Magnetic fields in galaxies – I. Radio discs in local late-type galaxies

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ABSTRACT

We develop an analytical model to follow the cosmological evolution of magnetic fields in disc galaxies. Our assumption is that fields are amplified from a small seed field via magnetohydrodynamical turbulence. We further assume that this process is fast compared to other relevant time-scales and occurs principally in the cold disc gas. We follow the turbulent energy density using a galaxy formation and evolution model. Three processes are important to the turbulent energy budget as follows: infall of cool gas on to the disc and supernova feedback increase the turbulence, while star formation removes gas and hence turbulent energy from the cold gas. Finally, we assume that field energy is continuously transferred from the incoherent random field into an ordered field by differential galactic rotation.

Model predictions are compared with observations of local late-type galaxies. The model reproduces observed magnetic field strengths and luminosities in low- and intermediate-mass galaxies. These quantities are overpredicted in the most massive hosts, suggesting that inclusion of gas ejection by powerful active galactic nuclei is necessary in order to quench gas cooling and reconcile the predicted and observed magnetic field strengths.

Key words: turbulence – galaxies: evolution – galaxies: formation – galaxies: luminosity function – galaxies: magnetic fields.

1 INTRODUCTION

Radio synchrotron emission of high energy electrons in the interstellar medium (ISM) indicates the presence of magnetic fields in galaxies. Rotation measures (RM) of background polarized sources indicate two varieties of field: a random field, which is not coherent on scales larger than the turbulence of the ISM, and a spiral ordered field, which exhibits large-scale coherence (e.g. Stepanov et al. 2008). For a typical galaxy, these fields have strengths of a few μG. In a galaxy such as M 51, the coherent magnetic field is observed to be associated with the optical spiral arms (Patrikeev et al. 2006). Such fields are important in star formation and the physics of cosmic rays and could also have an effect on galaxy evolution, yet, despite their importance, questions about their origin, evolution and structure remain largely unsolved.

The Square Kilometre Array (SKA) will help us answer questions such as these. The SKA will observe polarized synchrotron emission (Gaensler, Beck & Feretti 2004) and the ‘All-Sky SKA Rotation Measure Survey’ will expand RM data sets by five orders of magnitude, mapping the magnetic fields of galaxies in unprecedented detail (Gaensler 2006; Stepanov et al. 2008). In particular, the SKA will provide data on the evolution of galactic magnetic fields to high redshift (Gaensler 2006), making a theoretical model for this process very valuable. Here we present such a model within the context of hierarchical structure formation.

Our model is based on the observed properties of galactic magnetic fields. Observations and simulations suggest that the random field is generated by turbulence in the ISM, which is modelled as a single-phase magnetohydrodynamical (MHD) fluid, within which magnetic field lines are frozen (e.g. Cho et al. 2009). Simulations have shown that in such a turbulent MHD fluid, the random magnetic field energy and turbulent fluid kinetic energy are approximately equal after a few turnover times (Cho et al. 2009), so by writing an equation for the turbulent energy in the ISM the random magnetic field energy can also be evaluated. The large-scale ordered field is produced by the differential rotation of the galaxy, which winds the random field into a spiral – this is the basic operation of a dynamo. A simple model for this process is postulated. The energy sources which contribute or remove turbulence from the ISM are supernovae (SNe), star formation and accretion of gas from the hot gas halo, and these parameters can be determined from well-established semi-analytic galaxy models, in which galaxies form from gas condensing at the centres of hierarchically merging haloes (White & Rees 1978; Lacey & Silk 1991; Croton et al. 2006). The formation of magnetic fields in galaxies is intimately linked to...
galaxy formation, since the same physical processes are at work in both cases.

Recently, Arshakian et al. (2009) have presented a qualitatively similar model for the evolution of magnetic fields in late-type galaxies. These authors considered three processes. At high redshift, the initial seed field of $\sim 10^{-18} \text{ G}$ is amplified via the Biermann battery mechanism to generate what they refer to as the regular field. This field is rapidly (on eddy turnover time-scale, $\sim 10^9 \text{ yr}$ for the Milky Way) amplified by virialization turbulence. The mean-field galactic dynamo mechanism then amplifies this regular seed field, with a typical e-folding time of $\sim 10^8 \text{ yr}$, until it reaches equilibrium. By contrast, given the short (compared to cosmological) time-scales involved, in our model we simply assume instantaneous equality between the magnetic field energy and turbulent kinetic energy to estimate what we refer to as the random field. This field is then ordered by the mean-scale dynamo on much longer time-scales.

