
S_\nu = \frac{S_{\text{total}} \times p^2}{1.133 \, \theta_a \, \theta_b},
\]

where \(S_{\text{total}}\) is the total flux density (Jy) of the \(8^\circ \times 8^\circ\) (LMC) or \(6^\circ \times 6^\circ\) (SMC) image, \(p\) is the pixel size, \(\theta_a\) and \(\theta_b\) are the full-width-half-maximum (FWHM) of the telescope beam’s major and minor axis (refer Table 1). We also measure \(S_\nu\) from archival 1.4 GHz (Hughes et al. 2007) and 4.8 GHz (Haynes et al. 1991) images of the LMC. As for the SMC, archival 1.4 GHz (Staveley-Smith et al. 1997) and 2.37 GHz (Filipović et al. 2002) images are also used for determining \(S_\nu\). The same integration areas as those applied to the GLEAM images are used to determine \(S_\nu\) for the archival data.

The 4.8 GHz LMC image and 2.37 GHz SMC image were observed by the single-dish Parkes 64-m telescope. Both 1.4 GHz images of the LMC and SMC are combined single-dish and interferometer data. All measurements are brought to the same absolute flux density scale of Baars et al. (1977).

The errors for the measured integrated flux density are determined using

\[
\sigma_{\text{total}} = \sqrt{(\sigma_{\text{image}})^2 + (\sigma_{\text{scale}})^2},
\]

where \(\sigma_{\text{image}}\) is equal to \(\sigma_{\text{RMS}} \times \sqrt{N}\). \(N\) is the integrated area in units of the synthesized beam area, and \(\sigma_{\text{scale}}\) is the systematic uncertainty in the flux scale (see Section 2).

Tables 2–3 summarize our measurements and values obtained from the literature at other frequencies. We note that flux densities at 85.5 and 96.8 MHz in Mills (1959) revised by Klein et al. (1989) are significantly higher than our measurements despite these values have been scaled to match the flux density scale of Baars et al. (1977) and corrected for unrelated foreground and background sources. Despite this discrepancy, we still include 85.5 and 96.8 MHz values in our spectral fitting.

The LMC is located in a region of sky in which the Galactic foreground emission is negligible at MHz and GHz frequencies. However, extended Galactic foreground emission is known to be present at the location of the SMC (see discussion in Haynes et al. 1991 and references therein). Examining the SMC region in the 408 MHz all-sky survey of (Haslam et al. 1981), we find that the strongest Galactic foreground emission is located beyond the \(6^\circ \times 6^\circ\) region that we use in this study. Measurements of Haynes et al. (1991) have taken into account for the extended Galactic foreground emission because of the larger imaging area than ours. Their studies were conducted using a single-dish telescope. With the use of interferometer data from the MWA, it is possible to resolve out flux from large-scale structure. Based on the shortest baseline of phase I MWA (7.7 m), the largest angular scales for 76 MHz and 227 MHz are 29° and 10°, respectively. Since these angular scales are larger than our studied regions, we do not expect our measurements to be affected by missing flux in the GLEAM images.
where $\nu$ is the reference frequency, and $S_{\nu}$ is defined as

$$S_{\nu} = S_0 \left( \frac{\nu}{\nu_0} \right)^{\alpha_0} + S_1 \left( \frac{\nu}{\nu_0} \right)^{\alpha_1}. \quad (3)$$

or in logarithmic form as

$$\log_{10}(S_{\nu}) = \log_{10}(S_0) + \alpha \log_{10} \left( \frac{\nu}{\nu_0} \right). \quad (4)$$

where $\nu_0$ is the reference frequency, $S_0$ is the flux density at the reference frequency, and $\alpha$ is the spectral index. A curved power law extends the power law to a quadratic function in logarithmic form that allows for a curvature parameter, $c$,

$$\log_{10}(S_{\nu}) = \log_{10}(S_0) + \alpha \log_{10} \left( \frac{\nu}{\nu_0} \right) + c \log_{10} \left( \frac{\nu}{\nu_0} \right)^2. \quad (5)$$

