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Magnetic fields near the peripheries of galactic discs

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ABSTRACT

Context. Magnetic fields are observed beyond the peripheries of optically detected galactic discs, while numerical models of their origin and the typical magnitudes are still absent. Previously, studies of galactic dynamo have avoided considering the peripheries of galactic discs because of the very limited (though gradually growing) knowledge about the local properties of the interstellar medium.
Aims. Here we investigate the possibility that magnetic fields can be generated in the outskirts of discs, taking the Milky Way as an example.
Methods. We consider a simple evolving galactic dynamo model in the "no-z" formulation, applicable to peripheral regions of galaxies, for various assumptions about the radial and vertical profiles of the ionized gas disc.
Results. The magnetic field may grow as galaxies evolve, even in the more remote parts of the galactic disc, out to radii of 15 to 30 kpc, becoming substantial after times of about 10 Gyr. This result depends weakly on the adopted distributions of the half thickness and surface density of the ionized gas component. The model is robust to changes in the amplitude of the initial field and the position of its maximum strength. The magnetic field in the remote parts of the galactic disc could be generated in situ from a seed field by local dynamo action. Another possibility is field production in the central regions of a galaxy, followed by transport to the disc's periphery by the joint action of the dynamo and turbulent diffusivity.
Conclusions. Our results demonstrate the possibilities for the appearance and strengthening of magnetic fields at the peripheries of disc galaxies and emphasize the need for observational tests with new and anticipated radio telescopes (LOFAR, MWA, and SKA).

Key words. dynamo – ISM: magnetic fields – Galaxy: disk – galaxies: magnetic fields – galaxies: spiral

1. Introduction

Magnetic fields in spiral galaxies are relatively well understood observationally and theoretically, at least in several nearby galaxies (e.g. Donner & Brandenburg 1990; Subramanian & Mestel 1993; Beck & Wielebinski 2013; Gressel et al. 2013; Siejkowski et al. 2014; Brandenburg 2014). However, attention in such studies has been focussed on galactocentric distances up to about 10 kpc, sometimes to 15 kpc, as in the galaxy M 31 where magnetic fields are particularly pronounced. Polarized radio synchrotron emission and its Faraday rotation show that the regular magnetic fields in this radial range have a spiral form and, in a number of galaxies, are organized into magnetic arms that may be situated between material arms, as in e.g. NGC 6946 (Beck 2007; Chamandy et al. 2013; Moss et al. 2013). The typical strength of the regular magnetic field is several μG, and the strengths of magnetic fluctuations are comparable to those of the regular field.

Regular magnetic fields generated by differential rotation and mirror asymmetric interstellar turbulence, the mean-field dynamo[1], clearly become weaker at large galactocentric radii, and the polarized radio emission that traces the regular magnetic field also decreases towards the galactic periphery. On the other hand, no sharp radial boundary of the distributions of the relevant physical quantities is reported. Many papers on the topic (e.g. Moss et al. 1998) imply that a significant magnetic field may exist beyond 10 kpc, because the stellar discs of galaxies (and, indeed, their gaseous discs) can be traced far beyond the usually adopted optical radius (usually taken as the radius R_{25} within the isophote of 25th B-magnitude per square arcsec, see Gentile et al. 2007; Hunter et al. 2011; Holwerda et al. 2012).

We believe that the idea that discs of spiral galaxies can contain, at substantial galactocentric distances ($r > 10$ kpc), a regular magnetic field that is weaker than the field at $r < 10$ kpc, but still not negligible and possibly dynamically important, has now become an attractive topic for two reasons. Firstly, recent observations have revealed that the peripheries of galactic discs possess pronounced structures. In many cases spiral-like features are observed in the UV range beyond the main disc of a galaxy and reveal continuing star formation, although with low efficiency (see Bigiel et al. 2010, and references therein). Another type of outer structure is connected with the gaseous tidal tails of interacting galaxies – weak star formation may also take place there, in spite of the extremely low mean gas density (Smith et al. 2010).

Although we may assume that the influence of star formation on the dynamo mechanism may not be very significant (Mikhailov et al. 2012), the presence of young, massive stars provides the ionized gas layer that is necessary for magnetic field generation. In addition, the magnetic field plays an active role in the process of star formation both on large scales

[1] The mean-field dynamo generates *regular* fields with coherent direction. The magnetic fields traced by polarized emission can in fact be regular or *anisotropic turbulent*, generated from isotropic turbulent fields by compression or shear. For the sake of simplicity, the latter field component is neglected throughout this paper.

