

A spatially resolved radio spectral study of the galaxy M 51[★]

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ABSTRACT

Context. Radio continuum emission from galaxies at gigahertz frequencies can be used as an extinction-free tracer of star formation. However, at frequencies of a few hundred megahertz, there is evidence for low-frequency spectral flattening.

Aims. We wish to understand the origin of this low-frequency flattening better, and to this end, we performed a spatially resolved study of the nearby spiral galaxy M 51. We explored the different effects that can cause a flattening of the spectrum towards lower frequencies, such as free-free absorption and cosmic-ray ionisation losses.

Methods. We used radio continuum intensity maps between 54 and 8350 MHz at eight different frequencies, with observations at 240 MHz from the Giant Metrewave Radio Telescope presented for the first time. We corrected for the contribution from thermal free-free emission using an H α map that was corrected for extinction with 24 μ m data. We fitted free-free absorption models to the radio spectra to determine the emission measure (EM) as well as polynomial functions to measure the non-thermal spectral curvature. We also obtained a new extinction-corrected H α intensity map from the Metal-THINGS survey using integral field unit spectroscopy.

Results. The non-thermal low-frequency radio continuum spectrum between 54 and 144 MHz is very flat and even partially inverted, particularly in the spiral arms; in contrast, the spectrum at higher frequencies is typical for a non-thermal radio continuum spectrum. However, we did not find any correlation between the EMs calculated from radio and from H α observations; instead, the non-thermal spectral curvature weakly correlates with the H I gas-mass surface density. This suggests that cosmic-ray ionisation losses play an important role in the low-frequency spectral flattening.

Conclusions. The observed spectral flattening towards low frequencies in M 51 is caused by a combination of ionisation losses and free-free absorption. The reasons for this flattening need to be understood in order to use sub-gigahertz frequencies as a tracer of star formation.

Key words. radiation mechanisms: general – galaxies: ISM – galaxies: individual: M 51 – galaxies: spiral – galaxies: star formation – radio continuum: galaxies

1. Introduction

At radio frequencies of a few gigahertz and below, the majority of continuum emission from galaxies is non-thermal synchrotron radiation, produced by cosmic-ray electrons (Niklas et al. 1997; Basu et al. 2012a; Tabatabaei et al. 2017). These cosmic rays are accelerated in the shock-front of supernova explosions, and therefore, they originate from regions with higher star formation (Green 2014). The integrated spectrum of nearby galaxies

at gigahertz frequencies (approximately 0.5–10 GHz) mostly follows a power law, where the flux density scales with frequency as $S_\nu \propto \nu^\alpha$; the radio spectral index α has values between -1.2 and -0.5 (Gioia et al. 1982; Li et al. 2016; Tabatabaei et al. 2017). If frequencies below approximately 300 MHz are included, however, the observed spectra are curved with a spectral curvature of $\beta = -0.2$, which denotes the change in spectral index per logarithmic frequency decade assuming constant curvature (Marvil et al. 2015).

While the value for the radio spectral index generally agrees with models of the overall injection spectrum of cosmic rays from supernovae ($\alpha \approx -0.5$; Blandford & Eichler 1987),

[★] The fits map is available at the CDS via anonymous ftp to cdsarc.cds.unistra.fr (130.79.128.5) or via <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/689/A68>

including their energy losses mainly due to synchrotron and inverse-Compton radiation while propagating away from their origin (Gioia et al. 1982; Beck & Wielebinski 2013; Han 2017), the origin of the curvature is still a matter of debate (Basu et al. 2015; Mulcahy et al. 2018). Pohl & Schlickeiser (1990) and Pohl et al. (1991a,b) provided an explanation for curved spectra by combining ionisation and electronic excitation (Gould 1975), inverse-Compton radiation, synchrotron radiation, and relativistic bremsstrahlung, which would cause a smooth change in the spectral index of $\Delta\alpha = 0.5$ from higher to lower radio frequencies. On the other hand, Israel & Mahoney (1990) observed a dependence of the curvature on the inclination of the galaxies and concluded that a fragmented cool ionised medium with temperatures of 500–1000 K causes the curvature by thermally absorbing a part of the emitted synchrotron emission at lower frequencies. However, Hummel (1991) used the same data as Israel & Mahoney (1990) and were unable to find any correlation between the curvature in the sampled galaxies and their inclinations. A more recent study by Chyży et al. (2018) using additional data from the LOFAR¹ Multifrequency Snapshot Sky Survey (MSSS) at 150 MHz (Heald et al. 2015) confirmed the results by Hummel (1991).

Furthermore, integrated spectra of star-forming galaxies encompass a mixture of the complex interplay between thermal and non-thermal components and different energy loss and propagation effects in the most likely non-isotropic and inhomogeneous medium (Basu et al. 2015; Lisenfeld & Völk 2000). Studies of large samples of these objects are therefore limited by obtaining high-quality high-resolution observations at low radio frequencies ($\lesssim 300$ MHz). Advancements in data calibration and imaging techniques at these low-frequencies, especially for radio interferometers such as LOFAR (Tasse 2014; Tasse et al. 2018) and the Giant Metrewave Telescope (GMRT; Intema et al. 2009, 2017; Intema 2014), now allow the production of images with a high dynamic range with resolutions matching those of observations performed at gigahertz frequencies.

Spatially resolved studies are currently limited to nearby objects where individual star-forming regions can be analysed, and the radio emission of spiral-arm, inter-arm, and surrounding regions can be separated. Roy & Pramesh Rao (2006) showed that thermal absorption plays a key role in shaping the spectra of the centre of the Milky Way below 500 MHz, while its integrated-spectrum turns over at about 3 MHz (Brown 1973). Turnovers have also been detected for individual sources in the starburst galaxy M 82 (Adebahr et al. 2017) and in the integrated flux densities for the core regions of M 82 (Adebahr et al. 2013) and Arp 220 (Varenius et al. 2016) at around 1000 MHz. For these two objects, a flattening was also observed for the integrated (global) radio spectra (Klein et al. 1988; Condon 1992; Anantharamaiah et al. 2000), just like in the starburst galaxy NGC 253 (Marvil et al. 2015). Several of the compact H II-regions in the dwarf galaxy IC 10 show evidence of thermal free-free absorption in the radio spectra of the 320 MHz observations (Basu et al. 2017). Recently, evidence of low-frequency absorption was also found in the region of the edge-on galaxy NGC 4631 with a very flat radio spectrum (Stein et al. 2023). Local spectral turnovers were also observed in jellyfish galaxies, where they might be due to gas compression and subsequent ionisation losses (Lal et al. 2022; Ignesti et al. 2022; Roberts et al. 2024).

We chose M 51 as the target primarily because it benefits from multi-frequency radio continuum data. The face-on

Table 1. Basic properties of M51.

Name	M 51
Alternative names	NGC 5194/5155
RA ₂₀₀₀	13 ^h 29 ^m 56 ^s .2
DEC ₂₀₀₀	+47° 13′ 50″
Type	Galaxy pair (Sa + Sc) ^(a)
Apparent size (D ₂₅)	9′
Distance	8.58 ± 0.10 Mpc ^(b)
Position angle	12° 0′ ^(c)
Inclination angle	−20° 3′ ^(c)

References. ^(a)Karachentsev et al. (1985). ^(b)McQuinn et al. (2016). ^(c)Hu et al. (2013).

orientation and its proximity were also important because they facilitate resolving and separating the spiral arms. The other properties of M 51 are listed in Table 1. The entire galaxy is now mapped at 54 and 144 MHz with LOFAR (de Gasperin et al. 2021; Shimwell et al. 2022). Furthermore, data at 1370 and 1699 MHz were taken with the Westerbork Synthesis Radio Telescope (WSRT; Braun et al. 2007). At even higher frequencies, Fletcher et al. (2011) presented maps taken with the Very Large Array (VLA) at 4850 and 8350 MHz. The VLA maps were combined with maps observed with the 100 m Effelsberg telescope in order to observe all angular scales. These data were analysed by Heesen et al. (2023), who studied the transport of cosmic-ray electrons at kiloparsec scales and found it to be energy-independent diffusion for electrons with energies below 10 GeV.

In this paper, we extend the data with a new 240 MHz map from the GMRT. We used eight datasets observed at five different radio facilities (LOFAR, GMRT, WSRT, VLA, and Effelsberg) over the frequency range 54–8350 MHz to perform a spatially resolved radio spectrum study of the nearby spiral galaxy M 51. For the first time, we were able to separate the actively star-forming and non-star-forming regions of a nearby galaxy down to frequencies as low as 54 MHz. This allowed us to investigate the relation between the star formation and the flattening of the radio spectrum, and also to examine the origin of the flattening.

This article is structured as follows. In Sect. 2, we present our dataset spanning nine frequency windows. Section 3 describes the main data analysis, which included the subtraction of thermal emission (Sect. 3.2), the separation of galaxy regions (Sect. 3.3), spectral index maps (Sect. 3.4), and a comparison of low- and high-frequency spectral indices (Sect. 3.5). Spectral index flattening and low-frequency turnovers are investigated in Sect. 4. We summarise and conclude in Sect. 5.

2. Data handling

2.1. Observations with the Giant Metrewave Telescope

We analysed archival so far unpublished data of M 51 at 240 MHz, observed with the GMRT (Swarup et al. 1991) using the old hardware correlator (project code: 10AFA01). The map is presented here for the first time (see Fig. 1). The data were recorded by splitting the 16 MHz bandwidth into two bands of 8 MHz each, covered using 64 125 kHz wide channels, the upper and lower side bands, USB and LSB, respectively. We analysed only the USB data centred at 241.25 MHz because the LSB data were unusable due to radio frequency interference (RFI) and

¹ LOw Frequency ARray.

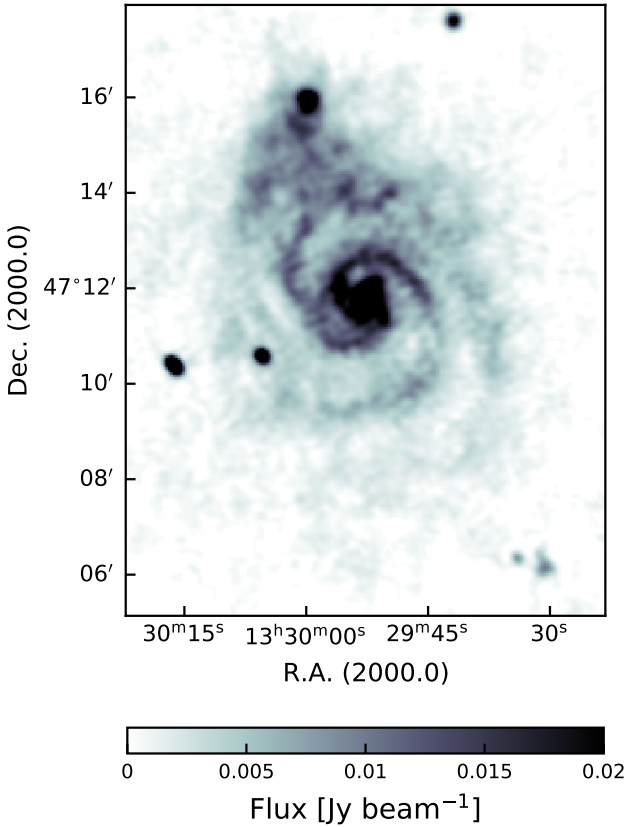


Fig. 1. Radio continuum map of M51 at 240 MHz observed with the GMRT. The map has an angular resolution of $14''.0 \times 12''.2$ and an rms noise of $500 \mu\text{Jy beam}^{-1}$.

correlator-related errors. The total duration of these observations is 11 h, wherein 4 min scans on a nearby bright point source, 3C 286, were interleaved every 25 min. 3C 286 was used to calibrate the flux scale, bandpass, and phase. An additional 15 min scans on 3C 286 were performed at the beginning and end of the observations run. In these observations, a total of 8.3 h was spent on M51. The data were analysed in AIPS² using the standard analysis protocol at low frequencies. The data were manually inspected, and data that were affected by RFI and bad baselines were flagged using the TVFLG, WIPER, and SPFLG tasks. The task FLGIT was used to automatically remove RFI-affected frequency channels, which have a residual spectral flux above 4σ level. In these observations, less than $\approx 35\%$ of the data were found to be corrupted in the USB overall, including three non-working antennas and corrupted baselines. We used the Baars et al. (1977) absolute flux-density scale to determine a flux density of 29.5 ± 1.6 Jy at 241.25 MHz for 3C 286³. RFI-removal and determining gain solutions were iteratively performed, and when the closure-phase errors determined using 3C 286 were below 1%, solutions were applied to the target M51.

