



Constraints on the Cosmological Evolution of Magnetic Fields in Galaxies

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Abstract. The far-infrared radio correlation is used to probe the variation of the magnetic field in galaxies with redshift. New observations of the Spitzer extragalactic First Look Survey field at 610 MHz with the Giant Metre Wave Radio Telescope are presented. A sample of objects is defined in the First Look Survey field which are detected at both 24 and 70 μm and also have radio data at two frequencies as well as a spectroscopic redshift. In order to do K-correction for the infrared data a large grid of model mid- to far-infrared spectral energy distributions are calculated and a likelihood analysis performed for each galaxy to estimate its K-correction. The far-infrared radio correlation is constructed and is found to show significant variation with redshift in the sense that the objects at higher redshift tend to be radio bright.

1. Introduction

Magnetic fields are known or suspected to play a crucial role in very many aspects of astrophysics. Despite this, to date there are very few observational constraints on the cosmological evolution of magnetic fields. In this paper we use the strong far-infrared radio correlation to place constraints on the evolution of magnetic fields in high redshift star forming galaxies found in the Spitzer extragalactic First Look Survey field.

There are certainly magnetic fields present in high redshift star forming galaxies – for example Ivison et al. (2005) detect steep spectrum radio continuum from a number of high redshift dusty galaxies characteristic of synchrotron emission. However, to probe the magnitude of the magnetic field in such galaxies an additional constraint is required and for this we make use of the far-infrared radio correlation (e.g. Niklas 1997; Yun, Reddy & Condon 1001; Sopp & Alexander 1991; Fitt, Alexander & Cox 1988). The correlation, which is known to hold over at least four orders of magnitude, provides a physical link between the non-thermal radio emission and the thermal far-infrared emission from dust. Since only the former depends on the magnetic field strength, the cosmological evolution of the far-infrared to radio ratio for a galaxy clearly provides information on how the physical conditions within galaxies are evolving with redshift and potentially therefore the strength of the magnetic field. The difficulty with interpreting such results is however that the underlying physical mechanism which gives the very strong correlation is still poorly understood. Importantly however, the fact that the correlation holds locally in galaxies (Murphy et al. 2006) rules out simple scaling and demonstrates that the correlation is reflecting physical processes on scales of about 1 kpc in galaxies.

2. Observations and data reduction

The far infrared data used in this study are taken from the Spitzer observations of the extragalactic First Look Survey (FLS) field. Here we make use of the data at 24 and 70 μm taken with the MIPS instrument (Rieke et al. 2004). Further details of the far infrared data are given in Frayer et al. (2006), Frayer et al. (2004) and Appleton et al. (2004).

Radio data at 1.4 GHz are taken from the survey by Condon et al. (2003). The survey was made using the VLA with 35 overlapping B-array pointings; sources are detected down to a limiting 5σ sensitivity of 115 μJy . Data at 610 MHz were obtained by the authors using the Giant Metre Wave Radio Telescope (GMRT); our survey consists of 7 pointings and reaches a noise level of about 30 $\mu\text{Jy}/\text{beam}$. Further details of the observations and reduction procedures will appear elsewhere. A representation of the FLS survey field observed with the GMRT is shown in Fig. 1.

Within the overlap region of the Spitzer, VLA and our GMRT surveys, a total of 3565 objects were detected at 1.4 GHz; of these 681 had both 5σ detections at 610 MHz and were also detected at 25 μm . Redshift data were obtained from the Sloan Digital Sky Survey, together with data taken from Papovich et al. (2006). A total of 119 radio-detected galaxies have Spitzer detections at both 24 and 70 μm together with a spectroscopic redshift. Both in the radio and infrared having data at two frequencies is crucial to permit K-corrections to be made.

3. K-corrections

K-correction of the data is crucial if the evolution of the far-infrared/radio correlation is to be determined reliably. This is most problematic in the infrared. For the two MIPS pass-bands used in this work (chosen to maximise the number of radio/infrared detections) we expect the

