LOW-FREQUENCY RADIO–FIR CORRELATION IN NORMAL GALAXIES AT ~1 kpc SCALES

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ABSTRACT

We study the radio–FIR correlation between the nonthermal (synchrotron) radio continuum emission at λ90 cm (333 MHz) and the far-infrared emission due to cool (~20 K) dust at λ70 μm in spatially resolved normal galaxies at scales of ~1 kpc. The slope of the radio–FIR correlation significantly differs between the arm and interarm regions. However, this change is not evident at a lower wavelength of λ20 cm (1.4 GHz). We find the slope of the correlation in the arm to be 0.8 ± 0.12 and use this to determine the coupling between equipartition magnetic field (Beq) and gas density (ρgas) as Beq ∝ ρgas^{0.51±0.12}. This is close to what is predicted by magnetohydrodynamic simulations of turbulent interstellar medium, provided the same region produces both the radio and far-infrared emission. We argue that at 1 kpc scales this condition is satisfied for radio emission at 1.4 GHz and may not be satisfied at 333 MHz. The change of slope observed in the interarm region could be caused by propagation of low energy (~1.5 GeV) and long-lived (~10^8 yr) cosmic-ray electrons at 333 MHz.

Key words: cosmic rays – galaxies: ISM – galaxies: spiral – infrared: galaxies – radio continuum: galaxies – techniques: image processing

1. INTRODUCTION

The radio–far-infrared (FIR) correlation in normal galaxies was first observed by van der Kruit (1971, 1973) and later extended by the IRAS mission. Subsequently, it was established that the correlation holds good (within a factor of two) over five orders of magnitude in radio and FIR luminosity (Condon 1992; Yun et al. 2001) for a wide morphological class of galaxies like spirals, irregulars, and dwarfs (Wunderlich et al. 1987; Dressel 1988; Price & Duric 1992) on global scales. Based on spatially resolved studies of normal and irregular galaxies, it is seen that the correlation holds even at scales of a few tens to hundreds of parsecs (see, e.g., Beck & Golla 1988; Xu et al. 1992; Hoernes et al. 1998; Murgia et al. 2005; Tabatabaei et al. 2007a; Hughes et al. 2006; Murphy et al. 2006; Paladino et al. 2006, 2009; Dumas et al. 2011).

The basic model that connects these two regimes of emission is via star formation (Harwit & Pacini 1975). The radio continuum emission arises due to synchrotron emission (henceforth nonthermal emission) from relativistic electrons, produced in supernova remnants. A good fraction of them originate from massive (>10 M_☉), short-lived (<10^6 yr) stars. The FIR emission arises from re-radiation by dust heated due to ultraviolet (UV) photons emitted by the above population of stars. Though the cause of the correlation is well understood, the tightness over several orders of magnitude still remains puzzling. Many models explaining the correlation require close coupling between the magnetic field (B) and the gas density (ρgas) of the form, B ∝ ρgas^{α} (see, e.g., Helou & Bicay 1993; Niklas & Beck 1997; Thompson et al. 2006). Such a coupling can be established by magnetohydrodynamic (MHD) turbulence of the interstellar medium (ISM; see Chandrasekhar & Fermi 1953; Cho & Vishniac 2000; Cho et al. 2003; Groves et al. 2003). Numerical simulations by Cho & Vishniac (2000) revealed that α = 0.5 is a manifestation of the equipartition condition, i.e., in steady MHD turbulence the magnetic field energy density and the energy density of the gas are similar. Similar values of α have been found through observations of magnetic field by Zeeman splitting observations in molecular clouds by Crutcher (1999), also by using equipartition magnetic field and molecular gas observations in external galaxies by Niklas & Beck (1997), and in the Milky Way and M31 by Berkhuijsen (1997). Alternatively, the slope of the radio–FIR correlation has been used to find α, where α = 0.4–0.6 (Niklas & Beck 1997; Hoernes et al. 1998; Dumas et al. 2011).