The task IMAGR was used to deconvolve the calibrated data. In order to minimise the effect of wide-field imaging with non-coplanar baselines, we used polyhedron imaging (Cornwell & Perley 1992) by subdividing the field of view ($\approx 3.7^\circ$) into $9 \times 9 = 81$ smaller facets. After flagging the first and last two

channels, we vector-averaged four adjacent frequency channels of 125 kHz each into 15 500 kHz channels to ensure that the bandwidth smearing near 240 MHz was smaller than the size of the synthesized beam. Thus, the final image was made using a 7.5 MHz bandwidth. Five rounds of phase-only self-calibration were performed by choosing point sources above 8σ using the task CCSEL. The solution interval was progressively reduced during each round, starting from 3 min at the start to 0.5 min in the last round. Additional flagging was also performed after each round until in the fifth round, the closure-phase error was below 0.5%. To prepare the final image, we employed the SDI clean algorithm (Steer et al. 1984) to deconvolve the extended emission in M51. After ensuring that point-like emission was cleaned using the BGC clean algorithm, SDI clean was used, and the clean-box masks were manually changed in order to deconvolve different scales. The final image at 240 MHz used in this work was produced at an angular resolution of $14''.0 \times 12''.2$ with an rms noise of $\approx 500 \mu\text{Jy beam}^{-1}$. While not a very sensitive map, it suffices for our analysis. The galaxy-integrated flux density of M51 at 240 MHz within the 3σ contour is found to be 6.07 ± 0.63 Jy. Fig. 3 shows that the total flux density of M51 agrees well with the flux densities in the literature when interpolated from higher- and lower-frequency observations.

The uncertainties on the estimated flux density depend on the absolute flux scale error and on the errors associated with uncalibrated system temperature (T_{sys}) variations (Basu et al. 2012a). The absolute flux scale error for 3C 286 is found to be 5.4% (Baars et al. 1977), and the T_{sys} variation for the old GMRT system, as used for the observations in this paper, was estimated to be $\approx 5\%$ (Roy & Rao 2004). The overall systematic error, added in quadrature, is therefore expected to be $\approx 7.5\%$. We used a slightly more conservative value of 10% for the systematic flux error of the GMRT data. The statistical measurement error due to the rms noise in the map was added to this, but this contribution is relatively small.

2.2. Archival radio continuum observations

In total, radio continuum image data of M51 were collected in nine different frequency bands between 54 MHz and 8350 MHz (see Table 2). All retrieved images were inspected for artefacts, and their integrated fluxes were cross-checked with literature values. Preferentially, single-dish or compact interferometric measurements were used to ensure that our images were not affected by the problem of missing spacing.

The lowest-frequency image at 54 MHz is from the LOFAR LBA Sky Survey (LoLSS; de Gasperin et al. 2021) using the low-band antennas. Flux calibrators were used to calibrate direction-independent effects as well as the bandpass response of the instrument. Additionally, the flux density of sources in the survey was compared to the Rees survey (8C; Hales et al. 1995) at 38 MHz, the VLA Low-Frequency Sky Survey redux (VLSSr; Lane et al. 2012) at 74 MHz, the LOFAR Two-metre Sky Survey data release 2 (LoTSS-DR2; Shimwell et al. 2022) at 144 MHz, and the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) at 1400 MHz. A conclusive estimate of the flux density accuracy could not be derived, but it is suggested that assuming a conservative 10% error on the LoLSS flux density scale is beneficial (de Gasperin et al. 2021). Heesen et al. (2022) investigated 45 nearby galaxies in LoTSS-DR2 that included M51. We used their re-processed map of M51. They confirmed that the integrated flux densities of the $6''$ and $20''$ maps are identical for the same integration area. This ensures that the high-resolution map that we used is sufficiently deconvolved. The flux densities from

² AIPS, the Astronomical Image Processing System, is free software available from the National Radio Astronomy Observatory.

³ The flux density of 3C 286 obtained with the Baars et al. (1977) is consistent with 28.15 Jy from the Perley & Butler (2017) absolute scale within the errors.

Table 2. Observation parameters for the nine radio maps used in the analysis.

Telescope (Survey)	Central frequency (MHz)	Beam size	σ rms noise (μ Jy)	Convolved σ_c rms noise (μ Jy)	Flux uncertainty ε_v (%)	Reference
LOFAR (LoLSS)	54	15'0 × 15'0	1500	1500	10	1
LOFAR (LoTSS)	144	6'0 × 6'0	45	100	10	2
GMRT	240	14'0 × 12'2	500	850	10	3
GMRT	333	15'0 × 15'0	200	350	10	4
GMRT ^(a)	619	5'7 × 4'6	27	125	10	5
WSRT (SINGS)	1370	17'5 × 12'5	22	25	5	6
WSRT (SINGS)	1699	13'5 × 10'0	27	30	5	6
VLA + Effelsberg	4850	15'0 × 15'0	30	30	5	7
VLA + Effelsberg	8350	15'0 × 15'0	20	20	5	7

Notes. ^(a)Map not used in the analysis due to possible deconvolution errors.

References. (1) [de Gasperin et al. \(2021\)](#); (2) [Shimwell et al. \(2022\)](#); (3) This work; (4) [Mulcahy et al. \(2016\)](#); (5) [Farnes et al. \(2013\)](#); (6) [Braun et al. \(2007\)](#); (7) [Fletcher et al. \(2011\)](#).

[Heesen et al. \(2022\)](#) were matched with the LoTSS-DR2 scale, whose error is below 10% ([Shimwell et al. 2022](#)). Therefore, we assumed a flux uncertainty of 10% for the LoTSS map.

The GMRT map at 333 MHz was already presented by [Mulcahy et al. \(2016\)](#). They used it for an analysis of the large-scale diffuse emission of M 51 and found no issues in relation to missing emission for the inner part of the disc. In contrast, the 619 MHz GMRT image of [Farnes et al. \(2013\)](#) showed a negative bowl around the diffuse emission of M 51, indicating deconvolution errors arising from missing emission. We therefore refrained from using the diffuse emission for further quantitative analyses. However, the bright emissions on small-scales, especially in the inner parts of the galaxy, might be less affected by missing-flux issues. The WSRT images at 1370 and 1699 MHz from [Braun et al. \(2007\)](#) were cross-checked with the VLA image at 1400 MHz published in [Fletcher et al. \(2011\)](#) and with literature flux density values. No differences in flux densities or morphology were found. The WSRT-SINGS observations were bracketed by observations of the total intensity calibration sources, yielding an absolute flux density calibration accuracy better than 5% [Braun et al. \(2007\)](#). We therefore assume a 5% flux uncertainty for the WSRT maps here. Finally, the VLA images at 4850 and 8350 MHz were previously combined with single-dish Effelsberg telescope data, as described in [Fletcher et al. \(2011\)](#), so that we do not expect any missing flux. The flux measurement errors are usually assumed to be 5% for VLA data [Konar et al. \(2013\)](#).

We convolved all images to the largest common beam of 17'5 × 15'0 (see Table 2) using the routine CONVOL of the software package called multichannel image reconstruction, image analysis, and display (MIRIAD, [Sault et al. 1995](#)). All images were then aligned to a common world coordinate system, re-gridded to a pixel size of 3'', and transformed into the reference pixel and image size. This was achieved using the REGRID routine of MIRIAD. The rms noise, σ , of each individual image was determined by calculating the standard deviation over an emission-free area. For the further analysis, only pixels above 4.5 σ were considered.

We assumed an absolute flux-scale uncertainty of 10% for the low-frequency data (for LOFAR and GMRT) and 5% for all other data (see Table 2). These estimates incorporate all errors and are conservative. There are several contributions. First, there is the accuracy of the absolute flux density of the calibrator

models. This is 3–5% ([Perley & Butler 2017](#)). However, for spectral index studies like our work, the relative scale is more relevant, the uncertainty of which is about 1%. Deconvolution errors are about 1%, but increase at low signal-to-noise ratios ([Offringa et al. 2014](#)). The background noise can be neglected except for local measurements, where we added the rms noise in quadrature. Other errors, such as the uncertainty of the primary beam correction, can be also neglected as the primary beam size is much larger than the size of source. For the combined VLA and Effelsberg maps, the uncertainty is limited by the feathering procedure, with which the interferometric and single-dish images can be combined ([Cotton 2017](#)). Their uncertainty may be higher in areas of low signal-to-noise ratios, but we restrict most of our analysis to areas where this is not expected to cause a strong difference.

2.3. Integral field unit (IFU) spectroscopy

We complemented our radio continuum data with new optical IFU spectroscopy data from the Metal-THINGS survey ([Lara-López et al. 2021](#)). Metal-THINGS is a survey of nearby galaxies observing with the George Mitchell and Cynthia Spectrograph (GCMS; formerly known as VIRUS-P), mounted to the 2.7 m Harlan J. Smith telescope located at the McDonald Observatory in Texas. The IFU has a field of view of 100'' × 102''. Due to the large angular size of M 51, a total of 12 pointings were needed to cover the entire galaxy. The spectroscopic data were processed with the spectral synthesis code STARLIGHT ([Cid Fernandes et al. 2011](#)) as described in [Lara-López et al. \(2021, 2023\)](#). We used an H α flux map corrected for extinction, where the correction was performed using the Balmer decrement. The map is shown in Fig. 2.