(e.g. via the Parker instability) and small scales (braking of molecular cloud rotation or resistance to gravitational compression of a cloud). The process of star formation in the rarefied gas in the disc periphery, although not well understood yet, can therefore be expected to be different in the presence or absence of magnetic fields. In some cases non-thermal radio emission is observed that is clearly connected with tidal features beyond the main bodies of galaxies, such as M 51 (Fletcher et al. 2011) and NGC 4038/39 (Chyży & Beck 2004). This provides direct evidence that non-trivial magnetic fields really exist at the peripheries of discs, playing a significant role in the process of forming of the outer structures and in star-forming activity in the more rarefied regions of galaxies. Moreover, it cannot be excluded that these magnetic fields may influence gas dynamics and, when strong enough, explain the distorted rotation curves measured from gas velocities (Ruiz-Granados et al. 2012; Jałocha et al. 2012).

Another indication of the presence of extended magnetic fields in the outer disc comes from the large radial scalelength of synchrotron emission, of about 4 kpc, in many galaxies (Basu & Roy 2013), e.g. in NGC 6946 (Beck 2007). In the case of energy equipartition between cosmic rays and total magnetic fields, the exponential scalelength of the magnetic field is about four times greater than that of the synchrotron emission, i.e. about 16 kpc, and thus may extend far into intergalactic space (Beck 2007, see also e.g. Lacki & Beck 2013, for discussions about constraints for equipartition).

Neronov & Semikoz (2009) and Neronov & Vovk (2009), from Fermi observations of blazars in the TeV range, claim that the regular magnetic field strength in the intergalactic medium is between 10^{-16} and 10^{-9} μG. Mean-field dynamos cannot excite regular magnetic fields in intergalactic space in the absence of differential rotation[2]. Magnetic field transport from galaxies and other objects within galaxies (for example, active galactic nuclei) is a possibility for explaining this finding. The presence of a magnetic field that is relatively weak on galactic scales, but much stronger than assumed in intergalactic space, would help in such a scenario.

A contemporary observational perspective also looks promising for studies of galactic magnetic fields on the peripheries of galactic discs. The point is that the key observations of magnetic fields at $r \leq 10$ kpc have been performed for wavelengths $\lambda \leq 20$ cm. Modern radio telescopes are designed to also work at longer wavelengths of $\lambda \approx 1-10$ m. In this wavelength range, observations of regular magnetic fields at moderate galactocentric distances ($r < 10$ kpc) are strongly hampered by Faraday depolarization, while the search for weak magnetic fields at $r > 10$ kpc is a suitable task for these telescopes. Of course, such investigations require very high sensitivity.

Previously, dynamo models (e.g. Beck et al. 1996; Moss et al. 2012) did not pay significant attention to the remote parts of galactic discs, mainly because of the lack of knowledge of the physical properties of the interstellar medium there. The ideas available have remained limited until recently, but now sufficient data have been accumulated to initiate such a discussion. In principle, the problem could be addressed by various types of galactic dynamo models. We choose a relatively recent approach (known as the no-z model, see below), which allows us to consider magnetic field evolution in a fairly simple form that is nonetheless sufficient for our limited knowledge of hydrodynamics in the remote parts of galactic discs. In the no-z formulation, vertical diffusion is to some extent parametrized, whereas radial diffusion (which helps by transporting field outwards in the disc) is explicitly represented.

The aim of this paper is to discuss, for model galaxies similar in general to the Milky Way, the galactocentric distance out to which a substantial regular magnetic field might be expected. The paper is organized as follows. Firstly (Sects. 2 and 3), we summarize the observational data and their theoretical consequences for the parameters, relevant to galactic dynamos, of the shape and hydrodynamics of the remote regions of galactic discs. In Sect. 4 we consider a simple galactic dynamo model applicable to the galactic periphery based on these governing parameters, in order to obtain magnetic field distributions in the outer regions. In Sect. 5 our results are discussed.

The main finding here is that excitation of magnetic fields in a radial range out to 20–25 kpc is possible, while interstellar turbulence and differential rotation can in principle maintain a regular field at even greater galactocentric distances. This result seems quite robust under changes in models for the underlying disc structure. In Sect. 5.1 the propagation of magnetic wave fronts is described: such fronts can also produce regular magnetic fields in the outer disc regions. In Sect. 6 we discuss possible observational tests for the presence of magnetic fields in peripheral regions of galactic discs and give some limitations on the possibilities of detecting them.