While our treatment of large-scale dynamo generation is simplified compared to that of Arshakian et al., it encapsulates the relevant physics and has the advantage of being simple enough to be included in a cosmological framework. In that sense, this work is highly complementary to the Arshakian et al. (2009) study. We present here the first (to our knowledge) attempt to include magnetic fields in a self-consistent galaxy formation and evolution model. A number of galaxy properties are predicted, and we compare these with available data. This paper primarily focuses on the radio properties of local late-type galaxies.

The paper is organized as follows. In Section 2, we outline the adopted galaxy formation model and develop models for both the random and ordered magnetic fields. Section 3 investigates the salient features of our model and constrains various parameters. Predictions of our model are compared with available observational data in Sections 4 and 5. We summarize our findings in Section 6.

Throughout the paper, we adopt a flat cosmology of $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, $h = 0.7$ and $\sigma_8 = 0.9$, consistent with the 2dF Galaxy Redshift Survey (Colless et al. 2001) and Wilkinson Microwave Anisotropy Probe (Seljak et al. 2005) results.

2 TRACING GALACTIC MAGNETIC FIELDS

2.1 Galaxy evolution model

We employ the analytical galaxy formation and evolution model of Shabala & Alexander (2009). This traces gas cooling, star formation and various feedback processes in a cosmological context. The model simultaneously reproduces the local galaxy properties, star formation history of the Universe, the evolution of the stellar mass function to $z = 1.5$ and the early build-up of massive galaxies. While details can be found in Shabala & Alexander (2009), below we briefly outline those features of the model pertinent to this paper.

The model follows average properties of a galaxy of a given mass at redshift zero. Mass accretion history of the host halo is followed via the formalism introduced by van den Bosch (2002), providing analytical fits to detailed N-body simulations. Following the conventional picture, baryons are assumed to be accreted on to the halo together with the dark matter. Thus, in our model each halo with a given redshift-zero mass can only host one galaxy. Reionization feedback from first generations of structure limits the accreted baryonic fraction. The accreted gas is shocked to the virial temperature and density and cools radiatively. Once cold, the gas is added to the galaxy disc on a dynamical time-scale, where star formation can take place.

These cooling processes complete with various modes of feedback. Stars more massive than $8M_\odot$ inject SN shocks into the surrounding gas as they expire; this type of feedback is important in low- and intermediate-mass galaxies. Gas cooling also fuels intermittent active galactic nucleus (AGN) activity, which becomes important in haloes more massive than $10^{12}M_\odot$.

Such detailed treatment of the gas heating and cooling processes as well as star formation in an analytical framework makes this model ideal for following the cosmological evolution of galactic magnetic fields, as we outline below.

2.2 Magnetic fields in galaxy discs

Observations of spiral galaxies, for instance using Faraday RM, have indicated the presence of random and ordered magnetic fields, of magnitudes of a few $\mu G$ (e.g. Stepanov et al. 2008). The random fields are coherent on small scales, of the order of parsec. The ordered fields are coherent on much larger scales and are observed to follow the spiral arms of the galaxy. In this section, we describe how we model both types of field and show how the random and ordered fields are linked by the differential rotation of the galaxy.

Simulations of a turbulent MHD fluid suggest that random magnetic fields can be generated within such fluids via turbulence (Kulsrud et al. 1997; Cho & Vishniac 2000; Cho et al. 2009). These simulations have shown that in such a turbulent MHD fluid, equality between random magnetic field energy and turbulent fluid kinetic energy is reached after several turnover times. This result forms the basis for our model of random magnetic fields in galaxies. We then model the formation of the large-scale ordered field by a simplified model based on the differential rotation of the galaxy.

The mechanism by which turbulence generates a microgauss random magnetic field is field line stretching. The turbulent fluid motions draw out field lines, and thus, in ideal MHD, the field strength along that direction must increase. This increases magnetic pressure, which opposes the stretching process. On a time-scale of several eddy turnover times, this build-up in magnetic pressure suppresses further field line stretching, and the process ceases when the random magnetic field energy is equal to the energy in turbulence of the fluid (Cho & Vishniac 2000).