3. Data analysis

3.1. Integrated spectrum

We started our analysis by calculating the integrated spectrum, which helped us to assess the robustness of the data. The spectrum is plotted and compared to the integrated spectrum from [Mulcahy et al. \(2014\)](#) in Fig. 3. The integrated spectrum follows a power law with a spectral index of $\alpha = -0.80 \pm 0.05$ without any flattening at low frequencies. This is consistent with the spectral

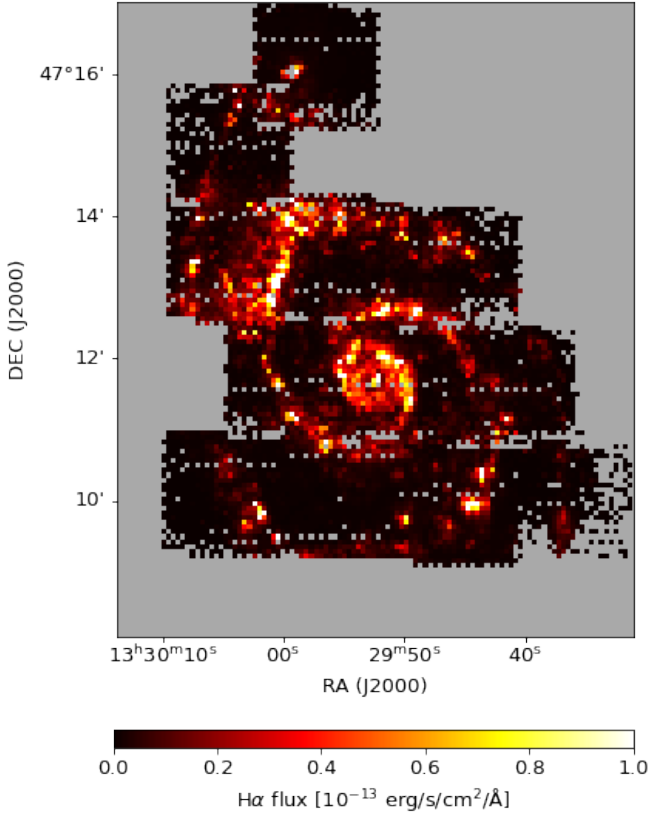


Fig. 2. H α flux density map of M51 from the Metal-THINGS survey, corrected for extinction using the Balmer decrement. The grey pixels were not observed.

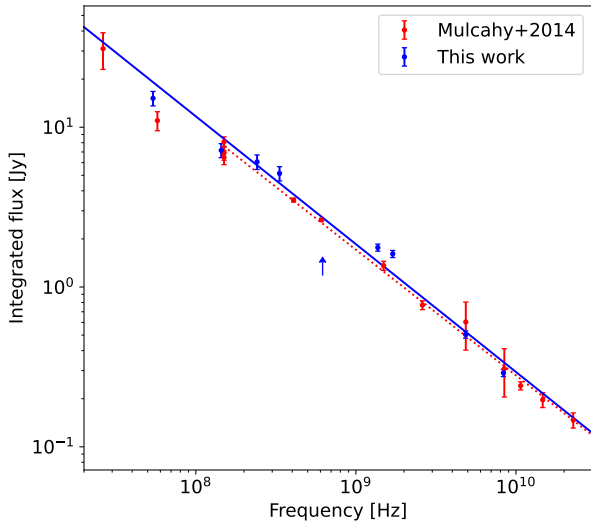


Fig. 3. Global radio continuum spectrum of M51. We show integrated flux densities calculated from our data and compare them with literature data compiled by Mulcahy et al. (2014). Power-law fits correspond to radio spectral indices of -0.80 ± 0.05 for our data (blue data points and solid line) and -0.79 ± 0.02 for the literature data (red data points and dotted line). The flux density at 619 MHz is only given as a lower limit and was not included in the fit.

index of -0.79 ± 0.02 calculated by Mulcahy et al. (2014). This test confirms that the integrated flux density of M51 in our maps matches previous observations.

3.2. Separation of thermal and synchrotron emission

To better determine the contribution of the thermal emission and separate the thermal from the non-thermal emission, we used H α to estimate the free-free emission in M51. To do this, we used a continuum-subtracted H α map obtained with the Kitt Peak National Observatory 2.1 m telescope using the narrow-band H α -filter KP1563 (Kennicutt et al. 2003). The map was downloaded from the ancillary data at the SINGS webpage⁴. The H α image, shown in Appendix A, has an angular resolution of $1''.35 \times 1''.35$ and an rms noise of $\approx 50 \mu\text{Jy beam}^{-1}$. Because the H α emission is easily absorbed by the dust, the observed H α intensity $I_{\text{H}\alpha, \text{obs}}$ needs to be corrected for foreground and internal extinction.

The foreground extinction is low in the direction of M51 (Schlafly & Finkbeiner 2011), and we therefore neglected it. The internal extinction within M51 was corrected for with a $24 \mu\text{m}$ mid-infrared map to obtain an extinction-corrected H α emission line flux (Kennicutt et al. 2009),

$$F_{\text{H}\alpha} = F_{\text{H}\alpha, \text{obs}} + 0.02 \nu_{24\mu\text{m}} I_{24\mu\text{m}}. \quad (1)$$

Here, $I_{24\mu\text{m}}$ is the intensity at $24 \mu\text{m}$, and it was obtained from a *Spitzer* map observed as a part of the SIRTf Nearby Galaxies Survey (SINGS; Kennicutt et al. 2003). The $24 \mu\text{m}$ map has an angular resolution of $6''$. We convolved the observed H α map to $6''$ and aligned it to the same coordinate system as the $24 \mu\text{m}$ map.

The thermal contribution to the radio continuum emission at a given frequency ν can then be calculated using (Deeg et al. 1997)

$$\frac{S_{\text{th}}(\nu)}{\text{erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}} = 1.14 \times 10^{-14} \left(\frac{\nu}{1000 \text{ MHz}} \right)^{-0.1} \times \left(\frac{T_e}{10^4 \text{ K}} \right)^{0.34} \left(\frac{F_{\text{H}\alpha}}{\text{erg cm}^{-2} \text{ s}^{-1}} \right), \quad (2)$$

where T_e is the thermal electron temperature.

The electron temperature of the ionised gas phase is usually anti-correlated with the metallicity of the corresponding H II regions (Alloin et al. 1979; Pagel et al. 1979; Stasińska et al. 1981). Since the metallicity usually increases towards the galaxy centre, T_e decreases. In order to address the radial variation in T_e , we used the catalogue of H II regions in M51 from Bresolin et al. (2004) and followed the linear fitting procedure of Tremblin et al. (2014) to calculate its radial profile. The data with the fit are shown in Fig. 4. The electron temperature T_e is found to follow the relation

$$\frac{T_e}{\text{K}} = (266 \pm 47) \left(\frac{R_{\text{gal}}}{\text{kpc}} \right) + (4533 \pm 374), \quad (3)$$

where R_{gal} is the galactocentric distance. We note here that the T_e measured in Bresolin et al. (2004) was derived from auroral lines, which can only be detected in low-metallicity H II regions. This could cause a bias towards higher temperatures in our profile because temperature and gas metallicity are anti-correlated, and for higher metallicities, auroral lines can no longer be detected. However, the overall radial dependence should still represent the average electron temperature in the H α gas.

The extinction-corrected H α map was then convolved to our common beam of $17''.5 \times 15''.0$, and re-gridded to the same

⁴ <http://irsa.ipac.caltech.edu/data/SPITZER/SINGS/>

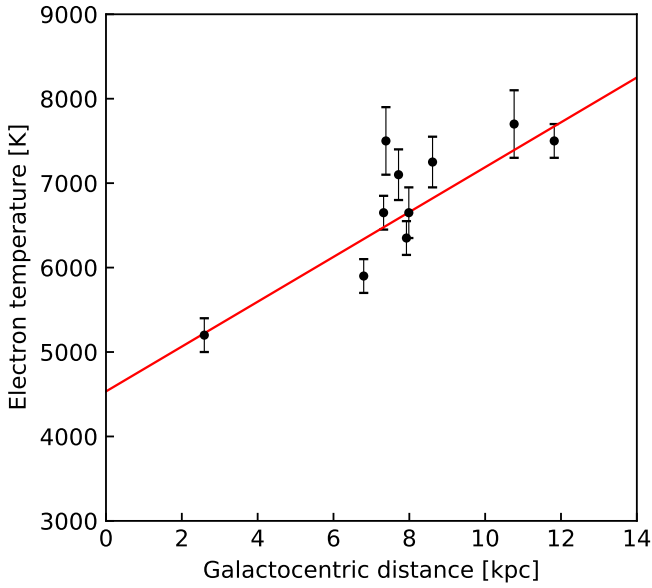


Fig. 4. Electron temperature T_e measured in H II regions as a function of galactocentric distance R_{gal} . The data are taken from Bresolin et al. (2004). The red line represents the best linear fit.

coordinate system as the radio maps. For each pixel of a radio continuum map at a given frequency ν , the thermal flux density was calculated using Eq. (2) and T_e from Eq. (3). The calculated thermal flux densities (Appendix A) were subtracted from the total flux densities in our radio maps. The resulting non-thermal maps were used for the majority of the following analysis.

We found thermal contributions between 0.98% and 4.8% at 54 MHz, and between 12% and 14% at 8350 MHz. For a relative error of ε_{th} in the estimated thermal fraction f_{th} , the relative error in the synchrotron emission fraction ($\sigma_{f_{\text{nth}}}$; where $f_{\text{nth}} = 1 - f_{\text{th}}$) is given by $\sigma_{f_{\text{nth}}} = [1 - (1 \pm \varepsilon_{\text{th}}) f_{\text{th}}] / [1 - f_{\text{th}}]$ (Basu et al. 2017)⁵. This means that an error of up to 20% ($\varepsilon_{\text{th}} = 0.2$) in a region with $f_{\text{th}} = 0.15$ (0.05) will propagate to an error of about 5 (2)% in the estimated synchrotron emission. Adding this (in quadrature) to the flux uncertainty will increase it from 5 (10)% to 6.6 (10.2)% assuming an exaggerated error of 20% on the thermal fraction. Because of this, the error on the thermal fraction does not significantly affect the results presented in the rest of this paper.

3.3. Spiral arm, inter-arm, and galaxy core regions

Previous work (Fletcher et al. 2011) has shown the radio continuum spectrum to be different depending on the location in the galaxy. In spiral arms, the radio spectral index indicates a flat non-thermal spectrum, whereas the inter-arm regions have steeper spectra. Moreover, the radio continuum emission depends on the star formation rate (SFR), and this relation of radio to SFR is different in the arm and inter-arm regions. We therefore now define arm- and inter-arm regions using the distribution of the atomic and molecular gas.

We decided to follow the approach of Hitschfeld et al. (2009) using a combination of H I and CO maps to generate a gas surface density map, which then represented the spiral arm structure tracing the density waves (Colombo et al. 2014). To this end, we used the integrated H I map (moment 0) from Walter et al.

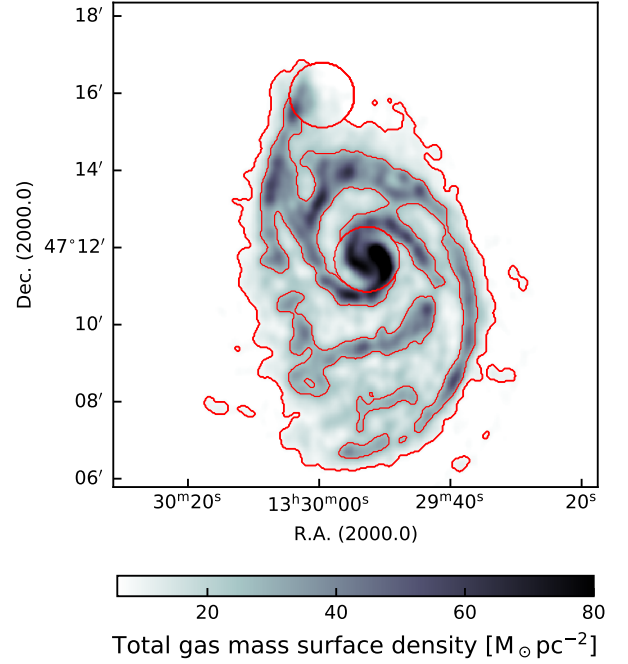


Fig. 5. Total gas-mass surface density as derived from a combination of atomic (H I) and molecular (H₂) gas maps. The contours at 8 and 25 $M_{\odot} \text{pc}^{-2}$ define the borders of the spiral arm and inter-arm regions, respectively. The circular apertures denote the core regions in M 51 and NGC 5195.

