Magnetic fields in nearby normal galaxies: Energy equipartition

Aritra Basu, Subhashis Roy

1National Center for Radio Astrophysics, TIFR, Pune University Campus, Ganeshkhind Road, Pune - 411007.

1 INTRODUCTION

Magnetic field strength plays an important role in determining the dynamics and energetics in a galaxy. It is believed that the magnetic pressure plays a role in determining the scale height of the galactic interstellar medium (ISM). Also, the magnetic field plays an important role in collapse of a gas cloud to help the star formation activity (Elmegreen 1981; Crutcher 1999). The density and distribution of cosmic rays depend on magnetic fields.

It is thought that the seed field, before formation of galaxies, was amplified by compression during collapse and shearing by a differentially rotating disk (Beck 2006). Dynamo action within the galaxy amplifies and maintains field strength over galactic life-times of $\sim 10^9$ year (see e.g., Moffatt 1978; Parker 1979; Moss & Shukurov 1996; Shukurov et al. 2006). Though the dynamo effect can amplify the large scale mean magnetic field, magnetohydrodynamic (MHD) turbulence can amplify the local magnetic field through field line stretching (Batchelor 1950; Groves et al. 2003) up to energy equipartition levels. In steady state, the energy density of magnetic field is close to energy density of gas. Gas density is known to fall as a function of galactocentric distance (see e.g., Leroy et al. 2008). Therefore, it is expected that the field strength will fall as a function of galactocentric distance.

Observationally, the magnetic field ($B$) can be traced by polarization studies at various wavebands, e.g., Faraday rotation and synchrotron radiation polarization in radio, polarization of starlight in optical and polarized dust emission in infrared. Zeeman splitting of spectral lines can be used to estimate the local magnetic field. Intensity of the synchrotron emission at radio wavelengths can provide estimates of $B$ though assumptions of ‘equipartition’ of energy between cosmic ray particles and magnetic field.

Faraday rotation can probe the line-of-sight averaged magnetic field ($B_\parallel$). However, this method uses polarized radio emission that may not be seen from a large fraction of a galaxy due to Faraday and/or beam depolarization (Sokoloff et al. 1998). Zeeman splitting can directly measure $B_\parallel$, but it is highly susceptible to high localized magnetic field. Moreover, its detection is difficult in external galaxies. Estimation of $B$ in the sky-plane using polarization of starlight or dust emission depends highly on several geometrical and physical parameters (Zweibel & Heiles 1997). Synchrotron emission is seen from large fraction of a galaxy and under the condition of ‘equipartition’, it provides a measure of total magnetic field. At low frequencies (0.33 GHz), more than 95 percent of the emission is synchrotron in origin (Basu et al. 2012a) therefore low radio frequency total intensity images can be used to determine $B$ in galaxies.

This method has been used to determine $B$ in some of the nearby star forming galaxies. In M51, Fletcher et al. (2011) found generally stronger fields of $\sim 20 - 25 \mu G$ in the spiral arms and $\sim 15 - 20 \mu G$ in the interarm regions. In this case, $B$ was deter-
mined using total intensity map at λ6 cm assuming a constant spectral index for thermal and synchrotron emission. This might introduce errors in the results as the nonthermal spectral index steepens from center to edge (Basu et al. 2012). In NGC 253, the field was found to be ~ 2 µG towards the center and fell to ~ 8 µG towards the edge (Heesen et al. 2009). In M82, the total field was found to be ~ 80 µG in the center and ~ 20 – 30 µG in the synchrotron emitting halo (Adebahr et al. 2012). However, these galaxies are known starbursts, the magnetic field in the disk could be significantly affected by mixing of magnetic field from other parts of the galaxy through galactic fountain (Shapiro & Field 1976; Bregman 1983; Norman & Ikeuchi 1984; Heald 2012).

To measure magnetic field and to compare its energy density with that in gas at high spatial resolution of ≤ 1 kpc we have observed five nearly face-on normal galaxies, namely, NGC 1097, NGC 4736, NGC 5055, NGC 5236 (M83) and NGC 6946. In Section 2, magnetic field strengths in these galaxies are determined using total intensity synchrotron emission at 0.33 GHz. In Section 3, we present the magnetic field maps and results. We discuss our results and compare the magnetic field energy with kinetic energies in turbulent gas in various phases of the ISM. Our results are summarized in Section 5.

### 2 DATA ANALYSIS

The galaxies studied here were chosen from (Basu et al. 2012) where a thorough separation of thermal emission from the total emission was done at 0.33 GHz (λ90 cm) and near 1.4 GHz (λ20 cm) using Hα as the tracer after correcting for dust absorption (Tabatabaei et al. 2007). Our sample comprises of NGC 1097, NGC 4736, NGC 5055, NGC 5236 and NGC 6946. The nonthermal spectral index (n) used to compute the equipartition magnetic field, was estimated between the above mentioned frequencies. The data sources for the sample galaxies are listed in Table 1. The 0.33 GHz observations were made using the Giant Metrewave Radio Telescope (GMRT). We broadly classified our studies between arm and interarm regions, i.e., regions of high and low gas density, identified from the Hα images for each galaxy.

Due to poorer resolution of the far infrared maps used for determining absorption correction of the Hα emission, the overall resolution of the nonthermal emission maps was only 40 arcsec. To improve the resolution of nonthermal emission we used λ24-µm emission from dust as a tracer of thermal emission (Murphy et al. 2008). The Spitzer MIPS λ24-µm maps have a resolution of 6 arcsec, better than the resolution of the radio maps. The resolution of the nonthermal maps are determined by the lowest resolution radio maps and subsequently the λ24-µm maps were convolved to it. However, λ24-µm emission from dust is not a direct tracer of thermal emission, and in certain cases show differences with measurements made from using a direct tracer like Hα (Pérez-González et al. 2006; Calzetti et al. 2005). Moreover, the λ24-µm emission arises not only from dust grains heated by ultra violet (UV) photons, but also from heating of diffuse cirrus clouds by the interstellar radiation field and also from old stars, mostly from the central regions. This could lead to overestimation of thermal emission in such regions. To avoid this shortcoming, and to ensure that both the methods give identical results at the resolution of the absorption corrected Hα emission, we corrected the thermal fraction determined from λ24-µm to the thermal fraction from Hα in the method described below. All the maps were brought to the same pixel size (3 arcsec) and aligned to a common coordinate system. All the pixels with signal-to-noise ratio more than 4 were considered for this analysis.