Whilst the random field can be accounted for through turbulence in the ISM, a mechanism for generating the ordered field must invoke the differential rotation of the galaxy. The galactic dynamo theory is commonly used to explain the presence of large-scale coherent ordered magnetic fields in spiral galaxies (e.g. Ruzmaikin, Sokoloff & Shukurov 1998). In dynamo theory, a radial magnetic field is wound into a toroidal field, and amplified, via the differential rotation of the galaxy. In addition to this so-called $\alpha$-effect, a further process exists whereby a toroidal field is transformed into a radial field – this is known as the ‘$\Omega$-effect’ (Parker 1955). Arshakian et al. (2009) have presented detailed calculations of these processes. In this paper, a simpler model for the generation of an ordered field is used. The generation of magnetic fields is broken up into a two-step process. In the first step, the turbulence in the ISM stretches and amplifies the random magnetic field. In the second step, differential rotation winds the random field to create an ordered field. Such a division is physically motivated by the relevant time-scales for the two steps. The random field is amplified on a time-scale comparable to the eddy turnover time. This scale is much shorter than the characteristic time-scale for ordered field generation, the galactic rotational period. In other words, it is a good approximation to treat the random field energy as amplified to a point at which it is equal to half the energy in turbulence, before allowing this random field energy to act as a seed for the ordered field.
to be converted into an ordered field by the large-scale differential rotation. Such an approach has the advantage of being simple while capturing the relevant physics, and therefore can be implemented in a self-consistent galaxy formation and evolution model.

The ordering of the magnetic field, performed by the mean-scale dynamo, is a much slower process. Arshakian et al. find the relevant time-scale to be proportional to disc size. By contrast, in our approximation the $e$-folding time for this process is simply related to the angular rotation velocity of the galaxy, and is thus constant at a given redshift. It is worth pointing out that the two time-scales are similar: Arshakian et al. (their equation 7) give the ordering time-scale $t_{ord} = \frac{10}{\Omega} \frac{\tau}{4}$, where the ratio of the disc scaleheight to turbulence length-scale is $\frac{h}{k} \approx 5$, and the angular velocity $\Omega$ of the galaxy can be expressed in terms of the rotation period $t_{rot}$. Therefore, their $t_{ord}$ is very close to our assumed rotation time-scale $t_{rot}$.

### 2.2.1 Random fields

As discussed above, since the turnover time-scale of turbulent eddies is much less than cosmological time-scales, the equality between random magnetic field energy and turbulent kinetic energy is assumed to hold instantaneously, at the point of energy injection. In the absence of an ordered field, the instantaneous equality between random magnetic field energy and turbulent energy demands that half the energy injected into the ISM goes into turbulent fluid motion and the other half into random magnetic field energy. The processes that inject and remove energy from the ISM will now be considered.

One of the most important sources of energy injection into the ISM are SNe. They inject energy at a rate $\Psi_{SF} \epsilon_{SN}$, where $\Psi_{SF}$ is the star formation rate in $M_{\odot} \text{yr}^{-1}$ and $\epsilon_{SN}$ is the energy released by SNe per solar mass of star formation. The quantity $\epsilon_{SN}$ can be estimated as follows. Assume the minimum stellar mass to be $0.1 M_{\odot}$, and taking all stars with masses greater than $8 M_{\odot}$ to terminate as SNe, the SN rate $R_{SN}$ can be related to the star formation rate by

$$R_{SN} = \Psi_{SF} \int_{0}^{\infty} \phi(M) dM$$

where we have assumed a Salpeter initial mass function $\phi(M) \propto M^{-2.35}$.

If each SN injects energy $E_{K}$ into the ISM,

$$\epsilon_{SN} = \frac{R_{SN} E_{K}}{\Psi_{SF}}$$

If $E_{K} \sim 10^{44}$ J, approximately the kinetic energy of the SN envelope, then $\epsilon_{SN} \sim 10^{46} \text{J} M_{\odot}^{-1}$.

Star formation removes turbulent energy. If $E_{\text{turb}}$ is the turbulent ISM energy, and $M_{\text{cool}}$ the mass of cold gas in the galaxy, the turbulent energy removed by the formation of a star of mass $M_{*}$ is $\frac{M_{*}}{M_{\text{cool}}}$ $E_{\text{turb}}$ (i.e. the fraction of total gas mass removed by star formation, multiplied by the turbulent energy). So the rate at which energy is removed by star formation is $\frac{\Psi_{SF} M_{\odot}}{\Psi_{SF}} E_{\text{turb}}$.

Gas accreting from the dark matter halo deposits its potential energy in turbulence. If a gas packet of mass $M_{\text{cool}}$ falls on to the galactic disc from a radius $r$, it adds energy $\int_{r}^{\infty} \frac{GM(<r) M_{\text{cool}}}{r^{2}} dr$ to the cold gas in the disc; we will assume that all this energy goes into turbulence. If we sum over all such gas packets, and then differentiate with respect to time, we find that the energy injection rate from accretion is $\Sigma \int_{r}^{\infty} \frac{GM(<r) M_{\text{cool}}}{r^{2}} dr$.