(2008) and the integrated ¹²CO 2–1 map from Schuster et al. (2007). Both maps were convolved to our common resolution of $17''.5 \times 15''.0$. We calculated the H I column density $N_{\text{H I}}$ using (Meyer et al. 2017)

$$N_{\text{H I}} = 1.10 \times 10^{24} \text{ cm}^{-2} \left(\frac{S_{\text{H I}}}{\text{Jy km s}^{-1}} \right) \left(\frac{a \times b}{\text{arcsec}^2} \right)^{-1}, \quad (4)$$

where $S_{\text{H I}}$ is the velocity-integrated H I flux density, and a and b are the major and minor axis of the synthesised beam, defined as the full width at half maximum, respectively.

In order to convert the CO map into an H₂ column density map, we used (Schuster et al. 2007)

$$N_{\text{H}_2} = 0.25 \frac{X_{\text{MW}}}{0.8} \frac{T_{\text{CO}}}{\text{K km s}^{-1}}, \quad (5)$$

where $X_{\text{MW}} = 2.3 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$ is the CO-to-H₂ conversion factor as determined for the Milky Way (Schuster et al. 2007), and T_{CO} is the velocity-integrated CO intensity, given as main beam antenna temperature. The factor 0.8 reflects the assumed 2–1/1–0 CO intensity ratio.

The atomic and molecular gas maps were first converted into their corresponding mass surface densities. To convert from the observed integrated intensities into the total gas surface densities, we used the relation $\Sigma_{\text{gas}} = 1.36 (\Sigma_{\text{H I}} + \Sigma_{\text{H}_2})$, which takes the mass contribution from He into account. The distribution of Σ_{gas} is presented in Fig. 5. As in Hitschfeld et al. (2009), we used a total mass surface density threshold in order to define the spiral arm regions. These regions were chosen to be similar to those in interferometric CO maps, in H α maps, and in 1400 MHz radio continuum maps. All pixels with $\Sigma_{\text{gas}} > 25 M_{\odot} \text{pc}^{-2}$ were attributed to the spiral arm regions and pixels

⁵ The relative error of the thermal fraction f_{th} is defined as $\varepsilon_{\text{th}} = \sigma_{f_{\text{th}}} / f_{\text{th}}$, where $\sigma_{f_{\text{th}}}$ is the absolute error of f_{th} .

with $8 M_{\odot} \text{pc}^{-2} \leq \Sigma_{\text{gas}} \leq 25 M_{\odot} \text{pc}^{-2}$ were attributed to the inter-arm regions. We defined two additional regions in the cores of M 51 and NGC 5195 with a radius of $25''$. The resulting map and the defined regions are shown in Fig. 5.

3.4. Non-thermal radio spectral index and curvature

In the next step, we explored the observed non-thermal radio continuum spectra in different regions of the galaxy on a point-by-point basis. We fitted a model spectrum consisting of a power law and a curvature component using a polynomial equation in logarithmic space (Perley & Butler 2013, 2017),

$$\log S_{\nu} = \log S_0 + \alpha_0 \log(\nu/\nu_0) + \beta [\log(\nu/\nu_0)]^2, \quad (6)$$

where S_{ν} is the flux density at a given frequency, ν is in GHz, S_0 is the flux density at the normalisation frequency $\nu_0 = 1$ GHz, α_0 is the non-thermal radio spectral index, and β the non-thermal radio spectral curvature. We note that $\beta < 0$ corresponds to a concave spectrum. The non-thermal radio spectral index α_0 needs to be defined at a single reference frequency because the spectral slope is frequency dependent in case of a curved spectrum. We started with this purely phenomenological model in order to explore the general shape of the spectrum without a bias towards a specific physical mechanism. We explore the underlying physics responsible for the shape of the spectrum in Sect. 4.

For each point in the maps, we fitted this model to eight data points at the frequencies listed in Table 2 (excluding 619 MHz). For simplicity, we ignored higher-order terms, and a more sophisticated modelling of the spectra needs to be deferred to future work. The data were fitted with a Levenberg–Marquardt least-squares algorithm. The resulting maps of best-fit α_0 and β and their corresponding error maps are shown in Fig. 6. The reduced χ^2 of the fit is shown in Fig. 7. The resulting parameter values were restricted to the frequency range between 54 and 8350 MHz and cannot be extrapolated towards arbitrary high or low frequencies.

The non-thermal radio spectral index at 1 GHz has values between -1.0 and -0.5 . The flatter radio spectra (α_0 from -0.7 to -0.5) are mostly found along the spiral arms, where the star-forming regions are located. The inter-arm regions have radio spectral indices between -1.0 and -0.8 . The tidal bridge region between M 51 and NGC 5195 (located north of M 51) is characterised by a similarly steep radio spectrum, whereas the spectrum flattens again towards the companion with spectral indices of $\alpha_0 \approx -0.7$. The errors usually lie below 0.04 and only rise to 0.10 in regions with lower signal-to-noise ratios. Our radio spectral index map is very similar to the 1400–4850 MHz map by Fletcher et al. (2011), who used a 1400 MHz map from the VLA instead of the WSRT map (and the same 4850 MHz map we used). Our radio spectral index is defined at a lower frequency of 1 GHz, and the deviations of 0.1–0.2 therefore become apparent in regions in which the absolute value of the spectral curvature is high.

The spectral curvature is negative, with values between -0.3 and 0.0. This means that the radio spectrum is concave, implying a suppression of radio emission at either low or high frequencies, or a combination of both. The suppression of the radio emission at low frequencies can be caused by free–free absorption, ionisation losses, or synchrotron self-absorption, and at high frequency, it can be caused by CR radiation losses Longair (2011). We further explored the process that causes the observed curvature in Sect. 4. Regions with flatter radio spectra tend to show

stronger curvatures ($\beta \leq -0.2$). The errors for the curvature are usually smaller than 0.06; only in regions with lower signal-to-noise ratios do they rise to 0.14. The reduced χ^2 is smaller than one in most of the galaxy. The value is higher in the areas in which the error on the fit parameters is also high. The areas in which the model does not fit the data so well are also less strongly curved. We assume that a better model in these areas would be just a power law.

3.5. Low- and high-frequency non-thermal radio spectral indices

We now study the non-thermal spectral index at both low and high frequencies. We compared the two-point low-frequency radio spectral index α_{low} between 54 and 144 MHz with the two-point high-frequency spectral index α_{high} between 1370 and 4850 MHz. The two-point spectral indices were calculated in a standard way by taking the logarithmic ratio of the flux densities in two maps over the logarithmic frequency ratio. The errors in the spectral index maps were calculated by propagating the errors from the individual maps, which are a combination of the flux error (listed in Table 2) and the rms noise measured away from the source. The two-point spectral index maps are shown in Fig. 8. We did not select the two highest frequencies because the galaxy at 8350 MHz is smaller, which would prevent us from studying the radio spectral index of the diffuse emission further in the outskirts of M 51. Additionally, skipping the 8350 MHz map gives a higher ratio between frequencies, which results in a more reliable spectra index map.

The maps of α_{low} and α_{high} have a similar morphology at first glance, but α_{low} is systematically higher than α_{high} . The values for α_{low} reach from -0.7 to 0.2 , with errors in the range of 0.17 – 0.25 . In contrast, the values for α_{high} reach from -1.3 to -0.6 , with errors in the range of 0.05 – 0.15 . Higher errors for the low-frequency spectral index are expected because of the higher calibration error and noise in these maps. The errors are also higher at the edges of the maps because the signal-to-noise ratio is lower. The higher values of $\alpha_{\text{high}} \approx -0.7$ correlate well with the spiral arm structure of M 51, which was reported by Fletcher et al. (2011). The values of α_{low} are similarly distributed, although the spiral arms are more diffuse and have an inverted radio spectrum, as indicated by radio spectral indices with values of up to ≈ 0.2 . Because of the cosmic-ray radiation losses of the CR electrons, we expect a steepening at the edges of the galaxy. This is shown in the α_{low} map, even though it might not be completely reliable because the signal-to-noise ratio is low in these regions. We attribute the strong flattening of the radio spectrum at higher frequencies towards the extreme north and south as visible in the map of α_{high} as spurious. The strong spurious flattening is likely due to the limitations of combining the interferometric and single-dish data (Cotton 2017). These data do not affect our results because they lie beyond the region of interest that we considered for our analysis (Sect. 2).

As the results of fitting for spectral index and curvature already suggested (Fig. 6), the spectral index flattens overall towards lower frequencies for the whole inner disc of M 51. In the following, we discuss the effects that might cause these flat and partially inverted spectra.

4. Spectral index flattening and low-frequency turnovers

Changes in the spectral indices over frequency may be due to a number of reasons. In the following, we investigate the