In step (i), the convolved λ24-µm emission was used to estimate the thermal emission using Equation 10 in Murphy et al.

#### Table 1. The sample galaxies.

| Name     | Type  | Angular size (D_{25}) (°) | i (°) | Distance (Mpc) | CO | Hi | FIR | Hα | Radio |
|----------|-------|--------------------------|-------|----------------|----|----|-----|----|-------|
| NGC 1097 | SBbc  | 9.3 × 6.3                | 45    | 14.5†          |    |    |     |    |       |
| NGC 4736 | SAb   | 11.2 × 9.1               | 41    | 4.66†          |    |    |     |    |       |
| NGC 5055 | SAbc  | 12.6 × 7.2               | 59    | 9.2†           |    |    |     |    |       |
| NGC 5236 | SABc  | 11.2 × 11                | 24    | 4.51           |    |    |     |    |       |
| NGC 6946 | SABcd | 11.5 × 9.8               | 33    | 6.8            |    |    |     |    |       |

In column 3 D_{25} refers to the optical diameter measured at the 25 magnitude arcsec^{-2} contour from de Vaucouleurs et al. (1991). Column 4 gives the inclination angle (i) defined such that 90° is face-on. Distances in column 5 are taken from: a Karachentsev et al. (2003), b Karachentsev et al. (2002), c Karachentsev, Sharina & Huchtmeier (2000) and the NED. Columns 6 and 7 lists the data used to trace the molecular and atomic gas respectively which were used to estimate the gas density. Column 9 lists the sources of Hα maps used to estimate the energy density of ionized gas in Section 4.2. Column 10 lists the sources of archival data at λ20 cm waveband. 4 VLA archival data using CD array configuration (project code: AS325), 5 VLA archival data using CD array configuration (project code: AW237), 6 VLA archival data using CD array (project code: AS325), 7 VLA archival map by combining data from C and D array (Beck 2007).

### Table 2. The resolution of available radio maps in units of arcsec

| Name     | λ90 cm | λ20 cm | nonthermal maps | linear scale (kpc) |
|----------|--------|--------|-----------------|-------------------|
| NGC 1097 | 16×11  | 40×30  | 40×40           | 2.80              |
| NGC 4736 | 13×12  | 19×125 | 20×20           | 0.45              |
| NGC 5055 | 17×10  | 18.5×12.5 | 20×20          | 0.90              |
| NGC 5236 | 16×12  | 26×14  | 26×14           | 0.55              |
| NGC 6946 | 12×11  | 15×15  | 15×15           | 0.50              |

1 Thermal fraction is defined as: \( f_{th} = S_{\nu,th}/S_{\nu,tot} \), where, \( S_{\nu,tot} \) and \( S_{\nu,th} \) are the flux densities of the total and thermal radio emission respectively at a radio frequency \( \nu \)
Figure 1. Top: histogram of the correction factor ($f_{\text{th}, \text{H}o}/f_{\text{th}, \lambda 24\mu m}$) after normalizing with median values of the ratio for each galaxy; bottom: distribution of $f_{\text{th}, \text{H}o}/f_{\text{th}, \lambda 24\mu m}$ for all the galaxies at 1.4 GHz determined within 40 arcsec regions. The grey and unfilled histograms are for arm and interarm regions.

Table 3. Mean values of the thermal fractions at $\lambda 20$ cm determined using H$\alpha$ method (column 2) and $\lambda 24\mu m$ method (column 3).

| Name        | $f_{\text{th}, \text{H}o}$ (%) | $f_{\text{th}, \lambda 24\mu m}$ (%) | $f_{\text{th}, \text{H}o}/f_{\text{th}, \lambda 24\mu m}$ |
|-------------|---------------------------------|-------------------------------------|--------------------------------------------------------|
| NGC 1097    | 5±3                             | 7±2                                 | 0.75±0.3                                               |
| NGC 4736    | 7±2                             | 10±2                                | 0.67±0.2                                               |
| NGC 5055    | 10±3                            | 11±2                                | 0.87±0.3                                               |
| NGC 5236    | 7±2                             | 8.5±3                               | 0.73±0.3                                               |
| NGC 6946    | 10±3                            | 8.5±2                               | 1.18±0.4                                               |

 Equipartition magnetic field

From basic synchrotron theory, and assuming energy equipartition between cosmic ray particles and the magnetic field, the total field strength could be estimated (e.g., Pacholczyk 1970, Miley 1980, Longair 2011). However, the limits of integration ($v_{\text{min}}$ to $v_{\text{max}}$) over the synchrotron spectrum to estimate the total energy in cosmic ray electrons (CRe) depends on the magnetic field (Beck & Krause 2005). This was ignored while minimizing the total energy in magnetic field and cosmic ray particles to derive the ‘classical’ equipartition formula (Equation 2 of Miley 1980). This gives rise to overestimation of the field in regions of steep nonthermal spectral index ($\gamma_{\text{nt}} > 0.7$, defined as $S_{\nu} \propto \nu^{-\gamma_{\text{nt}}}$).