2. Observations of ionized gas components

For the dynamo mechanism to be efficient, a layer of ionized or partially ionized gas tied to the magnetic field is needed. Such a medium exists in real galaxies and consists of two components: (1) Cool HI layer (clouds and intercloud medium) partially ionized by soft cosmic rays and soft X-rays. The ionization of intercloud HI is about 14% (see e.g. Berkhuijsen et al. 2006; Berkhuijsen & Müller 2008). A neutral component is tightly coupled to the magnetic field due to collisions between neutral and ionized atoms. (2) It also contains a diffuse warm ionized medium (WIM) that is mostly identified from optical recombination lines and pulsar dispersion measures (DMs). Its ionization is supported by ionizing photons that escape from the sites of star formation, and partially also from pre-white dwarfs (see Ferrière 2001; and Haffner et al. 2009, for reviews).

Observations give direct information concerning only the WIM parameters in the vicinity of Sun ($R_\odot \approx 8.5$ kpc), based on pulsar DMs and Hα emission. The averaged volume density of the WIM and its half thickness obtained by different authors lie in the ranges 0.015–0.03 cm^{-3} and 700−1800 pc, respectively (see Berkhuijsen et al. 2006; Gaensler et al. 2008; Schnitzeler 2012, and references therein). The thickness of the WIM layer exceeds what is expected for a layer in hydrostatic equilibrium with the observed temperature, presumably because of random (turbulent) gas motions. The latter may be characterized by a turbulent velocity (which we identify in the framework of this paper with the speed of sound) that is higher than the usual speed of sound in a thermal plasma. The vertical profile of the WIM found from the pulsar DMs is rather shallow, which may partially be due to the increase in its filling factor along the coordinate perpendicular to the disc, up to the height $|z| \approx 900$ pc. For larger $|z|$ the mean value of $\mathrm{DM_p} = \mathrm{DM} \cdot \sin|b|$ ceases to increase (Cordes & Lazio 2003; Berkhuijsen et al. 2006), which provides evidence of a sharp decrease in electron number density.

Unfortunately, the half thickness of the ionized medium at different galactocentric radii r in the Galaxy is poorly known,

[2] The question of whether a small-scale dynamo can work in intergalactic space deserves clarification, but is beyond the scope of this paper.

although some data suggest that its distribution is shallower than the radial density profile of the stellar disc (Cordes & Lazio 2002, 2003). In spite of the divergence of the data, a robust estimate of DM_p perpendicular to the disc plane is given by different authors as $DM_p \approx 20{-}26\ cm^{-3}$ pc (Cordes & Lazio 2002; Schnitzeler 2012; Gaensler et al. 2008), which corresponds to a column density of the WIM for the solar vicinity of $\Sigma_{i,0} = 2\,DM_p\,m_p \approx 1\ M_\odot/pc^2$, where m_p is the proton mass.

3. The parameter distributions

To study galactic dynamos in the no-z approximation, we need to know the radial distribution of the half thickness of the dynamo layer, its mean volume density, and the angular velocity of the rotating gas, $\Omega(r) = V_{rot}(r)/r$. The magnetic field growth is described by the dynamo number, which can be parameterized as $D = (3\,h_{dyn}\,\Omega/v)^2$, where h_{dyn} is the dynamo scaleheight (i.e. an estimate of the scale over which the magnetic field is expected to vary perpendicular to the disc), Ω is the angular velocity, and v is the velocity of turbulent motions. We emphasize that h_{dyn} can only be an order-of-magnitude estimate, and it is probably not realistic to identify it precisely with any specific physical scale. This approach has been verified as satisfactory in a number of cases, and we show that our conclusions about the existence of a dynamo-generated field beyond the normal boundaries of galaxies are not sensitively dependent on this choice. The growth of magnetic field from dynamo action is a threshold process: the field can grow if $D > D_{cr} \approx 7$ (Phillips 2001; Arshakian et al. 2009).

Observations give the rotation curve $V_{rot}(r)$ of the Galaxy up to 14−16 kpc from the galactic centre (Brand & Blitz 1993; Vallée 1994; Bovy et al. 2012). For our purposes it is sufficient to adopt a flat rotation curve in the range 5−30 kpc with a plateau at 220 km s^{-1}. We also tested a more detailed shape of the rotation curve; however, this does not significantly affect the results.