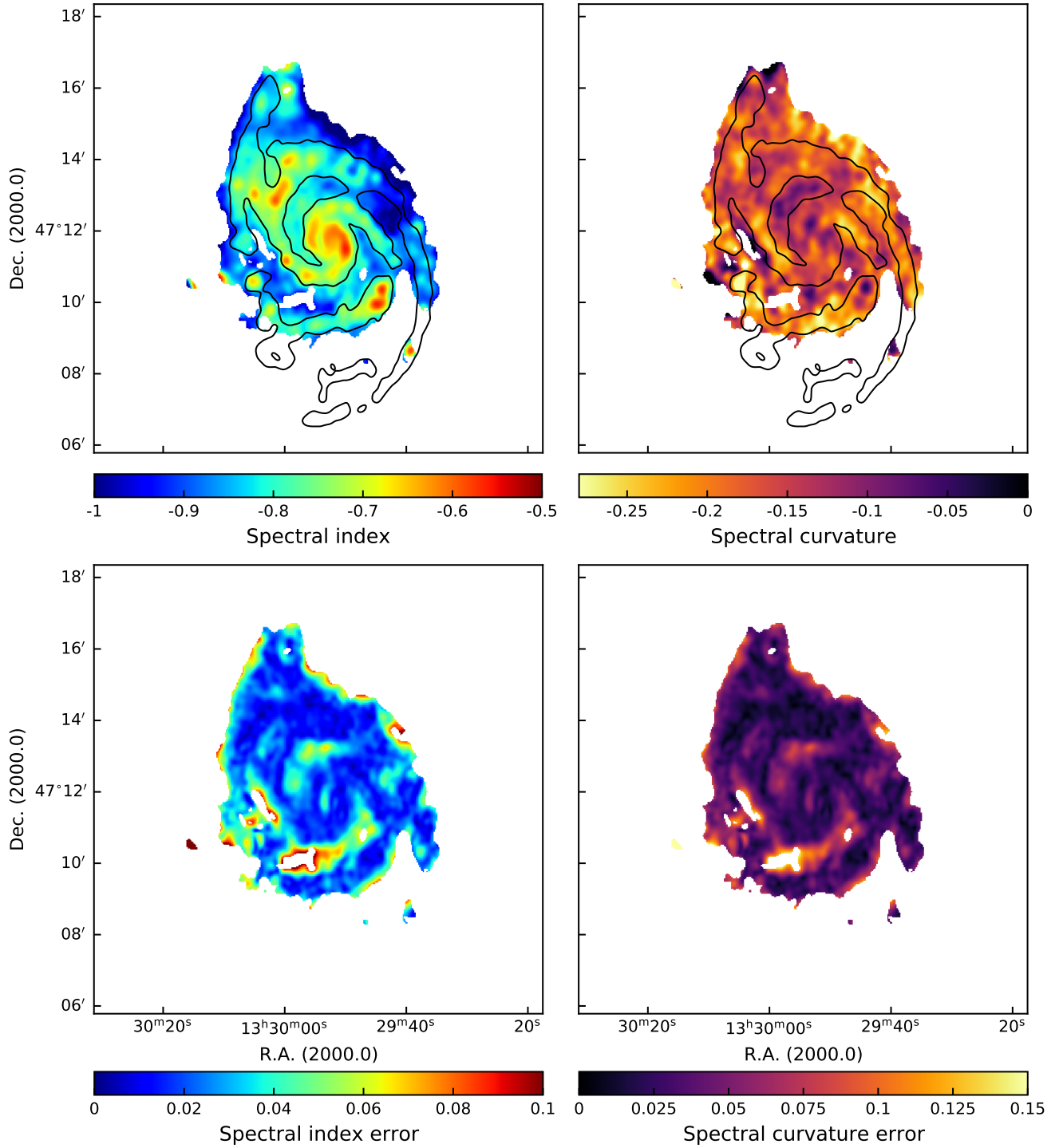


Fig. 6. Non-thermal radio spectral index and curvature at 1 GHz. Top panels: best-fit radio spectral index α_0 (left panel) and spectral curvature (right panel). The bottom panels show the corresponding uncertainty maps of the radio spectral index (left panel) and curvature (right panel). The black contours represent a total gas-mass surface density $25 M_{\odot} \text{pc}^{-2}$.

plausible mechanisms that can alter the radio continuum spectrum from a power-law to a concave spectrum. This can either be done by changing the cosmic-ray electron spectrum or by directly absorbing low-frequency radio emission. Previous work has shown (Heesen et al. 2023, 2024) that the diffusion coefficient of GeV CR electrons is independent of energy, at least over the relevant energy range. Hence, we do not expect diffusion to change the spectrum. Moreover, advection does not change the spectrum. Hence, we now consider cosmic-ray radiation losses,

synchrotron self-absorption, thermal free–free absorption, and cosmic-ray ionisation losses.

4.1. Cosmic-ray radiation losses

In regions with low gas densities, cosmic-ray electrons lose their energy due to synchrotron and inverse-Compton radiation losses, causing their spectra to age, that is, to steepen.

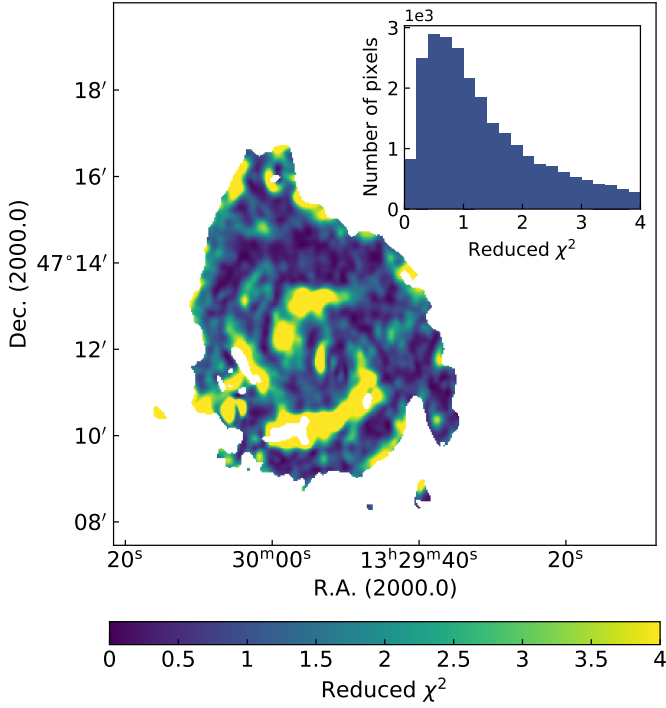


Fig. 7. Map of the reduced χ^2 of the fit presented in Fig. 6. The inset in the top right corner shows the histogram of the reduced χ^2 values.

In particular, spectral ageing predominantly affects the high-frequency radio spectral index (Sect. 3.5). Near star-forming regions, the values of $\Delta\alpha = \alpha_{\text{low}} - \alpha_{\text{high}}$ are lower (between 0.2 and 0.5) than in the inter-arm regions, where they are between 0.8 and 1.1. A proper modelling of CR ageing is not possible with the data, but we can make a few qualitative observations. Figure 6 clearly shows that the curvature is high, and the spectral index is lower in regions with low star formation, that is, in the inter-arm regions. Inside the spiral arms, the synchrotron emission at low frequencies is likely to be a mix of recently accelerated CR electrons and those from previous nearby sites of star formation, which fall within a resolution element. However, this is not true in the inter-arm regions, where the star formation is low. The data resolution is approximately $16''$, that is, 650 kpc. If we assume that the bulk of the CR electrons are produced in the arms, then CR electrons with energies lower than about 1.5 GeV will be able to diffuse to scales larger than 650 kpc (assuming $B = 10 \mu\text{G}$, and $D = 2 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$). This corresponds to CR electrons that are emitted at critical frequencies of 600–700 MHz. Hence, CR electrons emitting above 1 GHz lose energy before they can mix, especially in the inter-arm regions. Even in regions with a low star formation, the local CR electron injection timescale is much longer than the ageing timescale. This is quantitatively shown in Fig. 3 of Basu et al. (2015) in order to explain the steep spectra in low-density regions. This argument is also supported by the spatially resolved radio-FIR relation (see Fig. 5 and Sect. 4 of Basu et al. 2012b).

4.2. Synchrotron self-absorption

Synchrotron self-absorption is known to play a key role in the flattening of spectra in the inner cores of active galactic nuclei (AGN). We used the equation from Lacki (2013) to determine

the turnover frequency ν_{SSA} for integrated spectra of galaxies,

$$\nu_{\text{SSA}} = 2.4 \text{ MHz} \left(\frac{\Sigma_{\text{SFR}}}{50 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}} \right)^{0.39}, \quad (7)$$

where Σ_{SFR} is the star formation rate surface density. With a value of $\Sigma_{\text{SFR}} = 0.9$ from González-Lópezlira et al. (2013), we calculate a value of $\nu_{\text{SSA}} = 0.5 \text{ MHz}$. This value is lower by more than two orders of magnitude than our lowest observing frequency. Therefore, synchrotron self-absorption cannot be the dominant effect causing the flattening.

Similarly, diffuse large-scale structures in nearby galaxies are not very likely to be affected by synchrotron self-absorption because the required magnetic field strength is high. We can calculate this magnetic field strength B_{SSA} for a given frequency ν in GHz and brightness temperature T_b in K using the standard equation

$$B_{\text{SSA}} \approx 1.4 \times 10^{21} \nu T_b^{-2}. \quad (8)$$

T_b is defined as

$$T_b = 1.222 \times 10^3 \frac{I}{\nu^2 \theta_{\text{maj}} \theta_{\text{min}}} \text{ K}, \quad (9)$$

with the brightness I in Jy beam^{-1} and θ_{maj} and θ_{min} the synthesised major and minor beam half-power beam widths in arcseconds, respectively. When we insert our beam size of $17.5'' \times 15''$ and a brightness of $150 \text{ mJy beam}^{-1}$ as a maximum at 54 MHz, the resulting magnetic field is $1.3 \times 10^{15} \text{ G}$. From equipartition calculations, we know that the typical magnetic field strength in nearby galaxies is $9 \mu\text{G}$ (Beck 2005) with maximum values for extreme starburst cases such as M 82 of $100 \mu\text{G}$ (Adebahr et al. 2013). Lacki (2013) discussed the possible turnover frequency for extreme starburst cases, which would be about $\nu_{\text{SSA}} = 2.4 \text{ MHz}$. These results show that synchrotron self-absorption cannot play an important role in the flattening of the spectra at low frequencies in M 51.

4.3. Thermal free-free absorption

Free-free absorption is an effect caused by an ionised medium that absorbs radio waves while they propagate through it. The amount of absorption depends on the thermal electron number density n_e , the path length, and the frequency, such that the optical depth increases with decreasing frequency. Free-free absorption has been observed at frequencies below 500–1000 MHz in the core regions (Adebahr et al. 2013; Varenius et al. 2016) and individual star-forming regions (Wills 1997; Varenius et al. 2015; Basu et al. 2017) of starburst galaxies, and also in the Milky Way (Rishbeth 1958; Roy & Rao 2004). Observations at very low radio frequencies also showed a turnover for the global spectrum of the Milky Way at about 3 MHz (Brown 1973).

In the following, we investigate whether free-free absorption can explain the flattening of the radio spectrum towards lower frequencies. Following Wills et al. (1997), the spectrum in case of free-free absorption of sources inside an ionised medium is

$$S_{\nu} = S_0 \nu_0^{\eta} e^{-\tau_{\text{ff}}}, \quad (10)$$

with η the radio spectral index of the optically thin medium, and τ_{ff} the free-free emission optical depth. In the expression for the free-free Gaunt factor at radio wavelengths from Lequeux (2005), the optical depth is given as

$$\tau_{\text{ff}} = 8.2 \times 10^{-2} \nu_0^{-2.1} T_e^{-1.35} \text{ EM}, \quad (11)$$