2.1 Total magnetic field

We used the ‘revised’ equipartition formula given in Equation 3 of Beck & Krause (2005) to produce total magnetic field maps, where the equipartition field strength ($B_{\text{eq}}$) is given as,

$$B_{\text{eq}} = \left\{ 4\pi(K_0 + 1)E_{p}^{1-\gamma_{\text{tot}}} \frac{1}{c^2} \right\}^{1/(\gamma_{\text{nt}}+3)}.$$

(1)
Figure 2. The total equipartition magnetic field maps (in $\mu$G) for the galaxies NGC 1097, NGC 4736, NGC 5055, NGC 5236 and NGC 6946. The maps have angular resolution of $40 \times 40$ arcsec$^2$, $20 \times 20$ arcsec$^2$, $20 \times 20$ arcsec$^2$, $26 \times 14$ arcsec$^2$ and $15 \times 15$ arcsec$^2$ respectively (shown in the bottom left corner). The errors in the central (red) regions was found to be $\sim 2\%$, in the disk (green regions) $\sim 5 - 10\%$ and in the outer parts (blue regions) $\sim 15 - 20\%$. Overlaid are the 0.33 GHz contours from Basu et al. (2012a).
Here, $E_p$ is the rest mass energy of protons, $I_\nu$ is the nonthermal intensity at frequency $\nu$, $l$ is the path-length through the synchrotron emitting region, $k_0$ is the ratio of number density of relativistic protons and electrons, $c_1(i)$ is a constant depending on the inclination angle of the magnetic field. $f(\alpha_{nt})$ is a function of $\alpha_{nt}$ such that, $f(\alpha_{nt}) = (2\alpha_{nt} + 1)/[2(2\alpha_{nt} - 1)c_2(\alpha_{nt})^2 + 1]$, and $c_1$, $c_2$ are constants defined in Appendix of Beck & Krause (2005).

We assume $K_0$, the ratio of number densities of relativistic protons ($n_{CBp}$) and electrons ($n_{CBe}$), such that $K_0 = n_{CBp}/n_{CBe} \approx 100$. The path-length travelled through the source ($l$) is taken to be 2 kpc and corrected for the inclination. This could in principle be a function of galactocentric distance ($r$, i.e., $l \equiv l(r)$) depending on the shape of synchrotron emitting halo perpendicular to plane of galaxy disk. The scale height of the synchrotron emitting halo depends on the synchrotron lifetime ($\tau_{\text{syn}}$), and is expected to be uniform along the extent of the disk except perhaps near the central parts of the galaxies ($\sim 1$ kpc) or in high density regions. Also, $B(r) \propto l(r)^{-1/(\alpha_{nt}+5)}$ (see Eq. 1) shows weak dependence of magnetic field on $l(r)$. Therefore, we assume that the path-length through the source to be constant ($l \equiv l(r) = l_0 \approx 2$ kpc). The magnetic field thus estimated by us can be scaled by $[2 \times 10^{-2}(K_0 + 1)/l_0]^{-1/(\alpha_{nt}+5)}$ due to the assumption of $K_0 = 100$ and $l_0 = 2$ kpc.

The ‘revised’ equipartition formula in Eq. 1 diverges for $\alpha_{nt} \leq 0.5$. Thus for regions where $\alpha_{nt}$ was found to be less than 0.55, mostly in the center and inner arms of NGC 5236 and some parts in the ring of NGC 4736, we used a spectral index of 0.55 to avoid sudden rise in the total field strength. Such regions have high gas densities and perhaps dominated by ionization or bremsstrahlung losses giving rise to flatter $\alpha_{nt}$ (see Longair 2011). As a result, the magnetic field strength is overestimated in such regions (Lacki & Beck 2013). The regions of steep spectral index ($\alpha_{nt} > 1$) towards the outer parts of the galaxies arises due to dominant energy losses of CRe. Thus the energy spectral index between CRe and cosmic ray protons changes, which is assumed to be constant and the same between protons and electron in the equipartition formula. We have therefore set $\alpha_{nt}$ as 1 for such regions. This gives $\sim 6$–10 percent lower field strength as compared to steeper $\alpha_{nt}$.

### Table 4. Mean equipartition magnetic fields.

| Name      | $\langle B_{eq}\rangle$ | $\langle B_{eq}\rangle_{\text{arm}}$ | $\langle B_{eq}\rangle_{\text{interarm}}$ |
|-----------|------------------------|-------------------------------|-------------------------------------|
|           | ($\mu$G)              | ($\mu$G)                      | ($\mu$G)                           |
| NGC 1097  | 9.0±2.0               | 9.6±2.2                       | 8.9±2.3                            |
| NGC 4736  | 9.3±2.1               | 16.6±2.4                      | 9.5±0.7                            |
| NGC 5055  | 9.5±1.1               | 10.2±0.6                      | 9.9±0.6                            |
| NGC 5236  | 12.2±2.5              | 14.6±3.0                      | 12.0±2.4                           |
| NGC 6946  | 10.7±1.8              | 12.3±1.8                      | 11.2±1.2                           |

Note: The mean magnetic field strength for the galaxies were computed including the low surface brightness diffuse emission and is therefore less than the mean values in arm and interarm regions.

### 3 RESULTS

The estimated ‘equipartition’ magnetic field strength for the five galaxies, using Eq. 1, are shown in Figure 2 and is shown in the lower left corner of each image. Overlaid are the 0.33 GHz integrated mean values of magnetic field, $\langle B_{eq}\rangle$, are found to be $9.0 \pm 2.0$ $\mu$G, $9.3 \pm 2.1$ $\mu$G, $9.5 \pm 1.1$ $\mu$G, $12.2 \pm 3.0$ $\mu$G and $10.7 \pm 1.8$ $\mu$G for NGC 1097, NGC 4736, NGC 5055, NGC 5236 and NGC 6946 respectively (see Table 4).

Figure 3 shows $B_{eq}$ as a function of galactocentric distance ($r$) estimated by azimuthal averaging over annuli of one beam width. The field strength are found to be strongest near the central regions with $\langle B_{eq}\rangle \sim 20 - 25$ $\mu$G. In the disk, $\langle B_{eq}\rangle$ falls to $\sim 15$ $\mu$G.
and $\sim 10 \mu G$ in the outer parts of the galaxy. That is, in most of the cases it is seen that the magnetic field fall by $\sim$40-50% from the center to the edge, similar to what is seen for the Milky Way (Beck et al. 1996).