So far, spatially resolved and global study of the correlation has been done primarily using radio emission at 1.4 GHz and higher frequencies. The only low-frequency study done at 150 MHz (Cox et al. 1988) confirms that on global scales the radio–FIR correlation holds good and is similar to what is seen at 1.4 GHz. To our knowledge, no low-frequency (<1.4 GHz, such as 333 MHz) spatially resolved study of the radio–FIR correlation exists in the literature. The motivation to do such a study arises from the fact that at lower frequencies the emission is largely nonthermal, hence better exhibiting the relation between magnetic field and star formation. Second, since the cosmic-ray electrons (CREs) propagate larger distances in the galaxies at lower frequencies, it is important to assess how that affects the form of the radio–FIR correlation.

In this paper, we present a spatially resolved study of the radio–FIR correlation for four normal galaxies, NGC 4736, NGC 5055, NGC 5236, and NGC 6946 at a spatial resolution of ~1–1.5 kpc with radio observations made at 333 MHz (λ=0.90 cm) and 1.4 GHz (λ=0.20 cm). We also estimate the value of α and verify the equipartition assumptions. In Section 2, we discuss the various sources of maps used in this work and also define the parameter “q” which is used to quantify the correlation. In Section 3, we present our results on spatially resolved radio–FIR correlation using far-infrared emission at λ70 μm and radio emission at λ20 cm and λ90 cm. We discuss our results in Section 4.

2. DATA ANALYSIS

The four galaxies in the sample for this study were chosen from Basu et al. (2012). The large angular size of the galaxies ensures enough independent regions to carry out spatially resolved study. Our sample comprises of the galaxies NGC 4736,
NGC 5055, NGC 5236, and NGC 6946. Table 1 summarizes the salient features of our sample and the various sources of obtaining the archival data.

To study the radio–FIR correlation using nonthermal radio emission, a thorough separation of thermal radio emission is needed. We used nonthermal radio continuum maps at 20 cm and 90 cm after separating the thermal free–free component mainly originating from H II regions in recent star formation sites. Details of observation and data analysis are discussed in Basu et al. (2012). The thermal emission was estimated using the technique developed by Tabatabaei et al. (2007b), wherein the dust extinction-corrected Hα emission map. The thermal emission was estimated using the technique developed by Tabatabaei et al. (2007b), wherein the dust extinction-corrected Hα emission. This is then extrapolated to the desired radio frequency and subtracted from the total emission map. The 90 cm maps were obtained using the Giant Meterwave Radio Telescope (GMRT) while the 20 cm cm maps were obtained using archival data from various assorted sources (see Table 1). The nonthermal maps had 40 arcsec resolution with 9 arcsec pixel size. We scaled the flux of each galaxy to a common frequency of 1.4 GHz using the spectral index map obtained from the 333 MHz and near 1 GHz images for each pixel.

The galaxies were observed in the far-infrared by the Spitzer at 70 μm as a part of the Spitzer Infrared Nearby Galaxy Survey (SINGS; Kennicutt et al. 2003) using the Multiband Imaging Photometer for Spitzer (Rieke et al. 2004). The images were obtained from the publicly available database in SINGS Data Release 5.1 These images had a pixel size of 4.5 arcsec and a point-spread function of about 16 arcsec. They were convolved to the resolution of nonthermal radio maps (40 arcsec) and regridded to a common pixel size of 9 arcsec. All the maps were then aligned to the same coordinate system.

For the present study, the flux density per beam for the radio and FIR maps was determined within an area of ~40 arcsec diameter, with the adjacent region being about one beam away to ensure independence. Pixels with brightness above 2σ (σ is the rms noise in the map) were considered for the analysis. We estimate the slope of the radio–FIR and the quantity “q” introduced by Helou et al. (1985).

