



## Equipartition magnetic fields in normal galaxies

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**Abstract.** We studied the total magnetic field strength in normal star-forming galaxies estimated using energy equipartition assumption. Using the well known radio–far infrared correlation we demonstrate that the equipartition assumption is valid in galaxies at sub-kpc scales. We find that the magnetic field strength is strongly correlated with the surface star formation rate in the galaxies NGC 6946 and NGC 5236. Further, we compare the magnetic field energy density to the total (thermal + turbulent) energy densities of gas (neutral + ionized) to identify regions of efficient field amplification in the galaxy NGC 6946. We find that in regions of efficient star formation, the magnetic field energy density is comparable to that of the total energy density of various interstellar medium components and systematically dominates in regions of low star formation efficiency.

### 1. Introduction

It is believed that the magnetic field in star forming galaxies are amplified and maintained by dynamo action. At small scales ( $\lesssim 1$  kpc), the turbulent dynamo action, driven by Supernova shocks and star formation, amplifies the magnetic field strength efficiently up to energy equipartition values in  $\sim 10^6 - 10^7$  years. Such regions are characterized by small-scale random field with low degree of polarization (see e.g. Brandenburg et al. 2012; Arshakian et al. 2009; Bhat & Subramanian 2013). At larger scales ( $\sim 1 - 10$  kpc), the mean field dynamo action is responsible for amplification of the field in  $\sim 10^8 - 10^9$  years giving rise to large-scale coherent field with high degree of polarization (Arshakian et al. 2009; Subramanian 2008; Shukurov et al. 2006). Magnetic field strength grows due to stretching and twisting of the field lines up to energy equipartition values, i.e., energy density in magnetic field is similar to the kinetic energy density due to turbulent motions of gas. Numerical magnetohydrodynamic simulations of turbulent interstellar medium (ISM) have revealed that the magnetic

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field ( $B$ ) and gas density ( $\rho_{\text{gas}}$ ) are coupled as  $B \propto \rho_{\text{gas}}^{\kappa}$ , where  $\kappa$  is the coupling index (Cho & Vishniac 2000; Fiedler & Mouschovias 1993; Groves et al. 2003). Under the condition of equipartition of energy,  $\kappa$  assumes the value 0.5 (Cho & Vishniac 2000). It is therefore expected that the radial scale length of the magnetic field energy and that of gas density should remain similar. However, in contradiction, it is often observed that the magnetic energy density dominates over the total energy density of gas especially towards the outer parts of the galaxies (Basu & Roy 2013; Beck 2007). Star formation activity and shocks arising from supernova explosions drives turbulence at the smallest scale in the ISM. It is therefore imperative to do spatially resolved study of the various competing forces in the ISM with the magnetic field strength based on star formation activity.

## 2. Results

The galaxies studied here were observed using the Giant Meterwave Radio Telescope at 0.33 GHz (Basu et al. 2012a) and archival data observed using the Very Large Array at 1.4 GHz. The nonthermal emission maps were derived by subtracting the thermal free-free emission component at both the frequencies using a new technique developed by Basu & Roy (2013) at sub-kpc scales. It was found that at 0.33 GHz more than 95 percent and at 1.4 GHz about 90 percent of the total radio emission is nonthermal in origin. The nonthermal maps were used to determine the nonthermal spectral index<sup>1</sup>,  $\alpha_{\text{nt}}$ , for estimating the equipartition magnetic field strength maps and the coupling index  $\kappa$  from the slope of the radio–far infrared (FIR) correlation. We used the revised equipartition formula given by Beck & Krause (2005) to estimate the total magnetic field strength. Further, to validate the energy equipartition assumption, we study the spatially resolved radio–FIR correlation at sub-kpc scales for the galaxy NGC 6946.

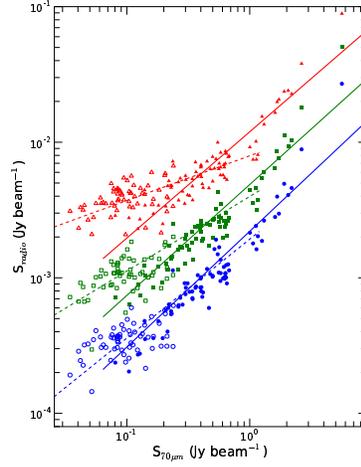
### 2.1 Radio–FIR correlation: A test for equipartition condition

Building on the model first proposed by Niklas & Beck (1997), Dumas et al. (2011) showed that, the slope of the radio–FIR correlation (as determined using the non-thermal part of the radio emission only),  $b$ , to be related with the coupling index  $\kappa$ , through the Kennicutt-Schmidt (KS) law index,  $n$  (Kennicutt 1998) and  $\alpha_{\text{nt}}$ . Depending of whether equipartition conditions are valid or not, one expects linear or non-linear slope of the radio–FIR correlation (Beck & Wielebinski 2013; Dumas et al. 2011; Basu et al. 2012b).

Basu et al. (2012b) from spatially resolved study at  $\sim 1$  kpc scales for four galaxies (NGC 4736, NGC 5055, NGC 5236 and NGC 6946) found  $\kappa = 0.51 \pm 0.12$  and thereby concluded the equipartition conditions to be valid at scales of  $\sim 1$  kpc. However, conversely, it could be presaged, if galaxies are in energy equipartition, i.e.,

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<sup>1</sup>Spectral index,  $\alpha$ , is defined as,  $S_{\nu} \propto \nu^{-\alpha}$ . Here,  $S_{\nu}$  is the flux density at a radio frequency  $\nu$ .