To select the best model, we first calculate the $\chi^2_{\text{red}}$ given by

$$\chi^2_{\text{red}} = \frac{\chi^2}{\text{dof}} = \frac{\chi^2}{N - k}. \quad (7)$$
where \( \text{dof} \) is the degree of freedom, \( N \) is the number of data points, and \( k \) is the number of fitted parameters. We also calculate the Bayesian Information Criterion (BIC; Schwarz 1978), which is defined as

\[
BIC = k \ln(N) - 2 \ln \hat{L},
\]

where \( \hat{L} \) is the likelihood function, \( k \) and \( N \) are the same parameters as in equation (7), \( S_{0i} \) and \( \sigma_{fi} \) are flux density and uncertainty at frequency \( v \), respectively. For comparing the two models, a \( \Delta BIC = BIC_{\text{model 1}} - BIC_{\text{model 2}} \) is calculated. If \( \Delta BIC \) is positive, it is in favour of model 2. The model with the lowest \( BIC \) is preferred and \( \Delta BIC \) needs to be \( > 2 \) to be statistically significant (Kass & Raftery 1995).

Our sequence of comparison starts from the first model and iteratively moves to the next model.

Based on the \( \Delta BIC \) values, we find the preferred model to be the double power law with fixed \( \alpha_1 = -0.1 \) (model 3) for the LMC. This model yields \( \alpha_0 = -0.66 \pm 0.08 \) (non-thermal). This suggests that synchrotron radiation dominates at lower frequencies and thermal free–free emission takes over at higher frequencies. For the SMC, \( \Delta BIC \) values of model 2–4 are negative which implies the power law (model 1) is the preferred model. A summary of the SED fitting results and associated statistical values is given in Table 4. Fig. 4 shows the best fitting models for the LMC and SMC, respectively.

### 4.2.2 Comparison with previous studies

The derived non-thermal spectral index \( \langle \alpha_0 \rangle = -0.66 \pm 0.08 \) between 19.7 MHz and 408 MHz, for the LMC is consistent with Klein et al. (1989), \( \alpha_{19.7 \text{ MHz}} = -0.70 \pm 0.06 \). For the SMC, we derive \( \alpha_{1.4 \text{ GHz}} = -0.82 \pm 0.03 \), which is also consistent with the literature value of \( \alpha_{1.4 \text{ GHz}} = -0.85 \pm 0.05 \) (Haynes et al. 1991). Comparing our derived spectral index of the SMC to the mean spectral index derived from all sources in the SMC \( \langle \alpha_{\text{SMC}} \rangle = -0.73 \pm 0.05 \); Filipovic et al. 1998), we do not find significant differences.

### 4.3 Intensity variation across the MCs

In Section 3, we show that the LMC exhibits an asymmetric morphology in the radio continuum map. We examine the intensity variation across the LMC in 10 MWA frequency bands (see Fig. 5). By dissecting the disc of the LMC through the 30 Doradus region, we find that there are a few peaks associated with the H\( \alpha \) regions and supernova remnants. The diffuse emission exhibits constant intensity on the eastern side. A gradual decline in intensity from right ascension \( \approx 5^\circ 16^\prime 48^\prime \) onward to the western end is noticeable. In the north–south direction, the intensity of diffuse emission declines when moving away from the 30 Doradus region. A steeper decline of intensity south of 30 Doradus is seen as compared to the northern part. Compared with the 1.4 GHz radio continuum intensity profiles as shown in Fig. 7 of Hughes et al. (2007), the north–south intensity profile is quite similar. We examined the intensity profiles across the bar and north–south direction of the SMC (not shown here), which show that there is no variation apart from a few intensity peaks contributed by the H\( \alpha \) regions.