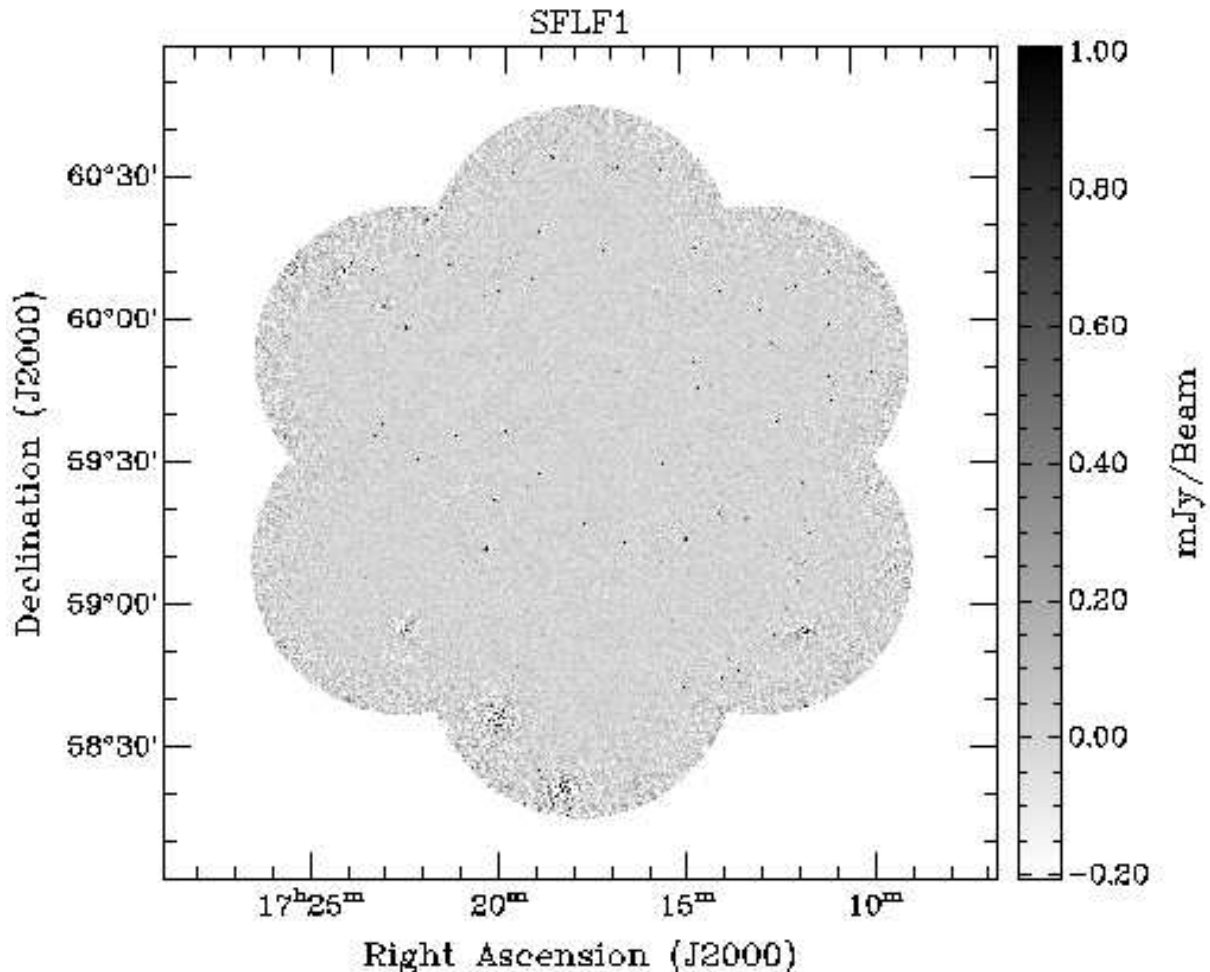


Fig. 1. GMRT observations of the Spitzer FLS field at 610 MHz; the noise level away from very bright sources is of order 30 $\mu\text{Jy}/\text{beam}$.

rest-frame 70- μm pass-band to be close to the peak of the grey-body curve, whereas the rest-frame 24- μm data to be dominated by transiently heated small grains. At even modest redshifts very significant K-corrections are required given the spectral shape between 24- and 70- μm . The problem is made more demanding since there are significant narrow-band emission and absorption features which greatly affect the spectrum at 24- μm and shorter wavelengths. With this in mind we have begun a detailed modelling study of the mid- to far-infrared spectral energy distributions of galaxies to determine K-corrections plus our uncertainty in the correction to be determined.

The K-correction for the radio data are obtained assuming a power-law synchrotron spectrum between 1.4 GHz and 610 MHz of the form

$$I_\nu = I_{\nu_0} \left(\frac{\nu}{\nu_0} \right)^{-\alpha}$$

The measured spectral indices for all objects in the sample are shown in Fig. 2.

For the infrared data we have constructed a grid of model mid-IR to far-IR spectral energy distributions. Full details of this modelling will be given elsewhere, here we give a brief overview. Our modelling of the dust emission consists of three distinct parts:

1. calculation of the radiation field heating it, and its absorption;

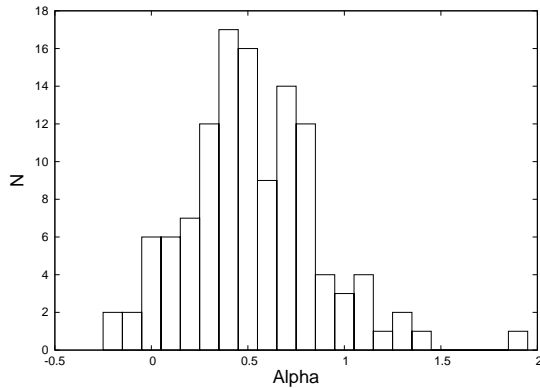


Fig. 2. Spectral index distribution between 1.4 GHz and 610 MHz for the galaxies used to construct the far-infrared radio correlation.