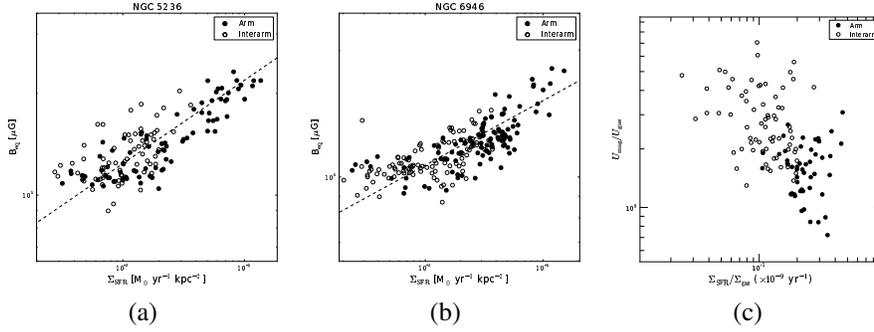


**Figure 1.** Multi frequency radio–FIR correlation for NGC 6946. The red triangles, green squares and blue circles are for 0.33, 1.4 and 5 GHz respectively. The filled and open symbols are for arm and interarm regions respectively.

$\kappa \sim 0.5$ , KS index  $n = 1.4$  (Kennicutt 1998) and the nonthermal spectral index is constrained ( $\alpha_{nt} \sim 0.8$ ; Basu et al. 2012a), then the slope of the radio–FIR correlation should be  $\sim 0.8$ . Moreover, the slope must remain the same when studied at different radio frequencies, i.e., independent of the energy of the cosmic ray electrons (CREs) giving rise to the correlation. This is indeed observed for the galaxy NGC 6946 between 0.33 GHz and 5 GHz. Fig. 1 shows the radio intensity at 0.33 GHz (red triangles), 1.4 GHz (green squares) and 5 GHz (blue circles) vs. FIR intensity at  $70 \mu\text{m}$ . The open and filled symbols represents for arm and interarm regions respectively. In the arm regions where the star formation rate is higher, the slope is found to be  $0.78 \pm 0.06$  at 0.33 GHz,  $0.82 \pm 0.06$  at 1.4 GHz and  $0.85 \pm 0.07$  at 5 GHz. In the interarm regions, i.e., regions of low star formation, the slope is observed to flatten significantly at 0.33 and 1.4 GHz due to propagation of CREs from the regions of generation in the arms to interarms (see e.g., Basu et al. 2012b).

## 2.2 Magnetic field and star formation activity

Star formation activity in galaxies plays an important role in driving turbulence and thereby amplification of magnetic fields. Magnetic field strength is expected to be correlated with the local star formation rate in galaxies as supernova shocks amplify the field strength. In Fig. 2 (a, b), we study the spatially resolved total magnetic field strength ( $B_{\text{eq}}$ ) with the surface star formation rate ( $\Sigma_{\text{SFR}}$ ) at scales of  $\sim 0.5$  kpc for the galaxies NGC 5236 (Fig. 2a) and NGC 6946 (Fig. 2b). The filled and unfilled circles are for the arm and interarm regions respectively. Magnetic field is seen to be significantly correlated with the star formation rate as a power law, i.e.,  $B_{\text{eq}} \propto (\Sigma_{\text{SFR}})^a$ ,



**Figure 2.** Variation of  $B_{\text{eq}}$  (in  $\mu\text{G}$ ) with  $\Sigma_{\text{SFR}}$  (in  $M_{\odot}\text{yr}^{-1}\text{kpc}^{-2}$ ) for the galaxy (a) NGC 6946 and (b) NGC 5236. Figure (c) shows the variation of  $U_{\text{mag}}/U_{\text{gas}}$  with  $\Sigma_{\text{SFR}}/\Sigma_{\text{gas}}$  (in  $\text{yr}^{-1}$ ) for the galaxy NGC 6946. The filled and unfilled symbols are for arm and interarm regions respectively.

where,  $a$  is the power law index. The Spearman's rank correlation for NGC 5236 is 0.80 and for NGC 6946 it is 0.74. The power law index,  $a$ , is found to be  $0.25 \pm 0.05$  and  $0.18 \pm 0.03$  for the galaxies NGC 5236 and NGC 6946 respectively. NGC 5236 shows comparatively steeper value of  $a$  than NGC 6946, indicating efficient magnetic field amplification, perhaps caused due to bar action. However, more data are required to firmly establish our results.

In Fig. 2(c) we plot the ratio of the magnetic field energy density ( $U_{\text{mag}} = B_{\text{eq}}^2/8\pi$ ) to that of the total energy density of ISM gas ( $U_{\text{gas}}$ ) as a function of star formation efficiency ( $\Sigma_{\text{SFR}}/\Sigma_{\text{gas}}$ ) for the galaxy NGC 6946 at scales of  $\sim 0.5$  kpc. Here,  $\Sigma_{\text{gas}}$  is the surface density of the total neutral gas. The total energy density of gas is computed from the thermal energy density of neutral and ionized gas ( $\frac{3}{2}\langle n \rangle kT$ ) and kinetic energy due to turbulent motion of neutral (atomic+molecular) gas ( $\frac{1}{2}\rho_{\text{gas}}\delta v_{\text{turb}}^2$ ; see Basu & Roy 2013, for details). The filled and unfilled circles are for arm and interarm regions respectively. It is seen that in the interarm regions, i.e., the regions of low star formation efficiency, magnetic field energy density is systematically higher than the total energy density of the various competing forces in the ISM. These are also the regions where large-scale coherent magnetic field is observed (Beck 2007). In the arm regions, i.e., regions of high star formation efficiency, ISM is roughly in energy equipartition within a factor of 2. Such regions are dominated by turbulence and perhaps the field is amplified by small-scale turbulent dynamo action.

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