The errors in the magnetic field strength was estimated using Monte-Carlo method, wherein $\sim 10^3$ random flux density samples were generated assuming Gaussian distribution of error in source flux densities at each frequency. These were used to determine the distribution of $B_{eq}$. For high signal-to-noise regions ($\geq 10\sigma$, i.e. towards the inner parts of the galaxies) the distribution of $B_{eq}$ can be modelled as Gaussian. However, for regions with lower signal-to-noise ($\leq 5\sigma$, i.e. in the outer parts of the galaxies) the distribution has a tail. The error in the total field strength was found to be $\sim 2\%$ towards the central regions (corresponding to red regions in Figure 2), $\sim 5 - 10\%$ in the disk (green regions in Figure 2) and $\sim 15 - 20\%$ in the outer parts (blue regions in Figure 2).

We compared the magnetic field determined using the revised and the classical formula. In the central regions and inner disk where the $\alpha_{nt}$ lies in the range 0.6 to 1, the fields match within $\sim 10\%$. However, in the outer parts of these galaxies where $\alpha_{nt}$ is steeper ($> 1.2$), the classical equipartition values are overestimated by $> 20\%$ and increases with steepening of the spectral index to up to 50–60\% towards the edge. Such a deviation between magnetic fields estimated by the two methods was shown in Beck & Krause (2005). Thus, the magnetic field determined using the classical formula is found to be constant or increasing as a function of galactocentric distance.

### 3.1 Comparison with existing studies

NGC 1097 was studied in polarization at high resolution that revealed magnetic field in the bar to be modelled as Gaussian. However, for regions with lower signal-to-noise ($\geq 10\sigma$, i.e. towards the inner parts of the galaxies) the distribution of $B_{eq}$ can be modelled as Gaussian. However, for regions with lower signal-to-noise ($\leq 5\sigma$, i.e. in the outer parts of the galaxies) the distribution has a tail. The error in the total field strength was found to be $\sim 2\%$ towards the central regions (corresponding to red regions in Figure 2), $\sim 5 - 10\%$ in the disk (green regions in Figure 2) and $\sim 15 - 20\%$ in the outer parts (blue regions in Figure 2).

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NGC 5236 (M83) is a starburst galaxy with uniform magnetic field seen in the outer parts of the galaxy and lower degree of uniformity towards the inner regions hosting star formation (Sukumar & Allen 1989; Neininger et al. 1991, 1993). Towards the center and inner spiral arms which harbors the starburst (Calzetti et al. 1999), the c$\alpha_{nt}$ was found to be flatter and lies in the range 0.4–0.55. For those regions we have assumed the value of $\alpha_{nt}$ as 0.55 to avoid any sudden discontinuities. The magnetic field strengths are overestimated in such regions. We found a mean total field strength of 24 $\mu G$ in the central 1 kpc regions. The magnetic field is found to be strong in the arms with strength $\sim$15–20 $\mu G$ and falls to $\sim 10 $ $\mu G$ in the interarms and towards the edge. The mean total field in the galaxy is found to be 12.2±2.5 $\mu G$, close to what was estimated by Neininger et al. (1991) within measurement errors.

Magnetic field in NGC 6946 was studied in detail by Beck (2007). The total magnetic field strength was found to be $\sim 20 \mu G$ in the spiral gas arms, close to what is estimated by us. In the arms turbulent fields dominate, while in the interarms large scale regular field was seen with high degree of polarization (30–60%) referred as the “magnetic arms” by Beck (2007). From our maps (see Fig.2), in the northern (roughly centered at RA $= 20^\circ 34''\text{m} 52'', \text{DEC} = +60^\circ 11' 59'' J2000$) and southern (roughly centered at RA $= 20^\circ 34''\text{m} 33'', \text{DEC} = +60^\circ 06' 46.75'' J2000$) magnetic arms, the average field is found to be $\sim 11 \mu G$, which is just 10–15\% stronger than other interarm regions, and this result is at $\geq 3\sigma$ significance. The “circular hole” of $\sim 1$ kpc diameter seen in the galaxy with low radio emission at RA $= 20^\circ 34''\text{m} 20'', \text{DEC} = +60^\circ 09' 40'' J2000$ is seen to have low magnetic field ($\sim 8.5 \mu G$) as compared to other parts and is $\sim 30\%$ lower than the surrounding regions.

### 3.2 Magnetic fields in arms and interarms

We studied the variation of magnetic field along arm and interarm regions for the galaxies NGC 1097, NGC 5055, NGC 5236 and NGC 6946 after correcting for the radial variations. This was not possible for the ringed galaxy NGC 4736, which do not have any prominent arm. Arms and interarm regions were chosen using the Spitzer $\lambda 24 \mu m$ images after smoothing to the resolution of non-thermal maps. For each of the galaxies, the beginning of arm or interarm were chosen leaving the central $\sim 1$ kpc region. We determined magnetic field within an area of one synthesized beam ensuring no overlap between adjacent beams. Each beam corresponds to $\sim 0.4$ to 2 kpc at the distance of the galaxies (see Table 2). The galaxy NGC 5055, where the arm and interarm are not clearly distinguishable, the mean field in arm was only about 5\% stronger than that in the interarm. For the other galaxies the mean magnetic field in the arms is stronger by 10–15\% (see Table 4). Overall, the mean magnetic field strength in the arm is higher than that in the interarm by $\sim 12\%$ percent, however, in certain regions it could be higher by up to 40\%. We note that, when magnetic fields are higher in the arms, the limited telescope resolution suppresses the observed field strength in the arms and increases that in the interarm regions. The same effect is caused by larger CRE diffusion length at 900 cm, so that more radio emission is observed in the interarm regions. Thus the differences seen in the magnetic field strength between arm and interarm regions are lower limits.