### 4.4 Contribution from background radio sources

The areas we use for measuring the total flux densities of the MCs include background radio sources. The contribution from the background radio sources can be estimated using a median filtering method. This method has been shown to be successful in eliminating most of the background point sources in the 1.4 GHz radio continuum image (Hughes et al. 2007). Sources intrinsic to the MCs, such as the H\( \alpha \) regions, are more compact and not point like. Thus, median filtering will not eliminate them. We perform the median filtering of GLEAM images using the FMEDIAN task in the FTOOLS package (Blackburn 1995). The task convolves an image with a median value within a defined box. Various smoothing window parameters have been tested and we find that the optimal smoothing window for median filtering most of the background sources is \( 17 \times 17 \) pixels in size. Subsequently, the median-filtered maps are compared to their corresponding non-filtered maps. The results suggested a \( \approx 10 \) per cent of flux contribution from background sources at the lowest frequency band of GLEAM and \( \approx 20 \) per cent

### Table 4. A summary of the fits to the SED of the MCs using four different models discussed in the text. The reference frequency is 0.2 GHz.

<table>
<thead>
<tr>
<th></th>
<th>LMC</th>
<th>SMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \chi^2 )</td>
<td>61.5</td>
<td>32.3</td>
</tr>
<tr>
<td>( \chi^2_{\text{red}} )</td>
<td>2.0</td>
<td>1.2</td>
</tr>
<tr>
<td>BIC</td>
<td>466.6</td>
<td>297.9</td>
</tr>
<tr>
<td>dof</td>
<td>31</td>
<td>27</td>
</tr>
<tr>
<td>( S_0 )</td>
<td>1258.2 ± 43.0 Jy</td>
<td>192.2 ± 9.6 Jy</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>-0.47 ± 0.02</td>
<td>-0.82 ± 0.03</td>
</tr>
<tr>
<td>( c )</td>
<td>0.73 ± 0.10</td>
<td>0.33 ± 0.09</td>
</tr>
</tbody>
</table>

Double power law, fixed \( \alpha_1 = -0.1 \)

<table>
<thead>
<tr>
<th>Model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \chi^2 )</td>
</tr>
<tr>
<td>( \chi^2_{\text{red}} )</td>
</tr>
<tr>
<td>BIC</td>
</tr>
<tr>
<td>dof</td>
</tr>
<tr>
<td>( S_0 )</td>
</tr>
<tr>
<td>( \alpha_0 )</td>
</tr>
<tr>
<td>( S_1 )</td>
</tr>
</tbody>
</table>

Double power law, fixed \( \alpha_1 = -0.1 \)

<table>
<thead>
<tr>
<th>Model 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \chi^2 )</td>
</tr>
<tr>
<td>( \chi^2_{\text{red}} )</td>
</tr>
<tr>
<td>BIC</td>
</tr>
<tr>
<td>dof</td>
</tr>
<tr>
<td>( S_0 )</td>
</tr>
<tr>
<td>( \alpha_0 )</td>
</tr>
<tr>
<td>( S_1 )</td>
</tr>
<tr>
<td>( \alpha_1 )</td>
</tr>
</tbody>
</table>

1http://heasarc.gsfc.nasa.gov/ftools/
Figure 4. Spectral energy distribution of the Large (top) and Small (bottom) Magellanic Cloud. Orange circles, red triangles, and blue squares represent MWA values from the literature and re-derived measurements in this study, respectively (refer to Tables 2–3). Top: A double power-law model, with $\alpha_0 = -0.66 \pm 0.08$ and $\alpha_1 = -0.1$, is fitted to the LMC spectrum as shown by the black dashed line. Bottom: A power law with $\alpha = -0.82 \pm 0.03$ is fitted to the SMC spectrum.

at the highest frequency band. We note that the difference in background sources contribution between lowest and highest GLEAM frequency band is probably due to resolution effect given that the spectral index of background sources is independent of frequency. Since this filtering method does not distinguish background point sources and point sources intrinsic to the MCs (Hughes et al. 2007), we do not subtract the contribution when measuring the total integrated flux densities.

4.5 Radio spectral index maps

The spectral index maps allow us to separate the thermal and non-thermal emission of the MCs. We use all GLEAM images but only present the spectral index maps from the GLEAM 166 MHz and the 1.4 GHz images. The GLEAM 166 MHz image is chosen because of its intermediate sensitivity and resolution that emphasizes both diffuse emission and discrete sources.