The total rate at which energy is injected into turbulence is equal to the sum of the three rates above. In front of each term in the equation, we add factors which reflect the efficiency with which energy is added to or removed from the ISM by a particular process. For the accretion this factor is labelled $\epsilon_{\text{acc}}$, for SNe feedback $\epsilon_{\text{SN}}$, and for star formation $\epsilon_{\text{SF}}$. Half of the energy injected into the ISM goes into turbulent motions of the fluid and the other half into the random magnetic field energy $E_{\text{B}}$, so the equation for the evolution of the random field energy in the absence of differential galactic rotation is

$$\frac{dE_{\text{B}}}{dt} = \frac{1}{2} \left[ \epsilon_{\text{SN}} \Psi_{SF} \epsilon_{SN} - \epsilon_{\text{SF}} \frac{E_{\text{turb}}}{M_{\text{cool}}} \Psi_{SF} + \epsilon_{\text{acc}} \right] \left[ \int_{r}^{\infty} \frac{GM(<r) M_{\text{cool}}}{r^{2}} dr \right]$$

where the sum is over the gas parcels cooling at the time-step of interest. Here, $\Psi_{SF}, M_{\text{cool}}$ and $M_{\text{cool}}$ are calculated self-consistently from the galaxy formation model. Note that in the absence of rotation (i.e. when the whole field is in the random component), we have $\frac{dE_{\text{B}}}{dt} = \frac{dE_{\text{turb}}}{dt}$.

### 2.2.2 Ordered fields

As discussed above, we assume that the ordered field is created through galactic differential rotation. If at time $t = 0$ the energy in the random field is $E_{\text{B}}$, assuming that there is no further energy injection, the energy in the ordered field at time $t$, $E_{\text{B}}(t)$, is

$$E_{\text{B}}(t) = E_{\text{B}}(0) \left( 1 - e^{-t/t_{\text{ord}}} \right)$$

where the time-scale for energy transfer from the random to ordered field is $t_{\text{ord}}$. We expect $t_{\text{ord}}$ to be comparable with $t_{\text{rot}}$, the rotational period of the galaxy, and therefore we set $t_{\text{ord}} = t_{\text{rot}}$.

In reality, energy is constantly injected into the ISM (by the processes considered above). Therefore, we must extend the above calculation to determine how the energy in the ordered magnetic field varies when energy is continually injected to the random magnetic field. Let the random field energy be $E_{\text{B}}(t)$ at time $t$. At $t + \Delta t$, the energy is $E_{\text{B}}(t + \Delta t) = E_{\text{B}}(t) + \frac{dE_{\text{B}}}{dt} \Delta t$. Thus, $(\frac{dE_{\text{B}}}{dt}) \Delta t$ has been added to the random field energy in the infinitesimal time interval $\Delta t$. For $\frac{dE_{\text{B}}}{dt} < 0$, the ordered field is assumed not to change – if the random energy declines there is no physical reason for the ordered field energy to decline also. If $\frac{dE_{\text{B}}}{dt} > 0$, using equation (4), the ordered field energy at time $t_{0}$ due to the random field energy added in the time interval $[t, t + \Delta t]$ is

$$\Delta E_{\text{B}}(t_{0}) = \left( \frac{dE_{\text{B}}(t)}{dt} \right) \Delta t \left( 1 - e^{-t_{0}/t_{\text{ord}}} \right)$$

The total energy in the ordered field can now be obtained by adding all contributions,

$$E_{\text{B, ordered}}(t_{0}) = \int_{0}^{t_{0}} \left( \frac{dE_{\text{B}}(t)}{dt} \right) f (t/t_{\text{ord}}) dt$$

where

$$f (t/t_{\text{ord}}) = \begin{cases} 1 - e^{-t/t_{\text{ord}}} & \text{for } \frac{dE_{\text{B}}}{dt} > 0 \\ 0 & \text{for } \frac{dE_{\text{B}}}{dt} \leq 0 \end{cases}$$

Equation (3) for the random field energy holds with an extra loss term included to reflect the fact that random field energy is

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continuously being converted into ordered field energy. The final equations for the evolution of the magnetic field energies are

\[
\frac{dE_{\text{ord}}^{\text{d}}}{dt} = \frac{dE_{\text{ord}}^{\text{d}}}{dt} f(t/t_{\text{rot}})
\]

\[
\frac{dE_{\text{ord}}^{\text{d}}}{dt} = \frac{1}{2} \frac{dE_{\text{ord}}^{\text{d}}}{dt} - \frac{dE_{\text{ord}}^{\text{d}}}{dt}.
\]

### 3 PRELIMINARY RESULTS

There are four free parameters in the model. Three parameters describe the efficiency with which turbulence is added/removed from the cold gas by gravitational infall (\(\epsilon_{\text{grav}}\)), SNe feedback (\(\epsilon_{\text{SNe}}\)) and star formation (\(\epsilon_{\text{SF}}\)). These determine the total magnetic field strength. The fourth parameter is a time-scale related to the rate at which the random magnetic field is transferred to the ordered field, \(\tau_{\text{edd}}\), which in the previous section we have set to the rotation period of the galaxy.