In Figure 4 we study the variation of the relative magnetic field strength $B_{eq}(r, \delta)/B_{eq}(r)$, where, $r$ is the galactocentric dis-
3.3 Radial scale lengths

It is believed that CRe originates from supernova explosions of OB stars found in HII complexes, i.e., regions of star formation. These CRe then propagate away to larger distances in galaxies giving rise to larger radial distribution of synchrotron emission than that of CRe sources and gas (see Tabatabaei et al. 2007; Beck 2007). The total intensity radio maps at \( \lambda 90 \) cm appears to be significantly smoother than that at \( \lambda 20 \) cm (see Basu et al. 2012a). The former mainly originates from older (\( \sim 10^8 \) yr) population of CRe that diffuses farther away from their formation sites than that at \( \lambda 20 \) cm. We estimate the exponential scale length of nonthermal emission at \( \lambda 20 \) cm (\( I_{90cm} \)) and \( \lambda 90 \) cm (\( I_{90cm}^{\lambda 90} \)) total equipartition magnetic fields and surface mass density of total gas (\( \Sigma_{\text{gas}} \)) to explore the effect of diffusion of CRe. \( \Sigma_{\text{gas}} \) is computed from atomic and molecular hydrogen surface mass density (see Appendix A). The scale lengths (\( l_0 \)) were obtained by fitting a function \( f(r) = f_0 \exp(-r/l_0) \) to the radial profiles shown in left panel of Fig. 6 leaving aside the central bulge. For the ringed galaxy NGC 4736, the scale lengths were computed leaving aside the ring. The scale lengths obtained are summarized in Table 3.

The scale length of the nonthermal emission (\( l_{90} \)) at \( \lambda 90 \) cm was found to be higher than that at \( \lambda 20 \) cm. This is caused due to higher diffusion scale lengths of low energy (\( \sim 1.5 \) GeV) CRe at \( \lambda 90 \) cm as compared to higher energy (\( \sim 3 \) GeV) CRe at \( \lambda 20 \) cm in a typical galactic magnetic field of \( \sim 10 \) \( \mu \)G. In the simple case of energy dependent diffusion of CRe, the diffusion length (\( l_{\text{diff}} \)) after time \( \tau \) is given by, \( l_{\text{diff}} \sim (D \tau)^{0.5} \). Here, \( D \) is the diffusion coefficient assumed to be constant, and is \( \sim 10^{28} \) \( \text{cm}^2\text{s}^{-1} \). We assume the diffusion time to be same as the synchrotron cooling timescales (\( t_{\text{syn}} \)) given by, \( t_{\text{syn}} = 8.35 \times 10^9 \left( E_{\text{CRe}}/\text{GeV} \right)^{-1} \left( B_{\text{eq}}/\mu \text{G} \right)^{-2} \) yr, where, \( E_{\text{CRe}} \) is the energy of the electrons. The expected diffusion length for the galax-
ies at λ00 cm and λ20 cm are ≈ 1.4 kpc and ≈ 1 kpc respectively, i.e., $l_{\text{diff,90 cm}}/l_{\text{diff,20 cm}} = (E_{\text{CRe,90 cm}}/E_{\text{CRe,20 cm}})^{-0.5} \approx 1.4$. CRe can also propagate by the streaming instability at the velocity of Alfvén wave in the ionized galactic medium and the propagation distance is given by, $l_A \approx v_A t_{\text{syn}}$. Here, $v_A$ is the Alfvén velocity assumed to be ≈ 50 km s$^{-1}$. In this scenario, the propagation distance at λ90 cm and λ20 cm are ≈ 1 kpc and ≈ 2 kpc respectively, i.e., $l_{\lambda,90 \text{cm}}/l_{\lambda,20 \text{cm}} = (E_{\text{CRe,90 cm}}/E_{\text{CRe,20 cm}})^{-1} \approx 2$. From our data, the ratio of scale length of nonthermal emission at λ90 cm and λ20 cm, i.e., $l_{\text{int,90 cm}}/l_{\text{int,20 cm}}$ are 1.77 ± 0.38, 1.37 ± 0.29, 1.92 ± 0.17, 1.64 ± 0.25 and 1.31 ± 0.15 for NGC 1097, NGC 4736, NGC 5055, NGC 5236 and NGC 6946 respectively. For 3 of the galaxies the increase in the estimated $l_{\text{int}}$ between λ90 and λ20 cm is larger than that expected from simple diffusion estimates and is consistent with streaming with Alfvénic velocity.

The scale length of nonthermal emission at λ20 cm for NGC 6946 is similar to what was found by Walsh et al. (2002) and Beck (2007). The nonthermal scale length is related to scale length of magnetic field ($l_B$) as $l_B = l_{\text{int}}(3 + \alpha_{\text{nt}})$ under the assumption of equipartition of energy between magnetic field and cosmic ray particles. For the galaxy NGC 5236, $l_B$ is found to be comparatively smaller than other galaxies and is only ~ 3 times than that of $l_{\text{int}}$ at λ20 cm and ~1.9 times at λ90 cm. This is perhaps the effect of magnetic field strength being overestimated towards the inner parts of the galaxy, where $\alpha_{\text{nt}}$ ≤ 0.5 (see Section 2.1). Thus the estimated $l_B$ for NGC 5236 is lower than the actual value. The scale length of the magnetic field for NGC 6946 is found to be slightly higher than what was estimated by Beck (2007). This is likely to be caused due to their assumption of a constant $\alpha_{\text{nt}}$ throughout the galaxy and use of nonthermal emission at λ20 cm which has a smaller $l_{\text{int}}$ as compared to our λ90 cm maps.

The scale length of total gas surface density ($l_{\text{gas}}$) is found to be smaller than that of the nonthermal emission. However, $l_{\text{gas}}$ is close to $l_{\text{int}}$ at λ20 cm and much smaller than $l_{\text{int}}$ at λ90 cm, suggesting the λ20 cm nonthermal emission is a better tracer of star forming activity than at λ90 cm, wherein the later mostly traces the older population of CRe which are well mixed.