2. calculation of the infrared radiation given a detailed dust model;
3. radiative transfer.

Assuming a spherical geometry, we model the heating source as a single stellar population, simulated using the STARBURST-99 (Leitherer et al. 1999) spectral synthesis package, with an assumed star formation history. For the purposes of the present paper we assume a star formation rate which is constant for 10^8 yr and consider different locations of an optically thin dust shell relative to the central star forming region. There is a degeneracy between the overall star formation rate and the location of the dust distribution which is not important when considering the K-correction.

The dust model is very important in determining the infrared spectrum. We assume two populations for the grains: one of silicates, and a second of carbonaceous grains. The carbonaceous grains are further divided into Polycyclic Aromatic Hydrocarbons (PAHs) and larger graphitic grains. As a basic model we use the preferred size distribution of Weingartner & Draine (2001) and then allow for variations about this distribution. We model the size distributions of the silicate and larger graphitic grains as power-laws and adopt two log-normal distributions to characterise the PAH size distributions. To calculate the infrared emission from the dust we follow the procedure of Draine & Li (2001), calculating an equilibrium temperature for the larger grains and allowing for transient heating and cooling of the small grains.

We have constructed a grid of approximately 1000 mid-to far-infrared spectral energy distributions representing variations in the properties of the grain size-distributions and the location of the dust. Examples of model spectra are shown in Fig. 3. For any given galaxy we cannot be sure from 2-point spectral data what the underlying heating source, geometry and dust properties are. There is therefore an uncertainty in the K-correction for each object. Our procedure is to calculate the likelihood of each model in the grid given the data and associated errors. We then calculate the weighted average K-correction to-

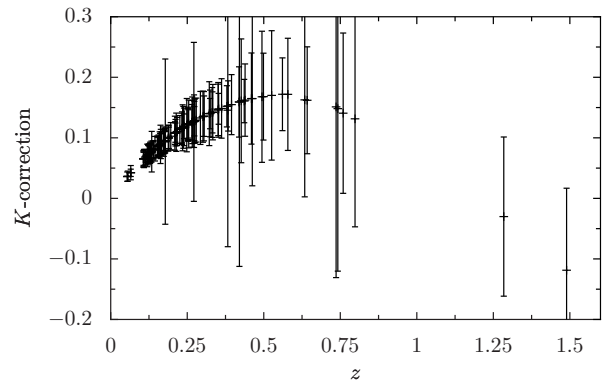


Fig. 4. Estimates of the K-correction for each galaxy in the sample as a function of redshift.

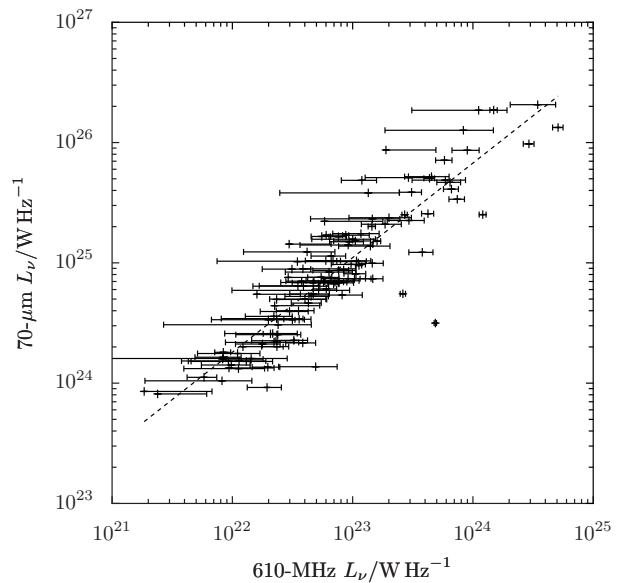


Fig. 5. The far-infrared radio correlation for the objects in our sample. The data are shown after K-correction and the straight line represents the best power-law fit to the data.

gether with an uncertainty using these likelihoods for each object. Results of this procedure for the objects in the current sample are shown in Fig. 4.