Taking the uncertainties in the data into account, we consider two simple models with very different, however feasible, parameters for the layer of partially ionized gas (WIM+HI). As the basic starting point, we assumed that this layer is not too thin, otherwise a magnetic field could not be generated (Phillips 2001; Arshakian et al. 2009; Moss & Sokoloff 2011). Also, the observed half thickness of the layer of partially ionized warm HI in the solar vicinity is about 400 pc (Cox 2005). The radial profile of the half thickness of this layer in the outer parts of the Galaxy is also little known, so we consider two different cases: a layer with constant half thickness and a layer that flares at large radial distances. Both models are normalized by the column density of ionized medium in the solar vicinity of about 1 $M_\odot/pc^2$, derived from pulsar observations (see the previous section). The radial profile of the column density $\Sigma_i(r)$ in both models is assumed to be proportional to the HI profile $\Sigma_{HI}(r)$. Following Kalberla et al. (2007), we represent the azimuthally averaged HI surface density by $\Sigma_{HI}(r) = 10\ M_\odot/pc^2$ for $r < 12.5$ kpc and $\Sigma_{HI}(r) = s_0 \cdot e^{-(r-R_\odot)/R_s}$ for $12.5 < r < 30$ kpc, where $s_0 = 30\ M_\odot/pc^2$ and $R_s = 3.75$ kpc.

Model 1. The dynamo layer has a constant scaleheight h_{dyn} = 1000 pc. In this case the velocity dispersion of ionized gas should decrease from 40 to 9 km s^{-1} in the range 5−25 kpc in order to agree with the gravitational potential of the disc. This parametrization of the scaleheight is close to the half thickness of the warm ionized gas layer (see previous section).

Model 2a. The dynamo scaleheight is h_{dyn} = 400 pc up to 18 kpc. This scaleheight is close to the half thickness of the layer of partially ionized warm HI. We assume here that it remains constant even at large distances from the galactic centre. Since the partially ionized layer cannot be thinner than the HI layer, we assumed that for $r > 18$ kpc h_{dyn} is close to h_{HI}, which grows exponentially with r as is observed in our Galaxy: $h_{HI} = h_0 \cdot e^{(R-R_\odot)/R_0}$, where $h_0 = 0.15$ kpc and $R_0 = 9.8$ kpc (Kalberla et al. 2007). The turbulent velocity of gas in this model is taken as 10 km s^{-1} which is usually valid for the peripheries of the discs of spiral galaxies (Walter et al. 2008). The half thickness for 10 kpc $< r <$ 18 kpc in this model is small, so that the dynamo number is not very large in this region. However, the magnetic field grows in the outer parts. We can conclude that for more realistic cases, the magnetic field strength will be at least as large as in this model.

Model 2b. This model is similar to Model 2a. The difference is that at large distances ($r > 12.5$ kpc), h_{dyn} was taken not from the Kalberla et al. (2007) approximation, but from a self-consistent equilibrium model of the gas layer, situated in the gravitational potential of the galactic disc and dark halo (see Kasparova & Zasov 2008, for details). In this model h_{dyn} at large radii grows more steeply with r than in Model 2a. The advantage of this model is that in principle it could be applied to other galaxies where, unlike the case of our Galaxy, an estimate for the thickness of the gas layer is not known directly from observations.

The early galactic dynamo models (e.g. Ruzmaikin et al. 1985) preferred v = 10 km s^{-1} and relatively thin discs with h_{dyn} = 400 pc. However, after the structure of interstellar gas became clearer, galactic dynamo models with thicker discs were considered (e.g. Poezd et al. 1993), and the choice of the disc thickness depends on the rms turbulent velocity adopted. Lower turbulent velocities were considered, retaining the other dynamo parameters, this would assist dynamo action because the dynamo number is inversely proportional to v^2.

4. A simple dynamo model for the remote parts of galactic discs

To model the magnetic field evolution in the outer parts of galactic discs, we used a simple model in the no-z formulation (e.g. Subramanian & Mestel 1993; Moss 1995 and subsequent papers), taking the $\alpha\omega$ approximation. The model was formulated for the field components parallel to the disc plane (B_r and B_ϕ) with the implicit understanding that the component perpendicular to this plane (i.e. in the z-direction) is given by the solenoidality condition and that the field has even parity with respect to the disc plane[3]. The field components parallel to the plane can be considered as mid-plane values, or as a form of vertical average through the disc (see e.g. Moss 1995). We assume that the large-scale magnetic field is axisymmetric.