4 DISCUSSIONS

4.1 Is synchrotron intensity an indicator of magnetic field?

4.1.1 Slope of the radio–FIR correlation

Simulations of MHD turbulence in the ISM revealed, under conditions of equipartition, the magnetic field ($B$) and the gas density ($\rho_{\text{gas}}$) are coupled as $B \propto \rho_{\text{gas}}^{\kappa}$, where $\kappa \approx 0.4 - 0.6$ (see e.g., Fiedler & Mouschovias 1993; Groves et al. 2003). The slope of the well known radio–far infrared (FIR) correlation was used to determine $\kappa$ for four of the galaxies at scales of ~ 1 kpc (Basu et al. 2012b). The radio–FIR correlation is used as a measure of the tightness of the radio–FIR correlation.

4.1.2 Dispersion of the radio–FIR correlation

Dispersion of quantity ‘q’ defined as $\log_{10}(I_{\text{FIR}}/I_{\text{int,\nu}})$ is widely used as a measure of the tightness of the radio–FIR correlation. Where, $I_{\text{FIR}}$ is the FIR flux density and $I_{\text{int,\nu}}$ is the nonthermal radio flux density at frequency, $\nu$. The far infrared flux density ($I_{\text{FIR}}$) can be written as, $I_{\text{FIR}} \propto n_{\text{UV}}Q(\lambda, \alpha)B(T_{\text{dust}})$, where $n_{\text{UV}}$ is the number density of the UV photons responsible for dust heating, $Q(\lambda, \alpha)$ is a wavelength (here $\lambda = 70$ µm) dependent absorption coefficient of dust grains of radius $a$ (Draine & Lee 1984, Alton et al. 2004). $B(T_{\text{dust}})$ is the Planck function for dust emitting at temperature $T_{\text{dust}}$. The flux density at radio frequency $\nu$, can be written as $I_{\text{int,\nu}} \propto n_{\text{CRe,\nu}}B^{1+\alpha_{\text{nt}}}$, where, $n_{\text{CRe,\nu}}$ is the number density of cosmic ray electrons (CRe) emitting at a frequency $\nu$ and $B$ is the actual magnetic field.

From the above, the ratio of FIR and radio flux density is, $I_{\text{FIR}}/I_{\text{int,\nu}} \propto (n_{\text{UV}}/n_{\text{CRe,\nu}})(1/B^{1+\alpha_{\text{nt}}})$, assuming same dust properties throughout the galaxy and $T_{\text{dust}}$ is seen to remain constant throughout the galaxy (see e.g., Tabatabaei et al. 2007, Basu et al. 2012a, Hummel (1986) showed that the cumulative frequency distribution of $I_{\text{FIR}}/I_{\text{int,\nu}}$ and that of $B^{1+\alpha_{\text{nt}}}$ follows each other indicating energy ‘equipartition’ between magnetic field and cosmic ray particles to hold good and thus $B_{\text{eq}}$ is close to...
B. In our case, for each of the galaxy, we determine the quantities \( I_{70\mu m}/I_{21cm} \) and \( B_{eq}^{1+\alpha_{nt}} \) within a region of \( \sim 1 \) kpc and normalized them with their respective median values. In Fig. we plot these median normalized cumulative distribution function of \( I_{70\mu m}/I_{21cm} \) (shown in gray) and \( B_{eq}^{1+\alpha_{nt}} \) (shown in black) for all the galaxies together. The left and right panels show the distribution in the arm and interarm regions respectively. In the arm regions, \( \alpha_{nt} \) do not change significantly, we assumed a constant value of 0.8. However, \( \alpha_{nt} \) varies significantly in the interarm regions, and we have used the observed values of \( \alpha_{nt} \) for each region from Basu et al. (2012a).

At \( \lambda 20 \) cm, the dispersion in the quantity \( I_{70\mu m}/I_{21cm} \) is similar to the dispersion in \( B_{eq}^{1+\alpha_{nt}} \) for both arms and interarm regions determined at spatial scales of \( \sim 1 \) kpc. Thus at scales of \( \sim 1 \) kpc, the variations in \( I_{70\mu m}/I_{21cm} \), i.e., dispersion seen in the quantity ‘q’ is caused due to variations in the magnetic field, where the magnetic field is represented by \( B_{eq}^{1+\alpha_{nt}} \). Thus, \( B_{eq}^{1+\alpha_{nt}} \) (or a constant multiple of it) is a good representative of the actual magnetic field, \( B \).

However, at \( \lambda 90 \) cm, the dispersion in \( I_{70\mu m}/I_{21cm} \) is \( \sim 20 \) percent higher than that of \( B_{eq}^{1+\alpha_{nt}} \) for the interarm regions. At \( \lambda 90 \) cm the low energy (\( \sim 1.5 \) GeV) CRe propagate to farther distances from the arms into the interarms, which has the effect of increasing the dispersion. We note that equipartition assumption is valid only at scales larger than the diffusion length, which is better fulfilled at \( \lambda 20 \) cm than at \( \lambda 90 \) cm.

### 4.2 Energy density in magnetic field and gas

Magnetic energy is expected to be in equipartition with ISM turbulent energy (Crutcher 1999; Cho & Vishniac 2000; Groves et al. 2003). In Section 3, we found that the magnetic field falls off as a function of galactocentric distance and had a larger scale length than that of the gas surface density. Here, we compare the magnetic field energy density \( U_{mag} = B_{eq}^2/(8\pi) \) with that of the ISM energy density from kinetic energy of gas due to turbulent motions \( U_{turb,gas} \), thermal energy density of warm ionized gas \( U_{ion} \) and total neutral (atomic; \( U_{th,HI} \) + molecular; \( U_{th,HI} \)) gas at spatial scales of \( 0.4 \) – \( 0.9 \) kpc, except for NGC 5236 for which the spatial resolution is \( \sim 1.2 \) kpc (see Appendix A for details). \( U_{turb,gas} \) is estimated from the surface mass density maps of atomic and molecular hydrogen, using \( U_{turb,gas} = 1.36(U_{trub,HI} + U_{trub,HI}) \). The factor 1.36 is to account for the presence of Helium and \( U_{turb,gas} = (1/2)(\Sigma_{HI}/H_{HI}) \), where, \( \Sigma_{HI}/H_{HI} \) are the surface mass density of atomic (\( H_I \)) and molec-