We set \(\epsilon_{\text{SF}} = 1\), as physically one would expect all turbulent energy associated with the cold gas to be removed once the gas turns into stars. Fig. 1 shows the interplay between the three mechanisms with this value fixed for a range of halo masses. Shabala & Alexander (2009) estimate that about 1 per cent of SNe energy must go towards heating and ejecting galactic gas in order to reproduce the low-mass end of the present-day stellar mass function. We therefore expect \(\epsilon_{\text{SNe}}\) to be of this order, i.e. \(\epsilon_{\text{SNe}} \sim 0.01\). Fig. 1 shows that in this case gravitational infall and star formation dominate SNe feedback, and thus the exact value of \(\epsilon_{\text{SNe}}\) is unimportant. We thus set \(\epsilon_{\text{SNe}} = 0.01\).

As halo mass increases, so do the contributions to turbulence from gas cooling and the removal of turbulence due to star formation. In low-mass haloes \((M_{\text{halo}} \lesssim 10^{12} M_\odot)\) at the present epoch, as halo mass increases, more turbulence is added through gas cooling than is removed by star formation. While significant amounts of gas can cool, an increase in the size of the galaxy disc means that the gas surface density drops, and thus star formation is less efficient. As a result, the magnetic field strength increases with mass (Fig. 2).

The turbulent energy density and magnetic field strength peak at \(M_{\text{halo}} \sim 10^{13} M_\odot\). At these masses, both SNe and AGN feedback are too weak to quench large amounts of gas cooling. Massive haloes are more likely to host powerful AGNs (Shabala et al. 2008), and thus in higher mass haloes (Figs 1g and h) AGN feedback truncates gas cooling and star formation at early epochs, with the turbulent energy density remaining unchanged since \(z \sim 1\). Because the gas cooling time increases with decreasing density, powerful AGNs in massive hosts play a more important role in quenching gas cooling and star formation than do their lower power counterparts in less massive haloes. In the most massive haloes \((M_{\text{halo}} > 10^{15} M_\odot)\) AGN feedback cannot completely quench gas cooling, and thus the magnetic field strength begins to increase once again.

The average magnetic field strength \(B\) in a galactic disc is a function of the turbulent energy density. Thus, apart from the amount of turbulence present, another important parameter is the size of the disc. In the following section, we use observations of local galaxies to constrain disc sizes and consequently find the value of \(\epsilon_{\text{grav}} \sim 0.003\). This is the value adopted for the rest of the paper.

Fig. 3 shows the evolution of the magnetic field for each of these haloes. The volume of the radio disc used to calculate magnetic field strengths was taken as \(\pi R_{\text{disc}}^2 T_{\text{disc}}\), where the disc radius is \(R_{\text{disc}} = 0.1R_{\text{eff}}\) (Shabala & Alexander 2009), and we adopt a disc thickness of \(T_{\text{disc}} = 0.6\text{kpc}\) (Fitt & Alexander 1993). In practice, disc radii derived from radio observations are subject to selection effects. We return to this point in the following section. Key features of the model are evident in Fig. 3. In low-mass haloes, interplay between the infall of cool gas and star formation results in substantial contributions to the turbulent energy budget right up to \(z = 0\) (Fig. 1). As a result, the bulk of the turbulent (and hence the magnetic field) energy density is in the random component. As halo mass increases, so does the strength of AGN feedback. Consequently, the most massive galaxies (Fig. 3d) are red and dead, with the bulk of the cooling and star formation taking place at \(z \geq 1\). Thus, by \(z = 0\) a greater fraction of the turbulent energy has had time to be transferred to the ordered field than in their lower mass counterparts.