The no-z dynamo equations in cylindrical polar coordinates (r, φ, z) can be written as

$$\frac{\partial B_r}{\partial \tau} = -\frac{\alpha B_\varphi}{h_{dyn}} + \eta\left\{-\frac{\pi^2 B_r}{4h_{dyn}^2} + \frac{\partial}{\partial r}\left(\frac{\partial}{r\partial r}(rB_r)\right)\right\}; \quad (1)$$

$$\frac{\partial B_\varphi}{\partial \tau} = r\frac{\partial \Omega}{\partial r}B_r + \eta\left\{-\frac{\pi^2 B_\varphi}{4h_{dyn}^2} + \frac{\partial}{\partial r}\left(\frac{\partial}{r\partial r}(rB_\varphi)\right)\right\}, \quad (2)$$

[3] We have checked a posteriori that $\partial B_z/\partial z \approx 10^{-4}\ \mu$G/pc even in the inner parts (in the outer parts it is less). Assuming $|\partial B_z/\partial z| \approx |B_z/h|$ and $h \approx 400$ pc, we typically obtain $B_z \lesssim 0.04\ \mu$G, which is consistent with the limits of the vertical field strength derived from observations of Faraday rotation measures (Mao et al. 2010).

where α characterizes turbulent motions, Ω is the angular velocity, $\eta = l\,v/3$ the turbulent diffusivity, l the length scale of turbulence (taken to be constant throughout the galaxy), and v the rms turbulent velocity (Arshakian et al. 2009). The z component does not appear explicitly, and the equations have been calibrated by factors of $\pi^2/4$ in the vertical diffusion terms (Phillips 2001). We use the system (1), (2) in dimensional form to aid physical interpretation of our results. Distances are measured in kpc, times in Gyr, and magnetic field strengths in μG.

We assume an algebraic non-linear α quenching, $\alpha \propto (1 + (B/B^*)^{-2})$, where $B^* \propto v\sqrt{4\pi\rho(r)}$ is the strength of the field in equipartition with the turbulent energy density field, which also depends on radius (ρ is the interstellar gas volume density), $B = \sqrt{B_r^2 + B_\varphi^2}$. This non-linear parametrization is quite empirical and implies that α is reduced if the magnetic field strength is close to B^*. We note that a more sophisticated dynamical quenching could be used (Sur et al. 2007; Mikhailov 2013), but this is not necessary for our purposes. The volume density is calculated by taking $\rho \propto \frac{\Sigma_\mathrm{i}}{2h_\mathrm{dyn}}$, where Σ_i is as described in Sect. 3. For simplicity, we take $B^* \approx 5\,\mu$G at $r = 8.5$ kpc.

We parametrize the α effect as $\alpha \sim \Omega\, l^2/h_\mathrm{dyn}$, where h_dyn is obtained from the models for the ionized gas component. There is some freedom in choosing the model of the interstellar gas. In models with constant dispersion of the turbulent velocity v, the scaleheight h_dyn should increase in the outer parts; otherwise, with h_dyn = const., v decreases. Moreover, the model allows choice of values for v and h_dyn, which are taken to achieve a general agreement with the observational data (Sect. 3). Model 1 uses constant $h_\mathrm{dyn} = 1.0$ kpc and decreasing v. Models 2a and 2b use constant $v = 10$ km s^{-1} and h_dyn increasing in the outer parts of the galaxy. We calculated the magnetic field strength for various models of the ionized gas component and confirmed that the results are quite similar for the different parameters.

For the initial conditions we take

$$B = B_0\left(\frac{r}{r_0}\right)\exp(-r/r_0),$$

where B_0 takes different values (see Fig. 3); using a random seed field does not affect the results significantly. Then we performed our modelling for $0 < r < 50$ kpc, assuming that $B(0) = B(50\,\mathrm{kpc}) = 0$. We experimented with different ranges of r, changing the outer limit from 30 to 100 kpc, and the results remained qualitatively similar. The magnetic fields are still significant for radii as large as $r \approx 15-30$ kpc. However, to exclude boundary effects near $r = r_\mathrm{max}$, r_max needs to be substantially larger than these values. We use $r_\mathrm{max} = 50$ kpc as the standard value, which seems to be quite satisfactory for our purposes.

Of course, our model could be developed to include various more complicated effects, such as spiral arms (Moss et al. 2013) or magnetic field reversals (e.g. Moss et al. 2012; Moss & Sokoloff 2013), but here we consider only the simplest situation.