Figure 5. Intensity profiles of the LMC in a logarithmic scale. Top: 166 MHz image over $10^\circ \times 10^\circ$. The red lines represent the slice axes in an interval of 0.02 $^\circ$ across 30 Doradus for the intensity profiles. The grey scale is in units of Jy beam$^{-1}$. Middle: Intensity profile in east-west direction. Bottom: Same as top except for south–north direction.
The 1.4 GHz images are convolved and regridded to match the resolution and pixel scale of the GLEAM images. Then, the spectral index maps are made measuring

\[ \alpha = \log_{10}(S_{\text{1.4 GHz}}/S_{\text{150 MHz}})/\log_{10}(S_{\text{GLEAM}}/1.4 \text{ GHz}), \]

for all pixels above 3\( \sigma \). Fig. 6 shows the variation of spectral indices across the LMC. The H\( \alpha \) regions are easily recognized from their radio spectra (\( \alpha > -0.1 \)). We zoom in to show two known H\( \alpha \) regions: 30 Doradus and N11, in the right-hand panels (a) and (b). At an angular resolution of \( \sim 3.7 \) arcmin, both H\( \alpha \) regions are not completely resolved at 166 MHz. The supernova remnant N132D as shown in right-hand panel (c) reveals a steep negative spectrum (\( \alpha \sim -0.7\pm0.02 \)), which is in good agreement with the derived spectral index (\( \alpha = -0.65\pm0.04 \)) from Bozzetto et al. (2017). The steep negative spectrum also indicates the non-thermal synchrotron emission from the shock fronts (Vogt & Dopita 2011). A similar spectrum (\( \alpha \sim -0.74\pm0.02 \)) is also derived between 0.072 and 8.64 GHz for SNR 1987A (Callingham et al. 2016).

In the top panels of Fig. 7, we compare the radio spectral index maps with the H\( \alpha \) images (shown in contours) from the Southern H-Alpha Sky Survey Atlas (SHASSA; Gaustad et al. 2001). The H\( \alpha \) images are in units of deciRayleighs (dR), where 1 R = \( 10^6 \) photons per 4\( \pi \) steradian = \( 2.42 \times 10^{-7} \) ergs cm\(^{-2} \) s\(^{-1} \) sr\(^{-1} \). They have a resolution of 0.8 arcmin and are convolved and regridded to match the resolution and pixel scale of the radio spectral index maps. Comparison shows a strong correlation between radio spectral index and H\( \alpha \) emission in giant H\( \alpha \) regions and star-forming complexes, which potentially also emit non-thermal emission. In Fig. 8, we show a pixel–pixel plot of H\( \alpha \) emission versus spectral index focused on the N66 H\( \alpha \) region. The calculated Pearson’s correlation coefficient is 0.89. Overlaying the 166 MHz intensity contours on to the H\( \alpha \) images shows the boundary of the diffuse emission at low frequency. There is a lack of diffuse emission in the south-west region of the LMC and the diffuse emission is slightly more extended than the H\( \alpha \) emission (bottom panels of Fig. 7).

5 STAR FORMATION IN THE MAGELLANIC CLOUDS

There are many star formation rate (SFR) indicators, ranging from ultraviolet, optical, infrared to radio wavelength (e.g. Kennicutt 1998; Bell 2003; Wu et al. 2005). Ultraviolet stellar continuum and optical recombination lines (H\( \alpha \)) have been widely used in the past but are both affected by dust attenuation. Efforts to find a better star formation indicator to circumvent the dust attenuation problem have turned to infrared (IR) and radio (e.g. Bell 2003; Calzetti et al. 2007). However, it is cautioned that using IR alone can present issues, such as heating of dust by hot evolved stars, which radiate at IR wavelength (e.g. Kennicutt 1998), and large uncertainties in extrapolation of IR luminosity in intermediate or high-redshift studies (e.g. Chapman et al. 2005). The calibration of SFR using far-IR and radio wavelengths has focused on higher frequency (>1.4 GHz) radio continuum emission. With recent radio continuum studies using low-frequency wavelengths, such as LOFAR (Low-Frequency Array; van Haarlem et al. 2013) and MWA, a new spectral window has been opened to investigate SFR using far-IR to radio continuum emission correlation down to 150 MHz (Brown et al. 2017; Calistro Rivera et al. 2017). A comprehensive study to calibrate SFR indicators at different wavelengths on an homogeneous scale has been carried out by Brown et al. (2017), hereafter B17. This study uses the 150 MHz flux densities of sources from the GLEAM catalogue (Hurley-Walker et al. 2017) to calibrate the SFR at low redshift. The LOFAR study provides SFR calibration of 150 MHz in a higher redshift regime (Calistro Rivera et al. 2017).