### 4 MAGNETIC FIELDS IN GALAXY DISCS

#### 4.1 Disc sizes

So far, we have assumed that radio emission is uniform across the disc. Contrary to the assumptions used to plot Figs 2 and 3, in real discs the emissivity typically decays exponentially away from the disc centre (Fremantle 1970). As a result, essentially all the source flux is observed within a few scaleheights, while the observed radial extent of the disc will be greatly affected by selection effects such as the limiting beam-averaged surface brightness. In general, it is difficult to quantify these effects, and we choose to parametrize the size of the radio disc via the quantity \(\epsilon_{\text{disc}}\), such that \(R_{\text{disc,radio}} = \epsilon_{\text{disc}} R_{\text{disc}}\).

Fig. 4 compares predicted disc sizes with observations of late-type galaxies from the sample of Fitt & Alexander (1993). These authors considered radio properties of an optically complete subsample of 165 late-type galaxies brighter than magnitude \(B_T = +12\), drawn from the Revised Shapley Ames (RSA) Catalogue (Sandage & Tammann 1981). These were complemented by Very Large Array (VLA) observations at 1.49 GHz (Condon 1987), yielding an optically complete sample of 146 galaxies with resolved radio discs. Of the remaining 19 galaxies, one had unresolved radio structure, eight more had no radio detections and the remainder suffered from confusion or were not properly imaged by the observations.

Stellar masses in Fig. 4 and the subsequent discussion were derived from \(K\)-band magnitudes under the assumption that all stars are of solar type (Nikolic, Cullen & Alexander 2004; Shabala et al. 2008). Comparison of predicted and observed disc sizes shows that setting \(\epsilon_{\text{disc}} = 0.25\) gives good agreement with observations. It is worth noting that since smaller discs are associated with higher turbulent energy densities (for fixed total turbulent energy), greater magnetic field strengths are predicted for these.

#### 4.2 Magnetic field strengths

Fitt & Alexander (1993) used the observed angular sizes of the radio disc to derive equipartition magnetic field strengths. They modelled the synchrotron disc in each galaxy as having the radius given by imaging the galaxy at 1.49 GHz and took an equivalent disc width of 0.6 kpc. This is the disc thickness we adopt for the rest of this paper. With disc volume fixed, magnetic field strength is a function of a single parameter \(\epsilon_{\text{grav}}\), parametrizing the efficiency with which the potential energy of infalling cold gas is converted to turbulent energy. The predicted and observed magnetic field strengths are
Figure 1. Total turbulent energy in the cold gas. Left-hand panels: $\epsilon_{\text{grav}} = 0.003$. Right-hand panels: $\epsilon_{\text{grav}} = 0.001$. All curves are for $\epsilon_{\text{SNe}} = 0.01$ and $\epsilon_{\text{SF}} = 1$. Star formation and cold gas infall dominate the SNe feedback contribution to turbulence. In high-mass haloes, early truncation (at $z \sim 1$) of gas cooling, followed after a time lag by a truncation in star formation, results in the spike in, and the eventual flattening of, the turbulent energy curve.

shown as a function of stellar mass for different values of $\epsilon_{\text{grav}}$ in Fig. 5.

VLA sensitivity sets a limit on the strength of the weakest detectable magnetic field in the Fitt & Alexander (1993) sample. This is given by (see their equation 2)

$$B_{\min} = \frac{384}{\mu G} \left( \frac{\sum_{\text{min}}}{\text{Jy} \left( \theta_{\text{FWHM}}/2 \text{arcsec} \right)^{-2}} \right)^{2/7}$$

(10)

where the coefficient is different to the Fitt & Alexander value due to their assumption of cosmic-ray energy densities being negligible.
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Figure 2. Magnetic field strength at the present epoch as a function of halo mass for $\epsilon_{\text{grav}} = 0.003$ (solid line), $\epsilon_{\text{grav}} = 0.01$ (dashed line) and $\epsilon_{\text{grav}} = 0.001$ (dotted line). All models have $\epsilon_{\text{SF}} = 1$, $\epsilon_{\text{SNe}} = 0.01$.

$(n_p \sim 0)$. By contrast, we assume a ratio of proton to electron energy densities of $n_p = 100$ that is typical for our Galaxy (e.g. Longair 1994 and references therein), yielding an extra factor of 3.7. The beam full width at half-maximum (FWHM) is $\theta_{\text{FWHM}} \sim 1$ arcmin and the limiting surface brightness is $\Sigma_{\text{min}} = 0.35$ mJy. This yields $B_{\text{min}} = 5.7 \, \mu\text{G}$.

Figure 3. Contributions to the total magnetic field (solid lines) from the random (dotted line) and ordered (dashed line) components as a function of halo mass. All models have $\epsilon_{\text{SF}} = 1$, $\epsilon_{\text{SNe}} = 0.01$, $\epsilon_{\text{grav}} = 0.003$.