The parameter q is used as a measure of the radio–FIR correlation, where its dispersion indicates the tightness of the correlation. Conventionally, it is defined as the logarithm of the ratio of total FIR flux between λ40 μm and λ120 μm and the radio flux measured at 1.4 GHz. However, we define q as per Appleton et al. (2004) using FIR flux density at λ70 μm, such that

\[ q_7 = \log_{10}(S_{70\mu m}/S_{\lambda}) \]

where \( \lambda \) is the radio wavelength (here \( \lambda = 20 \) cm or 90 cm) and \( S_{70\mu m} \) and \( S_\lambda \) are the flux densities of \( \lambda 70 \mu m \) and radio wavelength, respectively. The FIR emission from galaxies between λ40 μm and λ120 μm is dominated by the emission from cool dust with dust temperature, \( T_{\text{dust}} \sim 20 \) K (see, e.g., Xu et al. 1992; Hoernes et al. 1998; Tabatabaei et al. 2007b; Basu et al. 2012). The peak of this emission occurs at about λ100 μm. Note that a blackbody at ~20 K peaks at about λ145 μm, but a graybody (\( \lambda^{-\beta}B_\lambda(T) \), where \( \beta = 2 \) is the dust emissivity index and \( B_\lambda(T) \) is the Planck function) has a peak at ~1100 μm. The maps at 70 μm, which are nearest available to λ100 μm, essentially trace this component of the dust. Using monochromatic λ70 μm emission to study the radio–FIR correlation does not affect the conclusions significantly, except for a slight increase in the dispersion (Murphy et al. 2006).

3. RESULTS

The spatially resolved study of the radio–FIR correlation was done by broadly classifying the emission from the arm (including the central region) and interarm regions of these galaxies. The arms were identified from the Hα images for each galaxy. For the ringed galaxy NGC 4736, which has no prominent arms, the star-forming ring was taken as the arm. The arm and the interarm regions used in our analysis are plotted as circles which are overlaid on the 40 arcsec Hα images in Figure 1. The quantity \( q_7 \) was computed within each such region. Note that the calibration uncertainty at λ70 μm could be ~20% (Murphy et al. 2006). This would lead to a systematic error of about 10% in the values of \( q_7 \).

Table 2 gives the total flux density (in Jy) and map rms noise of the 40 arcsec images (in mJy beam\(^{-1}\)) of the galaxies. The galaxy-integrated mean values of \( q_{20\text{cm}} \) are 2.48 ± 0.1, 2.25 ± 0.07, 2.12 ± 0.06, and 2.14 ± 0.07, for the galaxies NGC 4736, NGC 5055, NGC 5236, and NGC 6946, respectively. The \( q_{90\text{cm}} \) are 2.02 ± 0.07, 1.5 ± 0.1, 1.66 ± 0.09, and 1.68 ± 0.08, respectively.

### Table 1

| Name     | Morphological Type | Angular Diameter (arcsec) | Distance (Mpc) | FIR λ70 μm (Jy) | FIR λ90 cm (Jy) | Radio λ20 cm (Jy) |
|----------|--------------------|---------------------------|---------------|----------------|----------------|------------------|
| NGC 4736 | SAB                | 11.2 × 9.1                | 41            | 4.66           | SINGS          | GMRT             |
| NGC 5055 | SABc               | 12.6 × 7.2                | 59            | 9.21           | SINGS          | GMRT             |
| NGC 5236 | SABC               | 11.2 × 11                 | 24            | 4.51           | SINGS          | VLA CD array     |
| NGC 6946 | SABcd              | 11.5 × 9.8                | 33            | 6.83           | SINGS          | VLA C + D array  |

Notes. In Column 3, \( D_{25} \) refers to the optical diameter measured at the 25 mag arcsec\(^{-2}\) contour from de Vaucouleurs et al. (1991). Column 4 gives the inclination angle \( i \) defined such that 0° is face-on. Distances in Column 5 are taken from 1 Karachentsev et al. (2003), 2 Karachentsev et al. (2002), 3 Karachentsev et al. (2000), and the NED. Columns 6 and 7 show the sources of data for the FIR maps and 333 MHz (90 cm) maps, respectively. Column 8 shows the data available at a higher frequency near 1 GHz (λ20 cm):