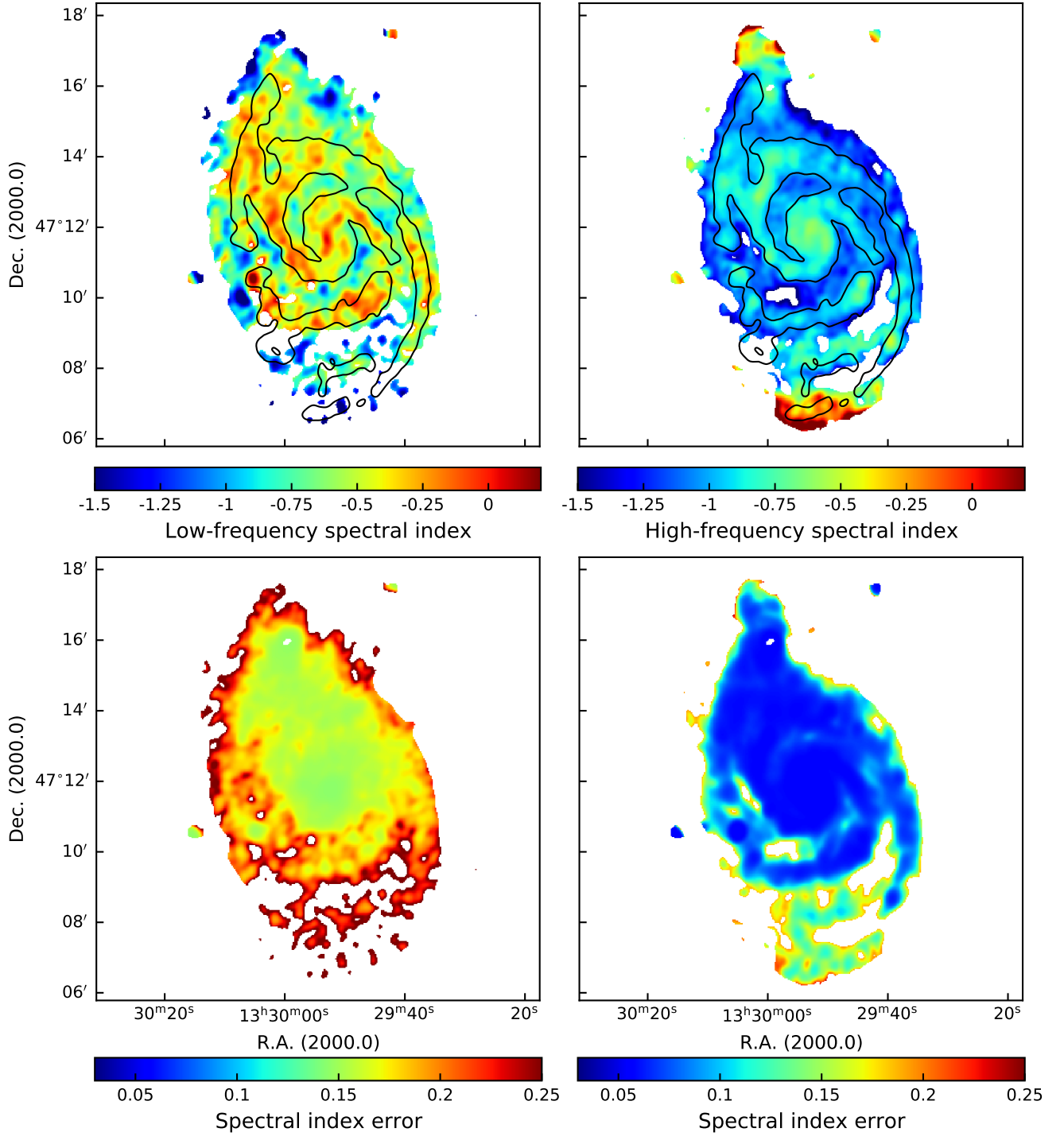


Fig. 8. Two point non-thermal radio spectral indices at low (α_{low} ; 54–144 MHz) and high (α_{high} ; 1370–4850 MHz) frequencies. The top panels show the spectral indices α_{low} (left panel) and at α_{high} (right panel). The bottom panels show the corresponding uncertainty maps. The black contours represent a total gas-mass surface density $25 M_{\odot} \text{pc}^{-2}$.

with the emission measure (EM) in units of $\text{cm}^{-6} \text{pc}$ and the electron temperature T_e in K. The EM is defined as

$$\left(\frac{\text{EM}}{\text{pc cm}^{-6}} \right) = \int_0^{s_0} \left(\frac{n_e}{\text{cm}^{-3}} \right)^2 \left(\frac{ds}{\text{pc}} \right), \quad (12)$$

where n_e is the thermal free electron density, and s is the distance along the line of sight between the source at s_0 and an observer at 0. The absorption model (Eq. (10)) was used to fit

the spectrum of M 51. We then derived the EM using Eq. (11), where we inserted the electron temperature as expressed by the galactocentric distance (Eq. (3)).

4.3.1. Local radio continuum spectra

We first investigated the effect of free-free absorption on our radio continuum spectra by analysing the integrated flux densities within the four regions of the arm, inter-arm, and

Table 3. Fitted parameters for the spectra of the spiral arm (SA), inter-arm (IA), and core (N5194c, N5195c) regions.

Region	S_0 (Jy)	η	EM (pc cm $^{-6}$)	S_0 (Jy)	α_0	β
SA _{syn}	0.630 ± 0.036	-0.839 ± 0.039	2800 ± 990	0.697 ± 0.013	-0.777 ± 0.0089	-0.176 ± 0.013
IA _{syn}	0.459 ± 0.026	-0.914 ± 0.041	2000 ± 790	0.507 ± 0.026	-0.881 ± 0.024	-0.147 ± 0.034
N5194c _{syn}	0.293 ± 0.014	-0.746 ± 0.032	2710 ± 980	0.3119 ± 0.0071	-0.674 ± 0.012	-0.144 ± 0.016
N5195c _{syn}	0.0917 ± 0.0036	-0.865 ± 0.027	2040 ± 570	0.09924 ± 0.0021	-0.821 ± 0.0097	-0.132 ± 0.014

Notes. Columns (2)–(4) list the free–free absorption, and Cols. (5)–(7) list the curved spectral model. Both are fitted to the non-thermal radio continuum spectra.

the two cores of M51 and NGC 5195 (Sect. 3.3). The thermal emission that we previously subtracted is also affected by free–free absorption. However, the absorption of the thermal radio continuum can be ignored because free–free absorption is only significant at low frequencies, where the thermal fraction is very low. Similarly, at high frequencies, free–free absorption is negligible. We can therefore justify using the non-thermal maps as produced above for the fitting and neglect the effect of free–free absorption on the thermal emission. For comparison, we also fitted the polynomial model (Eq. (6)) to the non-thermal radio continuum spectra (after thermal subtraction) in the four regions. The flux density error was estimated by assuming a statistical error caused by the map noise σ_{rms} , as well as a relative flux uncertainty ε_v due to calibration uncertainty (see Table 2). The error of the flux density measurements at each frequency was calculated using the following expression (Heesen et al. 2022):

$$\sigma_{S_\nu} = \sqrt{\left(\sigma_{\text{rms}} \sqrt{N_{\text{beams}}}\right)^2 + (\varepsilon_v S_\nu)^2}, \quad (13)$$

where S_ν is the flux density, and N_{beams} is the number of beams in the integration region.

Figure 9 shows the measured spectra within the regions together with the best-fitting absorption models. We show additional point spectra in Appendix B. The flattening of the spectra at low frequencies is highlighted by comparing the spectrum to a power law. The resulting parameters are listed in Table 3. The radio spectral indices η lie between -0.91 and -0.75 . For the polynomial fits, we find non-thermal radio spectral indices at 1 GHz between -0.88 and -0.67 .

We find that the EM has values between 2000 and 2800 cm $^{-6}$ pc. They mostly show the same tendency as the absolute values of the spectral curvature because the higher EM values are seen in the spiral arm regions and the lower values in the inter-arm regions. However, the EM values do not greatly differ statistically because the uncertainties are large.

4.3.2. Emission measure and radio spectral index

We now investigate the free–free absorption on a point-by-point basis in order to determine the spatial distribution of the EM. For each point in the radio maps, we fitted the free–free absorption model (Eq. (10)) to eight data points at the frequencies listed in Table 2 (excluding 619 MHz). We assumed the electron temperature from Eq. (3). The parameters of the model were the spectral index η and the EM. We present the resulting maps in Fig. 10. In general, regions with higher gas densities (the spiral arms) show flatter spectral indices and a slightly higher EM. While the steeper spectral index in the inter-arm regions can be explained by radiation losses of the cosmic-ray electrons during

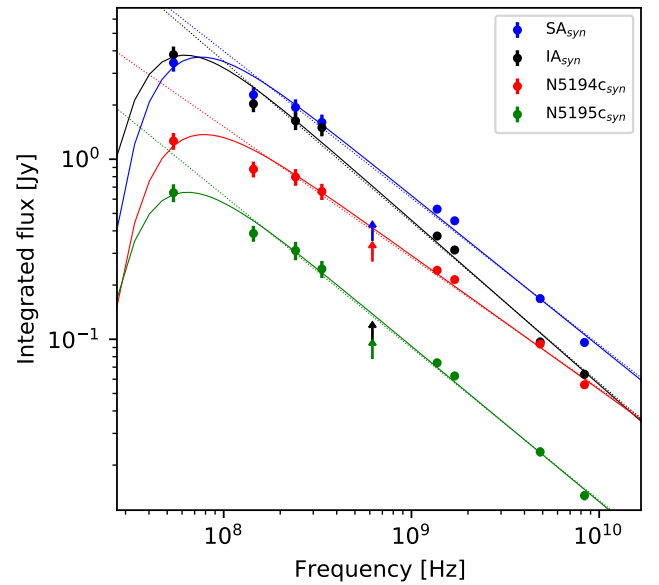


Fig. 9. Non-thermal radio continuum spectra for the spiral arm (SA), inter-arm (IA), and core regions (N5194c and N5195c). The flux densities at 619 MHz are only given as lower limits and are not included in the analysis. The solid lines are the best-fitting free–free absorption models (Eq. (10)). The dotted lines show the power-law fits for frequencies ≥ 144 MHz.

propagation away from their places of origin in the star-forming regions, the significant flattening in the spiral arms and in the cores of NGC 5194 and 5195 is difficult to explain without thermal absorption effects. The spectra presented in Fig. 9 show that the 54 MHz data points have much lower flux densities than what would be expected if the emission were to follow a power law. This is an indication of a flattening at low frequencies that is at least in part caused by free–free absorption.

We used the H α flux density map obtained using IFU spectroscopy to calculate an independent EM estimate. We first convolved the data to the same beam as the radio maps. To calculate the EM, we used the equation (Dettmar 1992)

$$\text{EM} = 5 \times 10^{17} F_{\text{H}\alpha} / \Omega \text{ cm}^{-6} \text{ pc}, \quad (14)$$

where $F_{\text{H}\alpha}$ is the measured flux in erg cm $^{-2}$ s $^{-1}$, and $\Omega = 1.133 \cdot 17''.5 \times 15''.0$ is the collecting area in $\square''$ calculated for our beam.