5. Results

We solved the dynamo Eqs. (1) and (2) for our various assumptions about the shape of the disc of ionized gas to obtain the evolution of the large-scale (regular) magnetic field in the outer parts. Figure 1 describes the results for the regions where magnetic fields have significant values (up to $r = 20-30$ kpc). We halted the calculations at the time 10 Gyr, close to the present time, and refer to the resulting magnetic fields as the "final" ones. These and the other figures in this paper show the strength of the large-scale field, calculated as $B = (B_r^2 + B_\varphi^2)^{1/2}$ (the no-z model does not explicitly calculate the z component, which is small). We stress that our models contain the azimuthal magnetic field B_φ, as well as the radial B_r; however, we note that the computed magnetic field is very close to azimuthal (Fig. 2). The pitch angle in different parts of the galaxy varies between 4° and 15°. As expected, the strength of the large-scale magnetic field is greater in the inner parts of the galactic disc than in the remote regions. It is, however, important that the magnetic field grows with time at the disc periphery up to radii 15−30 kpc, becoming substantial (but still weaker than in the inner regions) after $t \approx 10$ Gyr. In other words, the galactic dynamo can produce regular magnetic fields of astronomically interesting strengths at galactocentric radii of up to several tens of kpc. In any case, the large-scale magnetic field at such radii is much larger than the lower limit suggested by Neronov & Semikoz (2009) for intergalactic space.

A comparison of magnetic field evolution for the various parameters describing the ionized gas distribution is illustrated in the panels of Fig. 1. Although some details of the evolution are model dependent, the presence of substantial magnetic fields in the remote regions of galactic discs persists in all models.

In Fig. 1 (left-hand panels) we show the solutions for $B(r)$ at different times. In the right-hand panels, we reproduce $B(t)$ for different parts of the galaxy. A general conclusion is that the large-scale magnetic field grows quite rapidly at $r < 20$ kpc. Although it still grows at larger distances ($r > 20$ kpc), the growth rate is very slow there. We note that Model 2a demonstrates a local minimum at $r \approx 17$ kpc. This is connected with the constant half thickness of the disc out to $r = 18$ kpc. The dynamo number is quite small near to $r = 18$ kpc, and the field grows slowly. It looks implausible that this feature is real, and probably the disc becomes thicker at smaller radii. For us it is important, however, that even for this model, there is a quite noticeable magnetic field in the outer parts of the galaxy.

Next, we demonstrate that our model is quite robust. The final fields shown in Fig. 3 (top panel) are about 10 μG in the central parts of the galaxy and about 10^{-1} μG in the outer regions. The middle panel of Fig. 3 shows the final fields for various radial distances r_0 of the position of the maximum of the initial field. As can be seen, the final magnetic field is quite similar for the different models and does not depend significantly on the initial field strength. The bottom panel of Fig. 3 shows the final magnetic field for various models of the partially ionized gas layer. The results do not differ significantly, so we can claim that in all cases the magnetic field in the outer parts is about 10^{-1} μG. All these figures show the magnitude of the field as $B = (B_r^2 + B_\varphi^2)^{1/2}$.

5.1. Propagation of the magnetic field to the remote parts of the disc

A more detailed inspection of our model shows that there are at least two possibilities for obtaining a significant magnetic field in the remote parts of a galactic disc. Either the magnetic field can be generated in situ near the disc periphery from a seed field by local dynamo action or the magnetic field can be produced in the central region of the galaxy and then transported to the remote regions by the joint action of a dynamo and turbulent diffusivity. We illustrate the second possibility, which follows Moss et al. (1998). The limited radial extent of standard galactic dynamos has usually been insufficient to identify this positive role of radial diffusion.