1. Braun et al. (2007), 2 VLA archival data, 3 VLA archival data using the CD array configuration (project code: AS325), 4 VLA archival map by combining interferometric data from C and D array, Beck (2007).
The value of $q_\lambda$ shows the distribution of $\Delta q_\lambda$, however, this change is significant with changes slightly, by about 9%, between arms and interarms, respectively. However, the spatially resolved estimates of $q_{20\text{ cm}}$ and $q_{90\text{ cm}}$ suggest that their values vary between arm and interarm regions. Figure 2 shows the brightness of the nonthermal radio emission with the far-infrared emission at $\lambda 70\text{ m}$, both in units of Jy beam$^{-1}$, for all the four galaxies. The figure also shows the distribution of $q_\lambda$ for $\lambda 20\text{ cm}$ and $\lambda 90\text{ cm}$. It was seen that the star-forming, gas-rich spiral arms of the galaxies showed higher values for $q_\lambda$, when compared to the adjacent low star-forming interarm regions. Table 3 summarizes the mean value of the quantity $q_\lambda$ and its dispersion for arm and interarm regions.

The mean value in the arms for all the galaxies were found to be $(q_{20\text{ cm}})_{\text{arm}} = 2.32$ with a narrow dispersion of $\sigma_{q_{20\text{ cm}},\text{arm}} = 0.14$, while for the interarms $(q_{20\text{ cm}})_{\text{interarm}} = 2.15$ and $\sigma_{q_{20\text{ cm}},\text{interarm}} = 0.3$. At $\lambda 90\text{ cm}$, we find $(q_{90\text{ cm}})_{\text{arm}} = 1.85$ with $\sigma_{q_{90\text{ cm}},\text{arm}} = 0.22$ and $(q_{90\text{ cm}})_{\text{interarm}} = 1.43$ and $\sigma_{q_{90\text{ cm}},\text{interarm}} = 0.3$. Figure 3 shows the percentage change in the value of $q_\lambda$ between arms and interarms for each of the galaxies, where $\Delta q_\lambda = (q_\lambda)_{\text{arm}} - (q_\lambda)_{\text{interarm}}$. The squares are for $\lambda 20\text{ cm}$ and triangles are for $\lambda 90\text{ cm}$. The mean of the $q_{20\text{ cm}}$ changes slightly, by about 9%, between arms and interarms, however, this change is significant with $>99.9\%$ confidence using Kolmogorov–Smirnov test. At $\lambda 90\text{ cm}$, the change in the value of $(q_\lambda)$ between arm and interarm regions is much pronounced with $\Delta q_\lambda \sim 30\%$.

### 3.1. Fit to the Radio and IR Flux Densities

The data were fitted using the form $S_{\text{radio}} = a \times S_{\text{IR}}^{b}$, where $S_{\text{radio}}$ is the flux density of the radio emission at $\lambda 20\text{ cm}$ and $\lambda 90\text{ cm}$, and $S_{\text{IR}}$ is the flux density of the $\lambda 70\text{ m}$ infrared emission. We define a quantity $q_\lambda = -\log_{10} a$ for $S_{\text{IR}} = 1$, such that the value of $q_\lambda$ corresponds to the intercept of the straight line fit of $\log_{10} S_{\lambda} = -q_\lambda + b \times \log_{10} S_{\text{IR}}$. The slope of the radio–infrared correlation is given by the parameter “$b$.” Separate fits were done for arm and interarm regions using ordinary least-square “bisector method” (Isobe et al. 1990) in the log–log plane. The parameters obtained are summarized in Table 2 in the last four columns for $\lambda 20\text{ cm}$ and $\lambda 90\text{ cm}$. The fitted values of $q_{90\text{ cm}}$ and $q_{20\text{ cm}}$ are in good agreement with $(q_\lambda)$. The fitted parameters are plotted in Figure 2. The black lines are for fits at $\lambda 90\text{ cm}$ and the gray lines are at $\lambda 20\text{ cm}$. The solid lines are fit to the arm regions only and the dashed lines are for the interarms. All the correlations are highly significant.