We employ the 150 MHz–H\( \alpha \) relation in table 4 of B17 to calculate the global SFRs for the LMC and SMC. We find that the resulting SFRs depend on the adopted initial mass function (IMF). Conversions between SFR and the 150 MHz–H\( \alpha \) relation based on the IMF of Salpeter (1955), Kroupa (2001), Chabrier (2003) and Baldry & Glazebrook (2003) are given in B17. For comparison with the literature values, we calculate the global SFRs for the LMC and SMC using above IMFs. This yield 0.106 M\(_\odot\) yr\(^{-1}\) (LMC) and
Figure 7. Top panels: Contours of Hα at 2500 dR (black) and 10000 dR (green) overlaid on to the spectral index maps. Bottom panels: Intensity contours of 166 MHz continuum map at 0.1 Jy beam$^{-1}$ (white) and 0.4 Jy beam$^{-1}$ (green) overlaid on to the SHASSA Hα image.

Figure 8. An example of the relationship between Hα emission and spectral index in an H II region (N66) in the SMC.

6 H II REGIONS

The ionizing Lyman continuum photons from young massive OB stars are the cause of their surrounding H II regions. In these regions, the strong correlation between Hα and radio continuum emission indicates a thermal origin (only $\alpha \sim -0.1$). Pellegrini et al. (2012)
We assume $T$ in the optically thin regime. In this regime, the thermal spectral rate of Lyman continuum photons and varies weakly with electron density. Star-forming regions are the main contributors to the H II regions in Pellegrini et al. (2012) and SNRs in Bozzetto et al. (2017). The total $S_e$ from the SMC discrete sources is $\sim 59$ Jy. These yield $\sim 21$ per cent and $\sim 23$ per cent of the emission attributed to individual sources at 150 MHz for the LMC and SMC, respectively.

### Table 5. Lower limit of Lyman continuum photon production rates of selected H II regions in the LMC with $\alpha > 0$ (see section 6.1).

<table>
<thead>
<tr>
<th>Source</th>
<th>MCELS ID</th>
<th>R.A. (J2000) (h:m:s)</th>
<th>Decl. (J2000) ($^\circ$ arcmin arcsec)</th>
<th>$N_{UV}$ (s$^{-1}$)</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H II 1</td>
<td>L102</td>
<td>05:05:06.7</td>
<td>$-70:06:24.1$</td>
<td>$7.70 \times 10^{50}$</td>
<td>$-$</td>
</tr>
<tr>
<td>H II 2</td>
<td>L106</td>
<td>05:06:05.0</td>
<td>$-65:41:28.7$</td>
<td>$1.46 \times 10^{51}$</td>
<td>$-$</td>
</tr>
<tr>
<td>H II 3</td>
<td>L119</td>
<td>05:09:34.3</td>
<td>$-68:53:44.9$</td>
<td>$1.40 \times 10^{51}$</td>
<td>$0.05 \pm 0.03$</td>
</tr>
<tr>
<td>H II 4</td>
<td>L134</td>
<td>05:12:28.4</td>
<td>$-70:24:52.2$</td>
<td>$2.51 \times 10^{51}$</td>
<td>$-$</td>
</tr>
<tr>
<td>H II 5</td>
<td>L201</td>
<td>05:22:06.9</td>
<td>$-67:56:46.0$</td>
<td>$3.74 \times 10^{51}$</td>
<td>$0.04 \pm 0.03$</td>
</tr>
<tr>
<td>H II 6</td>
<td>L258</td>
<td>05:26:42.5</td>
<td>$-68:49:34.0$</td>
<td>$2.52 \times 10^{51}$</td>
<td>$0.12 \pm 0.04$</td>
</tr>
<tr>
<td>H II 7</td>
<td>L260</td>
<td>05:27:17.6</td>
<td>$-70:34:46.2$</td>
<td>$8.74 \times 10^{50}$</td>
<td>$-$</td>
</tr>
<tr>
<td>H II 8</td>
<td>L307</td>
<td>05:35:15.6</td>
<td>$-67:34:04.1$</td>
<td>$1.88 \times 10^{51}$</td>
<td>$0.09 \pm 0.03$</td>
</tr>
<tr>
<td>H II 9</td>
<td>L328</td>
<td>05:38:36.0</td>
<td>$-69:05:10.7$</td>
<td>$1.06 \times 10^{52}$</td>
<td>$-$</td>
</tr>
<tr>
<td>H II 10</td>
<td>L343</td>
<td>05:40:06.8</td>
<td>$-69:45:28.4$</td>
<td>$2.64 \times 10^{51}$</td>
<td>$0.09 \pm 0.03$</td>
</tr>
</tbody>
</table>