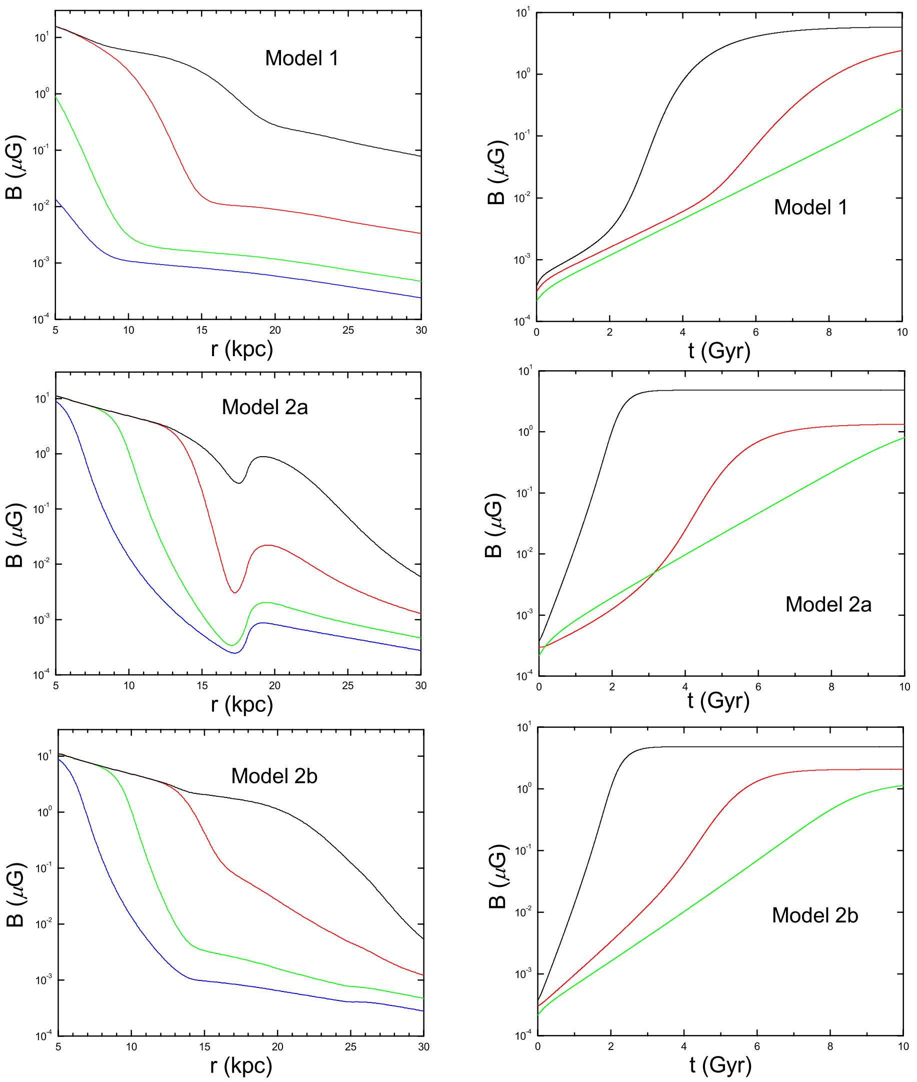

Fig. 1. *Left*: radial profile of B for three different profiles of the dynamo scaleheight (see text). The curves from bottom to top in each panel indicate magnetic fields at times t = 1, 2, 5, and 10 Gyr. *Right*: growth of the large-scale magnetic field at r = 10, 15, and 20 kpc (from top to bottom in each panel).

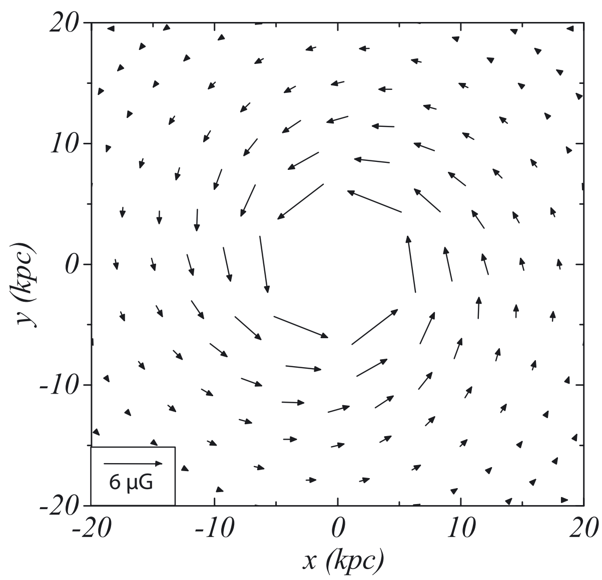

Fig. 2. Typical vector plot of the large-scale magnetic field (which is almost azimuthal).

We consider a magnetic field that grows at a rate Γ. The corresponding eigenfunctions are concentrated in the inner regions of the disc and decay in the outer parts of the disc as $\exp(-r/r_{\rm d})$ with $r_{\rm d} = (\eta/\Gamma)^{1/2}$. Then $B \propto \exp(-r/r_{\rm d})$ and the radius at which B exceeds a given level propagates along r to the remote parts of disc with the speed

$$V_{\rm prop} \approx 2\sqrt{\Gamma\eta}. \quad (3)$$

This process of propagation is similar to the Kolmogorov-Petrovsky-Piskunov effect (Kolmogorov 1937). We chose an initial condition concentrated at the inner part of the disc (Fig. 4) and find that the point at which $B = 10^{-5}\,\mu$G moves with a speed $V_{\rm prop} \approx 2$ kpc Gyr^{-1}, which agrees with the prediction of Eq. (3). For a seed field that smoothly decays with radius (Fig. 5), the shape of magnetic field distribution remains more or less the same, while its amplitude grows with time.