4. Results and Discussion

The far-infrared radio correlation for the objects in our sample is shown in Fig. 5; the error bars are dominated by the uncertainties in the K-correction. A good correlation is found in agreement with the results of Frayer et al. (2006) and Appleton et al. (2004). The slope of the correlation is 0.8 ± 0.1 considerably flatter than found previously. This is due to the presence in the sample of a number of objects at significant redshift. A better way to study the variation of the far-infrared radio correlation is to use the so-called q -parameter which is defined to be

$$q = \log \left(\frac{L_{70\mu\text{m}}}{L_{50\text{cm}}} \right)$$

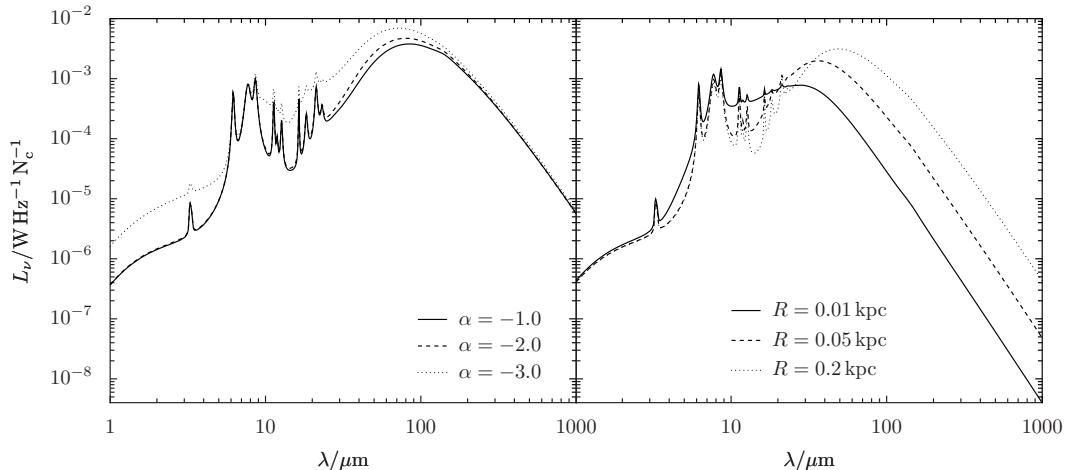


Fig. 3. Example IR model spectra. The figure to the left shows three spectra with different slopes of the silicate grain-size distribution, while the figure to the right shows spectra obtained with different inner radii of the dust cloud around the central star-forming region.

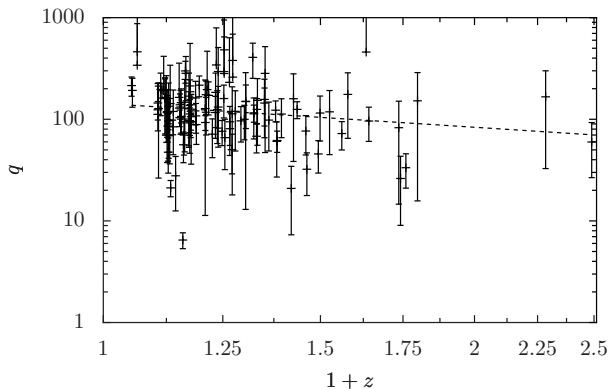


Fig. 6. The variation of the q -parameter with redshift.

In Fig. 6 we show the variation of q with $1+z$; the data show significant scatter but are consistent with a decline in q as approximately $(1+z)^{-0.7 \pm 0.4}$. Prior to K-correction we also find a decline in q with redshift as $(1+z)^{-1.35 \pm 0.15}$ in agreement with the results of Frayer et al. (2006). However, our results after K-correction are significantly different. Frayer et al. (2006) did not perform proper K-corrections, but argue that assuming a radio spectral index of 0.8 and a typical mid-IR spectral index of 2.4 the data are consistent with no variation of q with z . This argument significantly over estimates the K-correction in the infrared as is clear by inspection of the typical model spectra shown in Fig. 3. Furthermore the 24- and 70- μm data constrain further the possible K-corrections in most cases the observed spectral index between these two frequencies is considerably less than 2.4.

Figure 4 shows the calculated IR K-corrections; at high redshift the K-correction can in fact be negative; this occurs when the observed 24- to 70- μm colour favours a relatively warm grey-body temperature for the large grains with a peak shortward of 70 μm .

The variation of q with redshift after K-correction is strongly dependent on the form of the spectral energy distribution; for example fixing a very cool grey-body temperature can force q to increase with redshift. To establish the variation of q with redshift requires considerably more data and also a complete investigation of realistic infrared spectral models. However, we believe that there is some evidence for q to decline with increasing redshift, which is consistent with a relative increase in the radio luminosity. This in turn could either be due to an increase in the magnetic field, for example, or a higher incidence of radio bright AGN in the sample. Again further investigation is needed to distinguish between these possibilities.

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