### Table 2

Integrated Flux Densities of the Galaxies at $\lambda 90\text{ cm}$ (333 MHz; Basu et al. 2012), $\lambda 20\text{ cm}$ (1400 MHz; Spectral Index Scaled from Data Given in Column 8 of Table 1), and $\lambda 70\text{ m}$ (Taken from the NED)

| Name       | $S_{20\text{ cm}}$ (Jy) | $\sigma_{20\text{ cm}}$ (mJy beam$^{-1}$) | $S_{90\text{ cm}}$ (Jy) | $\sigma_{90\text{ cm}}$ (mJy beam$^{-1}$) | $S_{70\text{ m}}$ (Jy) | $\sigma_{70\text{ m}}$ (mJy beam$^{-1}$) |
|------------|-------------------------|------------------------------------------|-------------------------|------------------------------------------|-------------------------|------------------------------------------|
| NGC 4736   | 0.9 ± 0.06              | 2                                        | 0.31 ± 0.03             | 0.35                                     | 93.93 ± 7.34            | 15                                       |
| NGC 5055   | 2.3 ± 0.13              | 3                                        | 0.41 ± 0.05             | 0.4                                      | 72.57 ± 5.16            | 15                                       |
| NGC 5236   | 6.86 ± 0.62             | 2.5                                      | 2.36 ± 0.18             | 0.3                                      | 312.0 ± 15.6            | 30                                       |
| NGC 6946   | 4.3 ± 0.24              | 1                                        | 1.5 ± 0.1               | 0.2                                      | 207.2 ± 16.1            | 25                                       |

**Note.** The map noise ($\sigma$) for the 40 arcsec resolution images is also given.
Figure 2. Radio intensity vs. $\lambda$ 70 $\mu$m FIR intensity (in Jy beam$^{-1}$). The triangles are for $\lambda$ 90 cm and squares are for $\lambda$ 20 cm. The filled symbols are for arms and unfilled symbols are for interarms. The histograms are the distribution of $q_{90 \, \mathrm{cm}}$ and $q_{20 \, \mathrm{cm}}$, where arms are shown with filled gray and interarms with unfilled histograms. The lines are the fit to the data of the form $S_{\text{radio}} = a \times S_{70 \, \mu m}$ (see Table 3). The solid and dashed lines are fit to the arm and interarm regions. Black lines are for $\lambda$ 90 cm, while gray lines are for $\lambda$ 20 cm.

in our case with Pearson’s correlation coefficient, $r > 0.8$ (and $r > 0.9$ in most of the cases), except for interarm regions of NGC 4736 at $\lambda$ 90 cm, where $r = 0.68$.

The slope of the $\lambda$ 20 cm and $\lambda$ 70 $\mu$m flux density for the arm regions for all the galaxies lies between $\sim$0.65 and 0.9. However, for the interarm regions the slope is slightly shallower, lying in the range 0.55–1. The mean value of the parameters for arm and interarm after the fit can be written as

$$\log_{10} S_{20 \, \mathrm{cm}} = -(2.24 \pm 0.05) + (0.8 \pm 0.08) \log_{10} S_{70 \, \mu m}$$

for the arm, \hspace{1cm} (1)

$$\log_{10} S_{20 \, \mathrm{cm}} = -(2.17 \pm 0.05) + (0.76 \pm 0.14) \log_{10} S_{70 \, \mu m}$$

for the interarm. \hspace{1cm} (2)

The fitted value of $q_{20 \, \mathrm{cm}}$ and the slope differs slightly from arms to interarms.