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**Figure 6.** Left panel: energy densities in various ISM phases as a function of galactocentric distance. Black lines shows the magnetic field energy density \( U_{mag} \), the blue lines shows the kinetic energy density of total neutral gas due to turbulent motion \( U_{turb,gas} \), the red lines shows the thermal energy density of warm ionized gas \( U_{ion} \), the gray lines with dots and squares shows the thermal energy density of atomic and molecular gas \( U_{th,HI} \) and \( U_{th,HI} \) respectively. Right panel: the ratio of energy density in magnetic field and total ISM gas energy density \( U_{gas} = U_{turb,gas} + U_{ion} + U_{th,neutral} \) at scales of \( \leq 1 \) kpc as a function of galactocentric distance. The black and gray symbols are for arm and interarm regions respectively. The blue squares shows the radially averaged value of the ratio determined within annulus of one one synthesized beam width.
ular (H$_2$) gas. $v_{\text{turb}}$ is the velocity of the turbulent gas, assumed to be $\sim 9 \, \text{km s}^{-1}$ for H$_2$ and $\sim 6 \, \text{km s}^{-1}$ for H$_2$ (van der Kruit & Shostak 1982; Combres & Beck 1997; Sellwood & Balbus 1998; Kasparova & Zasov 2008) and $h_{\text{III},\text{H}_2}$ are the line of sight depth of atomic and molecular gas assumed to be $\sim 100 \, \text{pc}$ and $\sim 300 \, \text{pc}$ respectively. The surface mass densities were calculated using moment-0 maps of CO and H$_2$ line emission (see Appendix A for details).

The thermal energy densities of warm ionized gas and neutral gas were computed using, $U_{\text{th}} = \frac{3}{2}(n)kT$. Here, $(n)$ is the mean number density, $k$ is the Boltzmann constant and $T$ is the temperature. For the warm ionized gas, the mean number density of thermal electrons $(n_e)$ was calculated from the emission measure $(EM)$ maps, such that, $(n_e) \approx \left[EM f_{\text{II}}/h_{\text{ion}}\right]^{1/2}$. $EM$ was determined from dereddened H$_\alpha$ maps using Equation 9 in Valls-Gabaud (1998) (see Basu et al. 2012a, for details). We assumed a constant temperature of $\sim 10^4 \, \text{K}$ for estimating the energy density of warm ionized gas, and atomic (U$_{\text{III},\text{H}}$) gas, the number densities were determined from the corresponding surface mass density maps assuming a constant scale height as discussed above. We assumed a constant temperature of $\sim 50 \, \text{K}$ for molecular gas and $\sim 100 \, \text{K}$ for atomic gas.

In Figure 5(left panel) we study the variation of energy density of magnetic field ($U_{\text{mag}}$; shown in black diamonds), kinetic energy of total gas ($U_{\text{turb,gas}}$; shown in blue triangles) and thermal energy density of ionized gas ($U_{\text{ion}}$; shown in red triangles), molecular gas ($U_{\text{III},\text{H}_2}$; shown in gray circles) and atomic gas ($U_{\text{III},\text{H}}$; shown in gray squares) as a function of galactocentric distance for the galaxies NGC 4736, NGC 5055, NGC 5236 and NGC 6946. The energy density of the warm ionized gas is found to be about two orders of magnitude lower than that of magnetic field and kinetic energy of turbulent gas. For neutral gas, the thermal energies are about 3 orders of magnitude less. The energy density of magnetic field, turbulent energy of total gas, thermal energy of warm ionized gas and neutral gas matches well with Beck (2007) for the galaxy NGC 6946. However, due to simplistic assumption for $\alpha_{\text{nt}} \sim 1.0$ throughout the galaxy, the total magnetic field may be underestimated in Beck (2007), specially in the inner regions where $\alpha_{\text{nt}}$ is smaller than 0.7.

In Figure 5(right panel) we study the variation of the ratio of magnetic field energy density and total ISM gas energy density ($U_{\text{gas}}$) estimated at spatial scales of $\sim 0.4$ to $1.2 \, \text{kpc}$ depending on the distance of the galaxies. $U_{\text{gas}}$ was computed as, $U_{\text{gas}} = U_{\text{turb,gas}} + U_{\text{ion}} + 1.36(U_{\text{III},\text{H}} + 2U_{\text{III},\text{H}_2})$. The black and gray symbols denote arms and interarms respectively. The blue squares show the radially averaged value of the ratio determined within annulus of one beam width. Pixels more than $4\sigma$ in gas density were considered for this analysis.

The ratio of total ISM gas energy density and magnetic field are found to be almost constant throughout the galaxies except for a systematic offset from unity due to our assumed constant values of scale heights and velocity dispersion. After dividing by the mean values of the ratio for each of the galaxies, the ratio has a dispersion less than $\sim 30\%$ for arms and interarms of the galaxies, indicating energy/pressure balance between magnetic field and gas. For the galaxy NGC 6946, we observe that the ratio of the interarm regions to be higher than that in the arms by a factor $1.47 \pm 0.11$, i.e, magnetic field energy dominates over the turbulent gas energy. Overall, this difference is not significant for other galaxies, but for an adjacent arm-interarm, the ratio in the interarm could be higher by more than $50\%$ than the arm.

From our data we found that as we move from the center to the disk to the edge of the galaxies, magnetic field energy systematically dominates over the total ISM energy density. However, this trend disappears once we consider only the high signal-to-noise regions (> $4\sigma$) as is shown by the blue points in Fig. 5(right panel).