Figure 4. Distribution of radio disc sizes as a function of stellar mass. Curves are for models with $\epsilon_{\text{disc}} = 0.06$ (long-dashed), 0.25 (solid), 0.40 (short-dashed) and 1.0 (dotted). Data points are from Fitt & Alexander (1993).

Fig. 6 plots the distribution of magnetic field strengths. These were obtained by binning the Fitt & Alexander galaxies in stellar mass and convolving this distribution with the results of Fig. 5. Our model (left-hand panel in Fig. 6) provides a good match to the data at low and intermediate magnetic field strengths, corresponding to low- and intermediate-mass galaxies, respectively. The model overpredicts the counts at the bright end, primarily due to the expected...
peak in $B$ at $M* \sim 2 \times 10^{11} \text{M}_\odot$ (Fig. 5). A model with $\epsilon_{grav}$ being a factor of 3 higher than in our best-fitting model is included for comparison (right-hand panel in Fig. 6). Counts at low values of $B$ are significantly underpredicted, consistent with this model predicting higher values of $B$ at a given stellar mass than found by Fitt & Alexander (Fig. 5).

5 LOCAL RADIO LUMINOSITY FUNCTION IN LATE-TYPE GALAXIES

5.1 Synchrotron luminosity

Synchrotron luminosity is the most straightforward observational manifestation of magnetic fields. Following Longair (1994), assuming equipartition this luminosity is given by

$$L_{\text{sync}} = \frac{2}{3 \mu_0} \frac{B^{7/2}}{G(\alpha) \eta_p},$$

where $V$ is the volume of the emitting region and $\eta_p$ the ratio of proton to electron energy densities. Consistent with observations of our Galaxy (Longair 1994, and references therein), we adopt $\eta_p = 100$. The constant $G(\alpha)$ depends weakly on spectral index $\alpha$ and the minimum and maximum energy cut-offs $v_{\text{min}}$ and $v_{\text{max}}$, respectively. For an electron power-law distribution $N(E) \propto E^{-p}$ where $p = 2.5$, we have $\alpha = (p - 1)/2 = 0.75$. Adopting $v_{\text{min}} = 10 \text{MHz}$, we have (Longair 1994)

$$G(\alpha) = 4.15 \times 10^{11} \left( \frac{\nu}{\text{GHz}} \right)^{0.75}. \tag{12}$$

5.2 Radio luminosities

The Fitt & Alexander (1993) sample used in the preceding section is representative, but by no means complete. Using radio luminosity as a proxy for magnetic field strength allows us to use a complete (in both optical and radio) sample of Shabala et al. (2008). Synchrotron luminosity for late-type galaxies in the sample is plotted as a function of stellar mass in Fig. 7. Here, late-type galaxies are defined as galaxies with concentration indices in the Petrosian $r$ band of $C > 0.375$. Stellar masses were obtained from $z$-band magnitudes by assuming solar-type stars (Nikolic et al. 2004; Shabala et al. 2008).

Given a disc size (i.e. the parameter $\epsilon_{\text{disc}}$, set to 0.25 in Section 4.1), the model predicts a single radio luminosity for each halo and hence a given stellar mass. Fig. 7 shows that these agree well with mean observed luminosities at low stellar masses. However, at higher masses the radio luminosity is overpredicted. The radio-loud galaxies in the flux-limited sample of Shabala et al. make up the bright tail of the radio luminosity distribution. The majority of galaxies have radio luminosities below the detection limit, and thus the mean radio luminosity at a given stellar mass was calculated by assuming a Gaussian distribution with the observed scatter of 0.3 dex. By contrast, the Fitt & Alexander observations were performed with much greater sensitivity, and thus no such corrections are necessary.

The peak radio luminosity in Fig. 7 corresponds to the $B$-field peak in Fig. 2 and is related to an increase in gas cooling (and hence the random component of the magnetic field) at late times in haloes with $M_{\text{halo}} \sim 10^{13} \text{M}_\odot$ (Figs 1e and f, and 3c). This late cooling is a result of the way AGN feedback is implemented in our model. In haloes more massive than $\sim 10^{12} \text{M}_\odot$, SNe feedback is too weak to quench gas cooling and star formation. AGN heating can in principle do this; however, only the dense central regions can be heated by weak AGNs found in haloes with a mass of $\leq 10^{11} \text{M}_\odot$. These cores have short cooling times, and thus the net effect of AGN heating is
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5.3 Radio luminosity function

The stellar mass function for local late-type galaxies was constructed from the Shabala et al. sample. This stellar mass function was then converted into a halo mass function for late-type galaxies by using the best-fitting model of Shabala & Alexander (2009). The radio luminosity function can then be constructed from the halo mass function and predictions for individual haloes (Fig. 7).