We compared the EM from the H α flux density to the EM obtained by fitting the free–free absorption model to the radio data by plotting them against each other in Fig. 11. In contrast to our expectation, we see no correlation, with a Spearman rank correlation coefficient of $\rho_s = -0.04$. Free–free absorption might

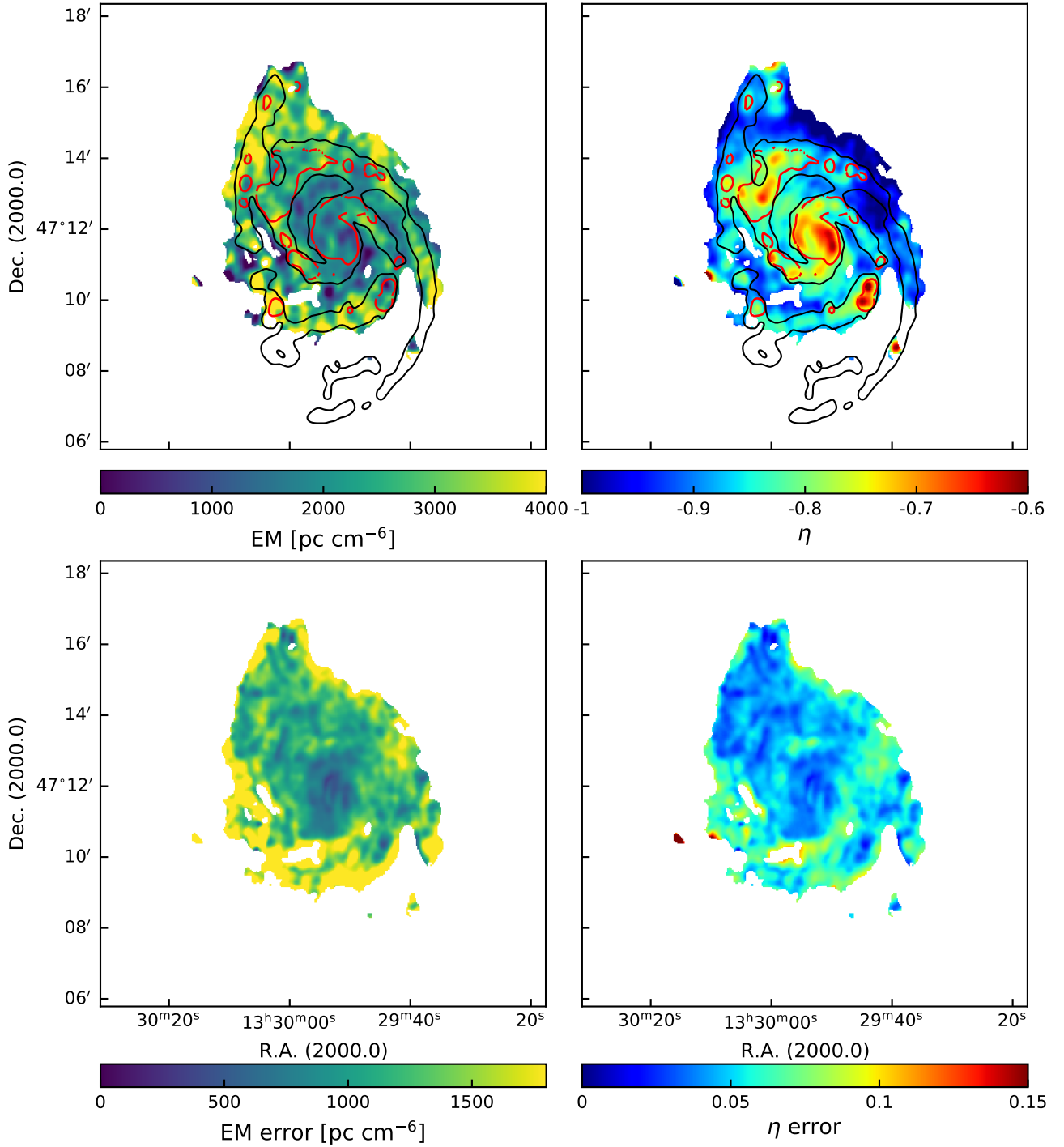


Fig. 10. Thermal free-free absorption. Results from fitting the thermal absorption model to the non-thermal radio continuum emission at eight frequencies between 45 and 8350 MHz (Table 2). The left column shows the resulting EM map (top panel) and its uncertainty map (bottom panel). The right column shows the radio spectral index of the optically thin medium η (top panel) and its uncertainty map (bottom panel). The red contours represent the H α flux value of $2.6 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1} \text{ beam}^{-1}$ from the Metal-THINGS survey. The black contours represent a total gas-mass surface density $25 M_{\odot} \text{ pc}^{-2}$.

therefore not the main mechanism for the low-frequency flattening that we observe (see Sect. 4.4). An alternative reason could be that H α directly traces the clumpy ionised gas, while the EM estimated from the radio spectrum also receives a contribution from the diffuse gas. The latter is known as the diffuse ionised gas that fills the space between the H II regions (Haffner et al. 2009). The radio free-free emission also originates from a medium like this. The lack of correlation, or putative

anti-correlation, may therefore be explained by the very different volume-filling factors.

4.4. Ionisation losses

The spectral curvature and the H I gas-mass surface density (Fig. 12) are related, however. We therefore explored ionisation losses as an alternative mechanism to explain the low-frequency

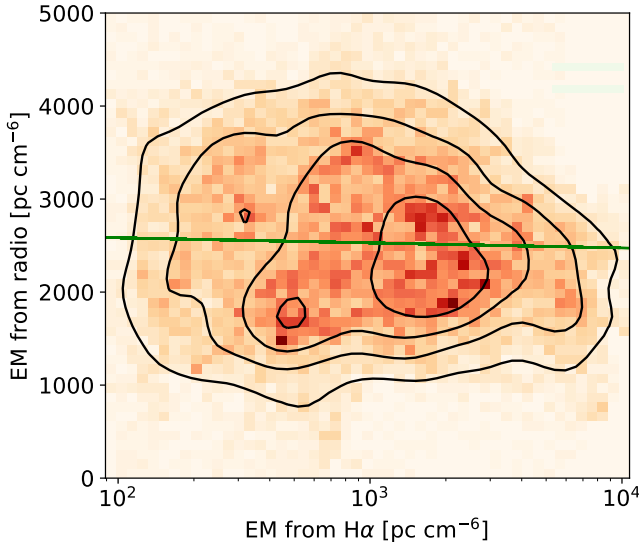


Fig. 11. Comparison of the EM from H α flux density to the EM obtained by fitting the free–free absorption model to the radio data. The colours and contours represent the data point density. The green line shows the best-fitting, if insignificant, correlation.

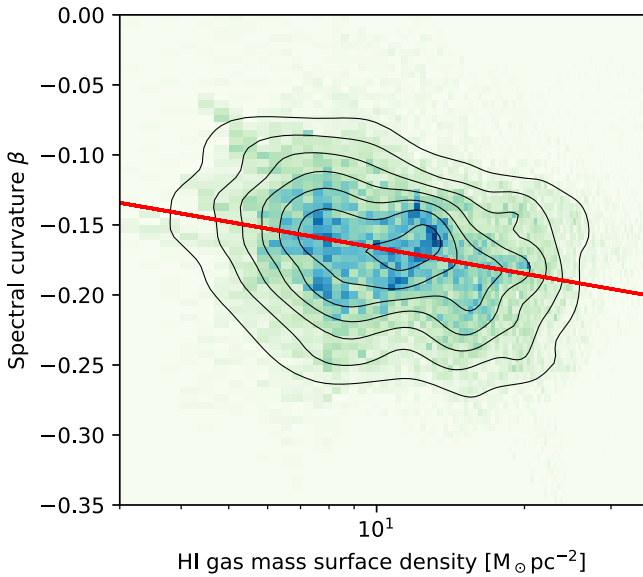


Fig. 12. Non-thermal radio spectral curvature as a function of the H I gas-mass surface density. The colours and contours show the data point density. The red line shows the best-fitting correlation.

flattening because it dominates in the neutral gas. Cosmic-ray electrons lose energy due to the ionisation of atomic and molecular hydrogen. The ionisation loss rate is directly proportional to the number density of neutral atoms and molecules n , as shown in the following expression in the case of neutral hydrogen (Longair 2011):

$$-\left(\frac{dE}{dt}\right)_{\text{ion}} = 7.64 \times 10^{-15} n (3 \ln \gamma + 19.8) \text{ eV s}^{-1}, \quad (15)$$

where E is the electron energy, and γ is the Lorentz factor. The dependence on energy is only logarithmic, and so it can be approximated as constant throughout the spectrum. At lower energies, a larger energy fraction is lost due to ionisation, and therefore the effect is stronger. The fraction of energy that is lost

is higher at lower CR energies because the total energy is lower while the lost energy is approximately constant. This means that the cosmic-ray electron number density (per energy bin) does decrease as function of time, and this effect is more pronounced at lower energies. The spectral index flattening due to ionisation losses should be $\Delta\alpha \leq 0.5$ in comparison to the injection spectrum (Basu et al. 2015).

In Fig. 12, we show the non-thermal spectral curvature as a function of H I gas-mass surface density. We find a weak negative correlation ($\rho_s = -0.21$). This can be explained if cosmic-ray ionisation losses cause the low-frequency flattening. At higher H I gas-mass surface densities, the spectrum becomes more concave (lower value of β), as expected if ionisation losses play a role. The timescale for ionisation losses is (Murphy 2009)

$$t_{\text{ion}} = 4.1 \times 10^9 \left(\frac{n}{\text{cm}^{-3}}\right)^{-1} \left(\frac{E}{\text{GeV}}\right) \left[3 \ln\left(\frac{E}{\text{GeV}}\right) + 42.5\right]^{-1} \text{ yr.} \quad (16)$$

For this timescale to be an important process to flatten the radio continuum spectrum at low frequencies, it therefore has to be shorter than the synchrotron loss timescale of approximately 100 Myr (Heesen et al. 2023). For cosmic-ray electrons with $E \approx 0.5$ GeV at the lowest frequency, we thus expect $t_{\text{ion}} \approx 100$ Myr for neutral gas densities of $n \approx 0.5 \text{ cm}^{-3}$. This is the case for mass surface densities of $\Sigma_{\text{gas}} = 2.5\text{--}5 M_{\odot} \text{ pc}^{-2}$, assuming a gas scale height of 100 pc (Cox 2005; Basu et al. 2015). This means that the suggested correlation between non-thermal spectral curvature and H I gas-mass surface density can indeed be ascribed to cosmic-ray ionisation losses that affect the low-energy cosmic-ray electrons most. In the absence of a spectral model for ionisation losses, we leave a more rigorous fitting of the spectra to future work. We currently cannot rule out the effect free–free absorption in addition to ionisation losses. We therefore conclude that the low-frequency flattening observed in M51 is probably caused by a combination of ionisation losses and free–free absorption.

Ionisation of the molecular component of the interstellar medium should also cause CR energy loss. We repeated the same analysis as shown in Fig. 12 to test the correlation between the spectral curvature and the total gas-mass density. In contrast to our expectation, they are not correlated ($\rho_s = -0.07$). The reason may be that cosmic rays (at least in the GeV range) do not enter molecular clouds because the magnetic field is strong and turbulent (Tabatabaei et al. 2013).

5. Summary and conclusions

Synchrotron spectra at low radio frequencies are shaped by several processes, such as cosmic-ray ionisation losses and free–free absorption, that suppress the emission. The cosmic-ray energy loss from ionisation is nearly independent of energy (the dependence is only logarithmic), and it therefore proportionally affects low-energy cosmic-ray electrons most, resulting in spectral flattening. Free–free absorption is also strongly dependent on frequency. Frequencies below 300 MHz (depending on EM) are more affected. This affects our ability to interpret low-frequency continuum emission as an extinction-free star formation tracer. On the other hand, strong free–free absorption would allow us to measure the EM, which itself is derived from radio spectra and thus is an extinction-free star-formation tracer. In order to study these effects, we compiled data of the nearby grand-design spiral galaxy M51 at nine different frequency bands between 54 and 8350 MHz, eight of which we used for the analysis. We presented for the first time new observation with the

GMRT at 240 MHz. We calculated the contribution of the thermal radio continuum emission based on the H α map corrected for extinction using 24 μ m mid-infrared data. This contribution was subtracted from the radio maps, so that we only studied the non-thermal emission. We also used new IFU spectroscopy data from Metal-THINGS in order to measure extinction-corrected H α intensities, which we used as an independent EM estimate.