At $\lambda$ 90 cm, we find that the slope lies in the range $\sim$0.45–0.7 for the arms, whereas in the interarm region the slope lies in the range $\sim$0.3–0.4. The slopes are much flatter than at $\lambda$ 20 cm. The mean values of the fitted parameters are found to be

$$\log_{10} S_{90 \, \mathrm{cm}} = -(1.64 \pm 0.05) + (0.6 \pm 0.1) \log_{10} S_{70 \, \mu m}$$

for the arm \hspace{1cm} (3)

$$\log_{10} S_{90 \, \mathrm{cm}} = -(1.53 \pm 0.04) + (0.33 \pm 0.07) \log_{10} S_{70 \, \mu m}$$

for the interarm. \hspace{1cm} (4)

There is a significant change in the value of $q_{90 \, \mathrm{cm}}$ and the slope between the arm and the interarm regions.
regions, $\alpha_{\text{nt}}$ and $q_2$, have a wide distribution with more than 50% dispersion. The values of “$q_2$” also systematically decrease as one moves from arms to interarms, indicating $\tau_{\text{esc}} \gg \tau_{\text{syn}}$ and thus the CRe loose energy before escaping the disk giving rise to steeper $\alpha_{\text{nt}}$. Similar results were found for IC 342 and NGC 5194 (Murgia et al. 2005; Paladino et al. 2006).

### 4. DISCUSSION

We have studied the radio–FIR correlation at $\sim$1 kpc scales for four normal galaxies using nonthermal radio maps at $\lambda$20 cm and $\lambda$20 cm and the far-infrared maps at $\lambda$70 $\mu$m. From the basic synchrotron theory (e.g., Moffet 1975) and considering the radio emission from CRe emitting at critical frequencies, the energy of CRe at $\lambda$90 cm is $\sim$1.5 GeV and at $\lambda$20 cm is $\sim$3 GeV when they are gyrating in a typical magnetic field of $\sim$10 $\mu$G. The far-infrared emission at $\lambda$70 $\mu$m originates from cool dust at $\sim$20 K heated by the interstellar radiation field due to $\sim$5–20 $M_\odot$ stars (Devereux & Eales 1989; Xu 1990; Xu & Helou 1996; Dumas et al. 2011). We separately examine these correlations for the arm and the interarm regions, that is, regions of high and low thermal fractions, respectively. The results of the various parameters as discussed in Section 3 are given in Table 3 for individual galaxies, and here we discuss the average properties. The dispersion on the parameter $q_2$ is a measure of the tightness of the radio–FIR correlation, which for the arm region is found to be less than 10% around ($q_2$) for both $\lambda$20 cm and $\lambda$90 cm. For the interarm region the dispersion is seen to increase to around 20% for both the frequencies. Further, we find that the slope of the radio–FIR correlation for the arm regions (also the high thermal fraction regions) remains similar at both the radio frequencies (see Table 3). It should be noted that a large number of global scale radio–FIR correlation studies exist, where the observed slope is steeper and closer to unity (see, e.g., Price & Duric 1992; Yun et al. 2001 and the references therein). However, the spatially resolved studies relating FIR cool dust emission to $\lambda$20 cm radio emission yield a value of the slope $\sim$0.6–0.9 for LMC (Hughes et al. 2006) and 0.80 $\pm$ 0.09 for M31 (Hoernes et al. 1998). It is difficult to compare the slopes obtained in global studies with the spatially resolved case. The flux in global studies is averaged over both arm and interarm regions and we are uncertain about the contribution from each component. Multifrequency spatially resolved studies can provide an understanding of the relation between global scale and spatially resolved studies. For the
Figure 4. Distribution of $\alpha_{\text{nt}}$ with $q_{20\,\text{cm}}$ (left) and $q_{90\,\text{cm}}$ (right). The top panel shows the distribution of $\alpha_{\text{nt}}$ estimated from $\lambda\,90\,\text{cm}$ and $\lambda\,20\,\text{cm}$ nonthermal emission radio maps within an area of $40 \times 40 \, \text{arcsec}^2$ and a step size of 0.05, while the right side horizontal panel shows the distribution of $q_{\lambda}$ within the same area and bin size of 0.05. The filled circles and histograms are for the arms and unfilled circles and histograms are for interarm regions for all the four galaxies combined.