6.1 T–T plot

To investigate a possible spatial variation of the spectral index across the resolved H II regions in both 227 MHz and 1.4 GHz images, we use the T–T method (Turtle et al. 1962). This method compares flux density (or brightness temperature) at two frequencies from different instruments and allows for possible foreground contamination as well as variations due to short spacings. If there is any difference in short spacings or contamination from foreground emission, it will result in a non-zero intercept in the T–T plot. We generate the T–T plot by convolving and regridding the LMC 1.4 GHz image to match the angular resolution and pixel scale of the 227 MHz GLEAM image. The 227 MHz GLEAM image is chosen because it has the highest angular resolution. Subsequently, we subsample the data points per 5 pixel ($\sim 1.3$ beam separation) in the image plane to remove pixel-to-pixel correlations. Then, we fit the subsampled data using linear least squares regression. The spectral index is then determined by $\alpha = \log$ (slope)/c, where c is log (227 MHz/1400 MHz).

We present the T–T plots in Fig. 9 and summarize the derived spectral indices in Table 5. All fits yield an overall $R^2 = 0.93$, which suggests no spatial variation of the spectral index across these H II regions. We cannot derive spectral indices for five of the H II regions using the T–T method because the sources are resolved at 1.4 GHz (multiple components) but not resolved in 227 MHz or affected by artefacts at 1.4 GHz (near the 30 Doradus region). The derived spectral indices of these H II regions ranges from $\sim 0.0$ to $\sim 0.1$, which suggests a “flat” spectrum dominated by thermal emission. These H II regions are in the optically thin regime in the MWA frequency range. We also attempted to derive the spectral index and to identify the turn-over frequency using the optically thick H II regions defined in the catalogue of Pellegrini et al. (2012). However, we do not see any convincing evidence of a turn over frequency due to difficulty in measuring accurate flux densities in the lower MWA frequency bands as a result of poor resolution.

7 CONCLUSIONS

We present a low-frequency radio continuum study of the Magellanic Clouds as part of the GLEAM survey. The intensity of the radio continuum emission is correlated with H I column density. Star-forming regions are the main contributors to the optical depth H II regions in the MCs using the images from the Magellanic Clouds Emission Line Survey (MCELS; Smith & MCELS Team 1998). The study categorized the H II regions into several groups, including optically thin and thick. Using the catalogue of Pellegrini et al. (2012), we first examined H II regions that are classified as optically thin. If they appear to be point sources or not complex at 150 MHz, we extract them as cutout images. This results in 46 H II regions for the LMC and 2 H II regions for the SMC. Subsequently, we obtain their integrated flux densities by fitting a two-dimensional Gaussian to these cutout images. Only for the SMC. Subsequently, we obtain their integrated flux densities by fitting a two-dimensional Gaussian to these cutout images. This results in 46 H II regions for the LMC and 2 H II regions for the SMC.
emission. Intensity variation is noticeable in the LMC but flat across the bar of the SMC. We derive spectral indices of the MCs using 200 MHz as a reference frequency. A double power-law model is required to fit the SED of the LMC. The fitted model yields $\alpha_0 = -0.66 \pm 0.08$ (non-thermal) when $\alpha_1$ (thermal) is fixed at $-0.1$. A power-law model is preferred for the SMC, which yields $\alpha_{8.5\text{GHz}}$ (SMC) = $-0.82 \pm 0.03$. Spectral index maps show a variation of $\alpha$ across the Magellanic Clouds, which reflects the presence of thermal and non-thermal components. H II regions have a distinctive flat spectral index and strongly correlate with H$_\alpha$, indicating mainly thermal emission. We also calculate the lower limit production rate of Lyman continuum photons of ten H II regions in the LMC using their integrated flux density at 150 MHz. An investigation of spectral index variation among the H II regions is carried out using the T–T method. The derived spectral indices for these H II regions are between about 0 and 0.1. The new H$_\alpha$–150 MHz SFR calibrations