First, we fitted a polynomial function to the logarithmic intensities to determine the non-thermal radio spectral index and spectral curvature, as shown in Fig. 6. The non-thermal radio spectral index at 1 GHz is relatively flat in the spiral arms, with $\alpha_0 \approx -0.6$, in agreement with the injection spectral index. The spectral curvature is negative throughout the galaxy, with more negative values in the spiral arms. This means that the spectrum is concave, where intensities both at low and high frequencies are suppressed. This is the expected behaviour for low-energy losses and absorption effects as well as strong synchrotron and inverse-Compton radiation losses at higher frequencies, resulting in spectral ageing. Next, we calculated the low- (54–144 MHz) and high-frequency (1370–4850 MHz) non-thermal two-point radio spectral indices separately, as shown in Fig. 8. The low-frequency radio spectral index is very flat and even positive in the spiral arms, with α_{low} between -0.5 and 0.2 , showing inverted radio continuum spectra. This clearly hints at either low frequency absorption or cosmic-ray ionisation losses. In contrast, the high-frequency radio spectra are fairly steep, with values of α_{high} between -1.5 and -0.7 . The differences throughout the galaxy can be explained by spectral ageing.

Next, we analysed the spatially resolved spectral index in more detail, starting with the effect of free–free absorption. In Fig. 9 we plot the integrated spectra of the spiral arms, inter-arm, and core regions. The spectra can be well fitted with a free–free absorption model (Wills et al. 1997). At 54 MHz the deviation from a power-law spectrum is most apparent.

Comparing the spiral arms with the inter-arm regions, we find that the turnover in the spiral arms occurs at higher frequencies, which implies stronger free–free absorption. This is confirmed by the values of the EM obtained by fitting the free–free absorption model. On the other hand, the difference in the EM between spiral arm and inter-arm regions is not statistically significant, suggesting that free–free absorption might not be the only effect.

We then fitted the free–free absorption model to our spatially resolved data. We obtained point-by-point maps of the EM and the radio spectral index η (Fig. 10). We compared the EM values obtained from the fit to the values estimated from the extinction-corrected H α measurements. The EMs calculated from different tracers are not correlated (Fig. 11). The lack of correlation may therefore be explained by the very different volume-filling factors, or the free–free absorption might not be the only process that causes the low-frequency flattening. Therefore, we also investigated the possible influence of cosmic-ray ionisation losses on the radio continuum spectrum. To this end, we studied the correlation between non-thermal spectral curvature and gas-mass surface density. We find a weak correlation between spectral curvature and H I gas-mass surface density (Fig. 12). The main process that causes the low-frequency flattening is therefore probably more dominant in the regions with neutral H I gas. In these regions, the cosmic rays lose energy due to ionisation. Because ionisation losses are nearly independent of frequency, they are more apparent at low frequencies, where low-energy cosmic-ray electrons emit. We therefore conclude that the low-frequency flattening in M51 is most likely

caused by a combination of free–free absorption and ionisation losses.

A low-frequency spectral flattening in an average spiral galaxy outside of the Milky Way is observed here for the first time. Previously, this effect was only observed in starburst galaxies (Adebahr et al. 2013, 2017; Basu et al. 2015; Varenus et al. 2016). Now we were able to spatially locate the galaxy region in which the spectra flattens at low frequencies. These areas generally have a higher density of H I gas. Curiously, spectral curvature and total gas-mass density are not correlated, suggesting that the cosmic-ray ionisation losses occur in the atomic gas phase, but not in the molecular gas phase, possibly because the cosmic rays do not enter molecular clouds due to the magnetic field (Tabatabaei et al. 2013). We also considered what our results mean for using sub-GHz radio continuum observations as an SFR tracer. Even when low frequencies of around 150 MHz (LOFAR HBA) are used as an SFR tracer, an understanding of the losses we investigated here is required (see e.g. Adebahr et al. 2013; Chyży et al. 2018). The forthcoming surveys with LOFAR at very low frequencies and high angular resolution will enable further studies in other nearby galaxies and allow us to investigate the influence of these effects in more detail.

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Appendix A: Thermal subtraction

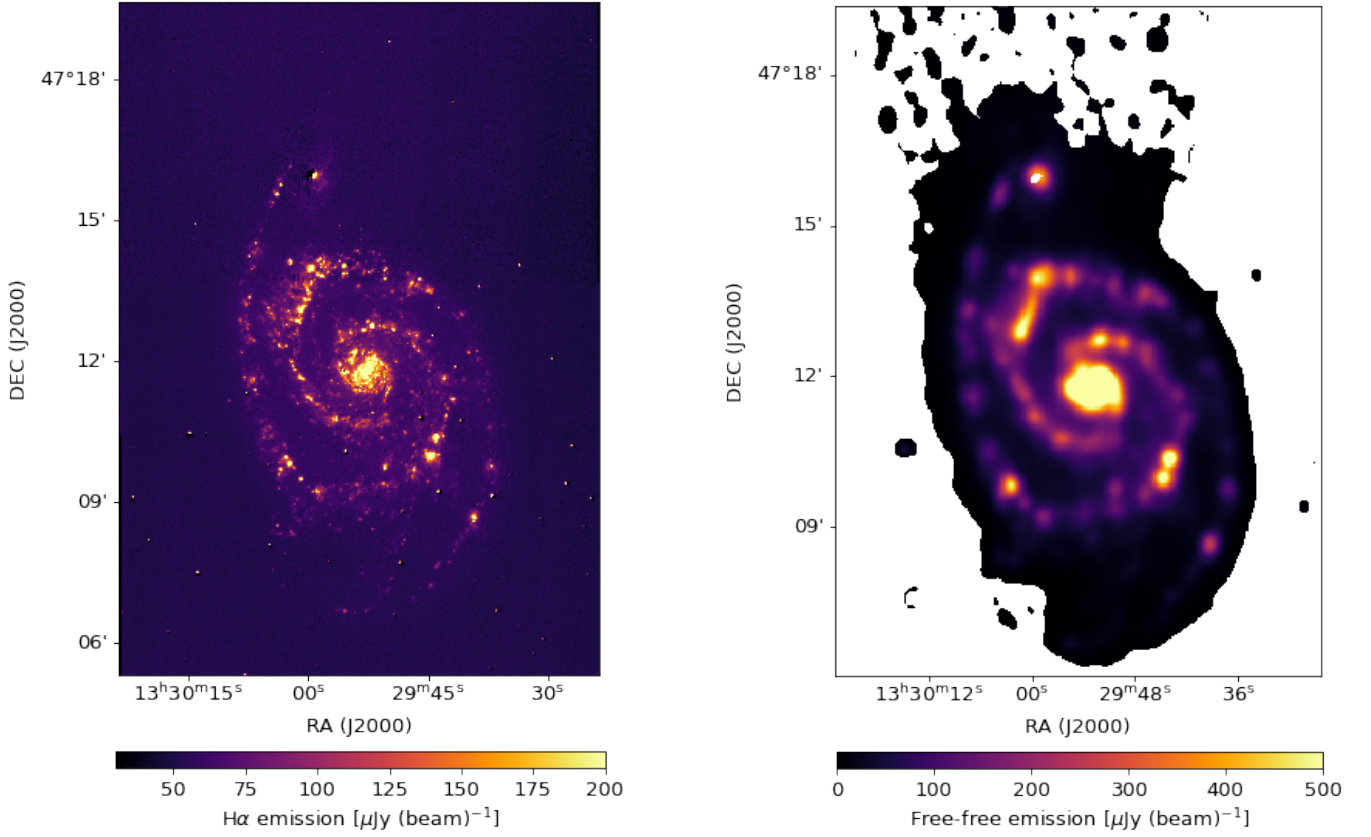


Fig. A.1: Intermediate data products in the subtraction of thermal emission in M51. Left panel: Initial continuum-subtracted H α map obtained with the Kitt Peak National Observatory 2.1-m telescope using the narrow-band H α -filter KP1563 (Kennicutt et al. 2003). The angular resolution is $1''.35 \times 1''.35$ and the rms noise is $\approx 50 \mu\text{Jy beam}^{-1}$. The map was downloaded from the ancillary data at the SINGS webpage.⁶ Right panel: Extinction corrected prediction of the free-free emission at 1370 MHz in M51. This emission was scaled to the appropriate frequency with the spectral index $\alpha = 0.1$. The map shown here was subtracted from the radio maps to get the non-thermal emission. The beam size is $17''.5 \times 15''.0$.

⁶ <http://irsa.ipac.caltech.edu/data/SPITZER/SINGS/>

Appendix B: Point spectra

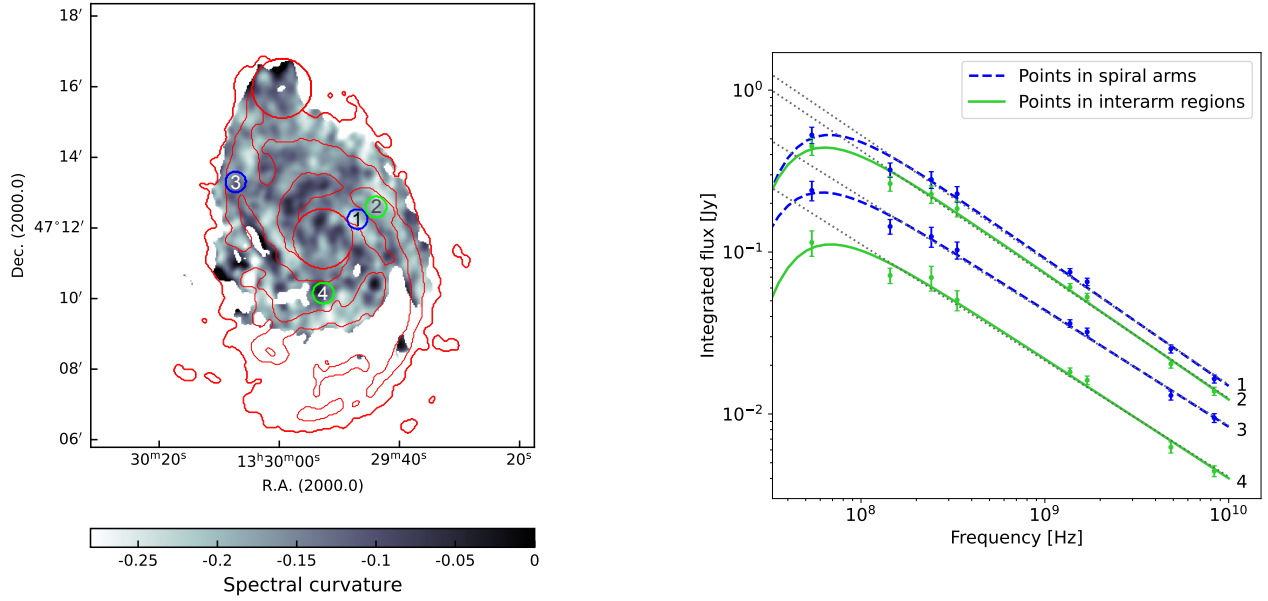


Fig. B.1: Individual point spectra. Left panel: The location of individual spectra from spiral arms (inter-arm regions) marked by green (blue) circles on top of the spectral curvature map. The size of the circles corresponds to the beam size. Red contours at the total gas-mass density of 8 and 25 $M_{\odot} \text{ pc}^{-2}$ define the borders of the spiral arm and inter-arm regions, respectively (Sect. 3.3). Right panel: Non-thermal radio continuum spectra for representative beam-sized regions marked in the left panel. Each spectrum is labeled with its corresponding number. Dotted lines show the power-law fits for frequencies ≥ 144 MHz. The individual spectra show the same trends as the integrated spectra in Fig. 9.