Magnetic fields in galaxies are amplified by two major processes, firstly the small scale fields are amplified by field line stretching and twisting due to turbulent motions of gas (small-scale dynamo) and secondly, large-scale amplification due to large-scale dynamo action. In the previous case, magnetic field and gas are closely coupled such that the magnetic field is amplified by transfer of kinetic energy from gas. The fields can be amplified up to equipartition levels (Groves et al. 2003; Cho & Vishniac 2000). This would result in small scale turbulent fields with low degree of polarization in regions of high gas density, i.e, the spiral arms. This is indeed observed in many of the galaxies. In NGC 6946 only 1–5% of the emission is polarized in the inner spiral arms (Beck 2007). In M51, turbulent magnetic field dominates in arms (Fletcher et al. 2011). In NGC 5236, low degree of uniform magnetic field is seen in the spiral arms in inner parts of the galaxy (Neininger et al. 1993). In NGC 4736, comparatively lower degree of polarization is seen in the star forming ring than in the outer parts (Chyž & Buta 2008). Our results show that in the gaseous arms, the magnetic field energy density and the energy density in gas to be similar and do not vary by more than 30 percent throughout the galaxies. This indicates that in the arms the magnetic field is perhaps amplified by field line stretching due to turbulent gas motions driven by star formation.

In the interarms and towards the outer parts, many galaxies show higher degree of ordered magnetic field caused by large scale dynamo action (see e.g. Beck et al. 1992; Beck 2007; Chyž & Buta 2008, and references therein). For NGC 6946, where ordered fields are observed in the interarm regions, it is thought that finite time dynamo relaxation causes a phase shift between magnetic and gas/star forming spiral arms, such that magnetic arms lags (Chamandy et al. 2013). Magnetic field energy dominating over the turbulent gas energy thus helps maintaining this field orderness in interarm regions and outer parts of the galaxies. For this galaxy, Walsh et al. (2002) found the regular magnetic field (using polarized emission at $\lambda 6 \, \text{cm}$) to trace regions of low star formation efficiency and coincides with the regions where the ratio was found to be significantly higher, suggesting insufficient energy in turbulent gas to amplify the turbulent magnetic field.

5 SUMMARY

We have measured total magnetic fields in five nearby normal galaxies, NGC 1097, NGC 4736, NGC 5055, NGC 5236 and NGC 6946, assuming equipartition of energy between cosmic ray particles and magnetic fields. In this study, magnetic fields were probed at sub-kpc scales except for NGC 1097, for that it was 2.8 kpc.

- The strengths of the total magnetic field decreases by $\sim 40 \text{–} 50\%$ from center to edge of the galaxies. The field changes by at least 15% between arms and interarms and do not change significantly along them after correcting for the radial variation.

- Our study shows synchrotron intensity to be a good tracer of the total magnetic field in galaxies. ‘Equipartition’ of energy between magnetic field and cosmic ray particles hold well at kpc scales for all the galaxies.
• The estimated energy densities of magnetic field and gas were seen to be within a factor $\lesssim 2$ in the arms and interarms at sub-kpc scales implying magnetic field to play important role in pressure balance of the ISM. The ratio $U_{\text{mag}}/U_{\text{gas}}$ is found to be roughly constant along radius.
• The energy density of the magnetic field was found to be larger than that of the kinetic energy density due to turbulent motion of gas in the interarm regions, particularly for NGC 6946, and in outer parts in general. Large scale dynamo action could maintain the magnetic field in such regions.

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APPENDIX A: ATOMIC AND MOLECULAR SURFACE GAS DENSITY

Four of the galaxies (NGC 4736, NGC 5055, NGC 5236 and NGC 6946) studied in this work were observed as a part of THINGS (Walter et al. 2008) to trace H\(_1\). We used natural weighted moment-0 H\(_1\) maps to calculate the surface density of atomic gas using the equation,

\[
\Sigma_{\text{HI}} (M_\odot \text{pc}^{-2}) = 0.02 \cos i I_{\text{HI}} (\text{K km s}^{-1}).
\]

Here, \(i\) is the inclination angle (0° for face-on) of the galaxy and \(I_{\text{HI}}\) is the line integrated intensity. The above equation includes a factor 1.36 to account for the presence of Helium.

CO is commonly used as a tracer for molecular gas. We used CO\(_{J=2-1}\) moment-0 maps from the HERACLES (Leroy et al. 2009) for three of the galaxies, namely NGC 4736, NGC 5055 and NGC 6946. These maps have an angular resolution of 13.4 arcsec, better than the resolution of the nonthermal maps. Assuming a constant CO-to-H\(_2\) conversion factor, \(X_{\text{CO}} = 2 \times 10^{20} \text{cm}^{-2}(\text{K km s}^{-1})^{-1}\) and a line ratio of 0.8 for converting CO\(_{J=2-1}\) flux to CO\(_{J=1-0}\) flux, the molecular gas surface density was calculated using,

\[
\Sigma_{\text{H}_2} (M_\odot \text{pc}^{-2}) = 5.5 \cos i I_{\text{CO, J=2-1}} (\text{K km s}^{-1}).
\]

Here, \(I_{\text{CO, J=2-1}}\) is the line integrated intensity. Note that, for NGC 6946, the \(\cos i\) factor was missing in Beck (2007) by mistake (Rainer Beck, private communication). However, this would not change their conclusions significantly.

For the galaxy NGC 5236 we used CO\(_{J=1-0}\) moment-0 map from the NRAO 12-m telescope (Crosthwaite et al. 2002) to calculate the molecular gas density. This map has an angular resolution of 55 arcsec. The line integrated flux density \(S_{\text{CO, J=1-0}}\) was converted into molecular gas mass \((M_{\text{H}_2})\) using the formula

\[
M_{\text{H}_2} (M_\odot) = 1.1 \times 10^4 D^2 (\text{Mpc})^2 \cos i S_{\text{CO, J=1-0}} (\text{Jy km s}^{-1})
\]

from Young et al. (1989). Here, \(D\) is the distance to the galaxy. The mass was then converted to surface density by diving by the linear area for each pixel.