present case, in the interarm regions (regions of low thermal fraction) for $\lambda\,20\,\text{cm}$ the slope is slightly flatter as compared to the arms (see Equations (1) and (2)). However, at $\lambda\,290\,\text{cm}$, the slopes become distinctly flatter than the arm regions (see Figure 2 and Equations (3) and (4)).

Our results can be used to determine the coupling between magnetic field ($B$) and the gas density ($\rho_{\text{gas}}$) as discussed in the Introduction and thereby validating the “equipartition” assumptions in these galaxies at 1 kpc scales. Dumas et al. (2011) showed that the slope of the radio–FIR correlation relates to $\kappa$ as

$$\kappa = \begin{cases} \frac{nb}{3 - \alpha_{\text{nt}}}, & \text{optically thick dust} \\ \frac{(n+1)b}{3 - \alpha_{\text{nt}}}, & \text{optically thin dust} \end{cases}$$

where $n = 1.4 \pm 0.15$ is the Kennicutt–Schmidt law index (see, e.g., Kennicutt 1998), $b$ is the slope of the radio–FIR correlation, and $\alpha_{\text{nt}}$ is the nonthermal spectral index. For these face-on galaxies we use the assumption of optically thin dust to UV photons to estimate $\kappa$. We find that $\kappa = 0.51 \pm 0.1$ at $\lambda\,20\,\text{cm}$ and $\kappa = 0.4 \pm 0.1$ at $\lambda\,90\,\text{cm}$ in the arms. Similarly, for interarm regions due to a large range of $\alpha_{\text{nt}}$, we find $\kappa$ in the range 0.41–0.5 at $\lambda\,20\,\text{cm}$ and between 0.18 and 0.22 at $\lambda\,90\,\text{cm}$. Our estimated values of $\kappa$, using the correlation between $\lambda\,20\,\text{cm}$ and $\lambda\,70\,\mu\text{m}$, are consistent with the predictions of numerical MHD simulations of different ISM turbulence models, where $\kappa \approx 0.4–0.6$ (see, e.g., Fiedler & Mouschovias 1993; Kim et al. 2001; Thompson et al. 2006; Groves et al. 2003).

In the arm regions, the slope and thus $\kappa$ remain similar for both $\lambda\,20\,\text{cm}$ and $\lambda\,90\,\text{cm}$. Note that the above prescription to determine $\kappa$ is valid provided that the radio and the FIR emission arises from the same emitting volume, with a diameter of about 1 kpc for most of the observations reported here. In the arm regions, the UV photon has a mean free path of $\sim 100 \, \text{pc}$ within which most of the FIR emission arises. On the other hand, the CRe which gives rise to the radio emission diffuse farther away to $\sim 1 \, \text{kpc}$ at 1400 MHz and $\sim 2 \, \text{kpc}$ at 333 MHz in a galactic magnetic field of $\sim 10 \, \mu\text{G}$. Hence, in order to have a similar slope with frequency, the energy spectrum of the CRe giving rise to the radio emission should be independent of the volume element. This can only happen if the timescale for CRe diffusion/propagation ($\tau_{\text{diff}}$) is significantly larger than their generation timescale ($\tau_{\text{gen}}$). It turns out that the $\tau_{\text{diff}}$ is about $8 \times 10^7 \, \text{yr}$ at $333 \, \text{MHz}$ and $4 \times 10^7 \, \text{yr}$ at $1400 \, \text{MHz}$ which is significantly larger than the $\tau_{\text{gen}}$ as evident from the supernova rates, which is one every $10^4–10^5 \, \text{yr kpc}^{-2}$ in Milky Way. We assume the same rate for these galaxies.