Figure 9. T–T plots for the five optically thin H II regions in the LMC using 1.4 GHz and 227 MHz images. The 1.4 GHz cutout images have been convolved and regridded to match the resolution and pixel scale of the 227 MHz images. The data points have been subsampled every 5 pixel in the image plane. The fitted lines are the spectral indices of these regions. Error of $S_{1400}$ is $\sim 0.3$ mJy beam$^{-1}$, which makes the error bars too small to be visible in these plots.
et al. 2006; Leverenz & Filipović 2013). These studies focused on FIR correlation has been performed in the past for the MCs (Hughes
will be presented in a subsequent paper. An analysis of the radio-
ova remnants, and background sources in the GLEAM images
available at the GLEAM Virtual Observatory (VO) server.²

8 FUTURE WORK
A detailed study of discrete sources such as H II regions, supernova
remnants, and background sources in the GLEAM images will be presented in a subsequent paper. An analysis of the radio-
FIR correlation has been performed in the past for the MCs (Hughes et al. 2006; Leverenz & Filipović 2013). These studies focused on
1.4 GHz and Infrared Astronomical Satellite (IRAS) images. Future
work includes an investigation of the radio-FIR correlation on different spatial scales using MWA and Herschel images (as part of the HERschel Inventory of The Agents of Galaxy Evolution survey: HERITAGE; Meixner et al. 2013). A deep survey of the Magellanic System (MAGE-X; led by L. Staveley-Smith) using the MWA phase II system has been commenced. The survey will focus on quantifying the energy spectrum of cosmic ray electrons at higher angular resolution.

ACKNOWLEDGEMENTS
This scientific work makes use of the Murchison Radio-astronomy Observatory, operated by CSIRO. We acknowledge the Wajarri Yamatji people as the traditional owners of the Observatory site. Support for the operation of the Murchison Widefield Array is provided by the Australian Government (NCRIS), under a contract to Curtin University administered by Astronomy Australia Limited. We acknowledge the Pawsey Supercomputing Centre which is supported by the Western Australian and Australian Governments and the Centre of Excellence for All-sky Astrophysics (CAASTRO), which is an Australian Research Council Centre of Excellence, funded by grant CE11001020. Parts of this research were conducted with the support of Australian Research Council Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), through project number CE170100013. This research also made use of Montage, a detailed study of discrete sources such as H II regions, supernova remnants, and background sources in the GLEAM images
available at the GLEAM Virtual Observatory (VO) server.²

REFERENCES

2http://gleam-vo.icrar.org/gleam_postage/q/form

Bowman J. D. et al., 2013, PASA, 30, e031
Diaz J., Bekki K., 2011, PASA, 28, 117
Lonsdale C. J. et al., 2009, IEEE Proceedings, 97, 1497
Mills B. Y., 1959, Handbuch der Physik, 53, 239
Mills B. Y., 1959, Handbuch der Physik, 53, 239
Mills B. Y., 1959, Handbuch der Physik, 53, 239
Offringa A. R. et al., 2015, PASA, 32, e008
Pietrzyński G. et al., 2013, Nature, 495, 76

Smith R. C., MCELS Team, 1998, PASA, 15, 163
Tingay S. J. et al., 2013, IAU Symp. 9, Observations of Extragalactic Radio Emission. Stanford Univ. Press, Stanford, CA

Wayth R. B. et al., 2015, PASA, 32, e025

This paper has been typeset from a TeX/LaTeX file prepared by the author.