The resultant radio luminosity function is shown in Fig. 8. As in Fig. 7, the number of bright sources is vastly overpredicted. Decreasing the amount of cold gas by a factor of ~10 reconciles the model with observations, suggesting that outward gas transport by powerful radio sources is important to the evolution of galactic magnetic fields. Observationally, it should be possible to distinguish between the gas heating and ejection scenarios through use of X-ray data. Frequent AGN heating and subsequent cooling (due to short cooling times) in dense central regions would manifest themselves in copious amounts of X-ray emission. By contrast, gas transport to large radii would simply suppress cooling and thus not give rise to any appreciable X-ray signatures.

6 SUMMARY

We have developed an analytical model to follow the cosmological evolution of magnetic fields in disc galaxies. This is done by assuming equality between the magnetic field energy density and the turbulent energy density in cold disc gas. The gas cooling and star formation histories are followed using the Shabala & Alexander (2009) galaxy evolution model, which includes a physically motivated prescription for AGN feedback, together with SNe and reionization feedback. The model successfully reproduces the observed stellar mass functions and shutdown of star formation in massive galaxies out to redshifts of 1.5.
Three mechanisms alter the turbulent energy budget in the cold gas. Star formation removes turbulence associated with gas parcels that collapse to form the stars. The turbulence is increased by gravitational infall of cool gas on to the disc and also by high-mass stars driving shocks through the ISM as they end their lives in SNe explosions. Two types of magnetic fields are identified: the random field, which is incoherent on scales comparable with the turbulent eddy scale, and the ordered field, generated from the random field by differential rotation of the galaxy.

Two local samples are used to test the models. The model reproduces magnetic field strengths and radio luminosities well across a wide range of low- and intermediate-mass galaxies. However, the radio luminosities and magnetic field strengths are overpredicted significantly in high-mass galaxies due to an overprediction in the amount of gas cooling. Inclusion of outward gas transport by powerful radio sources is required to reconcile the model with observations.

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REFERENCES

Alexander P., 2002, MNRAS, 335, 610
Arshakian T. G., Beck R., Krause M., Sokoloff D., 2009, A&A, 494, 21
Basson J. F., Alexander P., 2003, MNRAS, 339, 353
Cho J., Vishniac E. T., 2000, ApJ, 538, 217
Cho J., Vishniac E. T., Beresnyak A., Lazarian A., Ryu D., 2009, ApJ, 693, 1449
Colless M. et al., 2001, MNRAS, 328, 1039
Condon J. J., 1987, ApJS, 65, 485
Croton D. J. et al., 2006, MNRAS, 365, 11
Fitt A. J., Alexander P., 1993, MNRAS, 261, 445
Freeman K. C., 1970, ApJ, 160, 811
Gaensler B. M., 2006, Astron. Nachr., 327, 387
Gaensler B. M., Beck R., Feretti L., 2004, New Astron. Rev., 48, 1003
Kulsrud R. M., Cen R., Ostriker J. P., Ryu D., 1997, ApJ, 480, 481
Lacey C., Silk J., 1991, ApJ, 381, 14
Longair M. S., 1994, High Energy Astrophysics. Cambridge Univ. Press, Cambridge
Nikolic B., Cullen H., Alexander P., 2004, MNRAS, 355, 874
Parker E. N., 1955, ApJ, 122, 293
Patrikeev I., Fletcher A., Stepanov R., Beck R., Berkhuijsen E. M., Frick P., Horellou C., 2006, A&A, 458, 441
Ruzmaikin A., Sokoloff D., Shukurov A., 1998, Nat, 336, 341
Sandage A., Tammann G. A., 1981, Revised Shapley-Ames Catalog of Bright Galaxies. Carnegie Institute of Washington
Seljak U. et al., 2005, Phys. Rev. D, 71, 103515
Shabala S. S., Alexander P., 2009, ApJ, 699, 525
Shabala S. S., Ash S. A., Alexander P., Riley J. M., 2008, MNRAS, 388, 625
Stepanov R., Arshakian T. G., Beck R., Frick P., Krause M., 2008, A&A, 480, 45
van den Bosch F. C., 2002, MNRAS, 331, 98
White S. D. M., Rees M. J., 1978, MNRAS, 183, 341
Zwaan M. A. et al., 2003, AJ, 125, 2842

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