The slope of the radio–FIR correlation in the interarm (low thermal fraction) region is similar to that of the arm at $\lambda\,20\,\text{cm}$; however, it becomes distinctly flatter at $\lambda\,90\,\text{cm}$. The flattening primarily happens due to relative increase in radio flux at $\lambda\,90\,\text{cm}$ as compared to $\lambda\,20\,\text{cm}$, which has the effect that $\alpha_{\text{nt}}$ gradually becomes steeper in the interarms. This relative increase in $\lambda\,90\,\text{cm}$ flux can be explained by continuous generation of CRe in the arm, which subsequently propagates into the interarm (e.g., from A to B or from farther regions in arms like C to B in Figure 5). The propagation timescale for these CRe are few times $10^7 \, \text{yr}$ assuming Alfvén velocity of $100 \, \text{km s}^{-1}$ and typical arm to interarm distance of 1–2 kpc.

In such a scenario, using Equation (6) of Kardasev (1962), in a typical galactic magnetic field of $\sim 10 \, \mu\text{G}$, there would be a break in the energy spectrum for electrons above $\sim 2 \, \text{GeV}$. This break frequency lies below $\lambda\,90 \, \text{cm}$ or above $333 \, \text{MHz}$. Such breaks have been seen at $\sim 900 \, \text{MHz}$ and $\sim 1 \, \text{GHz}$ for similar normal galaxies, NGC 3627 and NGC 7331, respectively (Paladino et al. 2009). Thus, the CRe emitting at $\lambda\,90\,\text{cm}$, which lie above the break, do not lose a significant amount of energy as compared to their higher energy counterparts. Hence, this results in increasing the relative flux at $\lambda\,90\,\text{cm}$.

For the slope to remain similar between arms and interarm regions at $\lambda\,20\,\text{cm}$ (below the break), the ratio of the radio to FIR flux densities should remain similar. Observed radio flux between arm and interarm changes by a factor of $\sim 2–2.5$. A similar ratio of flux density between arm and interarm regions at $\lambda\,20\,\text{cm}$ can be caused due to steeping of the spectral index
implies that the FIR flux should change by a factor of \(\sim 2.5\) to \(\sim 2.3\) between arm and interarm regions for radio–FIR slope of 0.8. The FIR flux density \((F_\nu)\) depends on the dust temperature \((T_{\text{dust}})\) and its density \((\rho_{\text{dust}})\) as \(F_\nu \propto \rho_{\text{dust}} Q_{\text{abs}}(a, \lambda) B_\nu(T_{\text{dust}})\), where \(Q_{\text{abs}}(a, \lambda)\) is the FIR wavelength \((\lambda)\) dependent absorption coefficient for gain radius, \(a\) (Draine & Lee 1984; Alton et al. 2004). The temperature does not change significantly between arm and interarm for these galaxies (Basu et al. 2012). For a constant gas-to-dust ratio, i.e., \(\rho_{\text{dust}} \propto \rho_{\text{gas}}\), a factor of 2–4 drop in average gas density between arm and interarm regions (found using the \(CO_{12-1}\) maps from Heracles; Leroy et al. 2009) would therefore cause the factor of 2–3 drop in FIR emission.

The slope of 0.8 \(\pm 0.1\) of the radio–FIR correlation indicates that the energy equipartition assumption between cosmic-ray particles and magnetic field may be valid in the gas-rich arms of the galaxies at our spatial resolution of \(\sim 1\) kpc. For the interarm regions at \(\lambda 20\) cm, the slope is similar to what is seen in arms, and thereby satisfying the equipartition conditions. The flattening of the slope at \(\lambda 90\) cm does not indicate any breakdown of equipartition condition, but results due to overlapping emissions from adjacent regions.

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