6. Observational tests

Reliable data on the magnetic field distribution in the outer disc regions, which can be compared with those theoretically expected, may be obtained from radio observations of non-thermal radiation of galaxies at large radial distances. Total radio emission is stronger and hence easier to detect, but its detection is limited by the background of unresolved sources ("confusion"). Furthermore, inverse Compton losses of the cosmic ray electrons interacting with photons of the cosmic microwave background

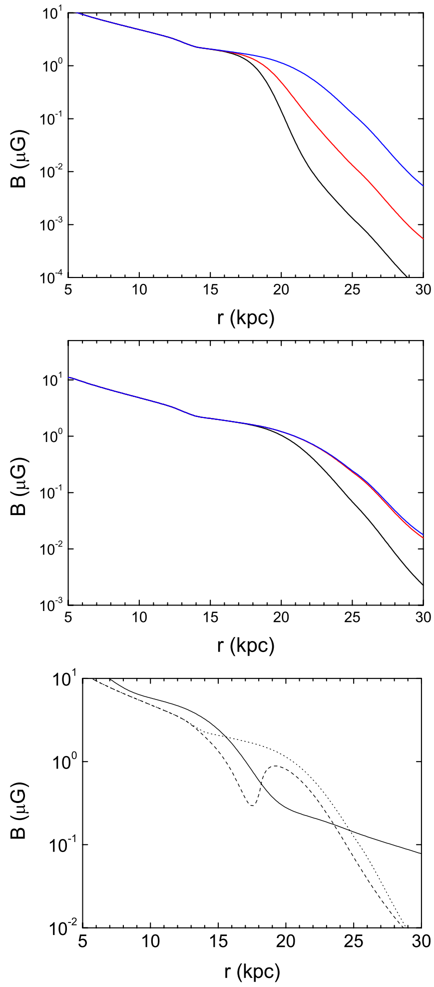

Fig. 3. Large-scale magnetic field strengths for different models of the ionized gas component and initial conditions. The *top panel* shows the strength of the final magnetic fields (i.e. at 10 Gyr) for different amplitudes of the initial conditions: curves from bottom to top indicate $B_0 = 10^{-5}$ μG, $B_0 = 10^{-4}$ μG, and $B_0 = 10^{-3}$ μG. The *middle panel* shows the final field strengths for different distances of the peak of the initial field from the centre: curves from bottom to top show $r_0 = 6$ kpc, $r_0 = 16$ kpc, and $r_0 = 20$ kpc. The *bottom panel* shows the final magnetic field strengths for different models of the dynamo scaleheight: the solid curve corresponds to model 1, the dashed curve to model 2a, the dotted curve to model 2b.

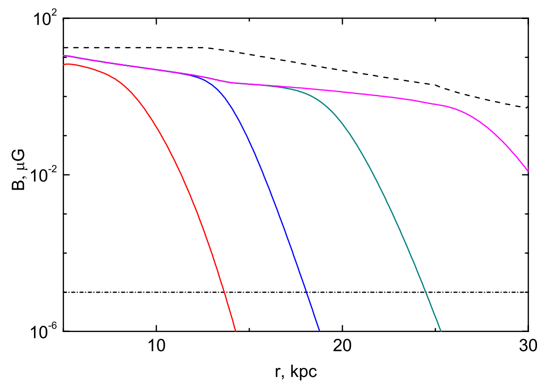

Fig. 4. Growth of an initial large-scale field concentrated in the inner parts of the disc. Solid curves from bottom to top show t = 2, 5, 10, 20 Gyr; the dashed curve shows the equipartition field strength; the dot-dashed line shows the field strength for which the speed of propagation is estimated. See text.

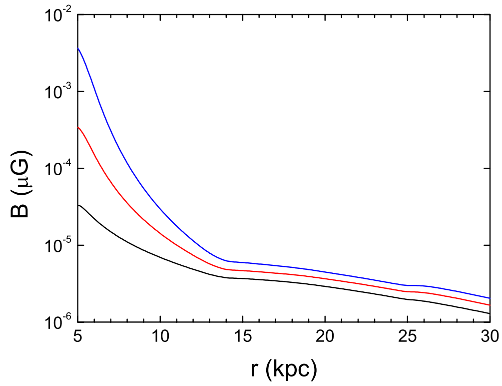

Fig. 5. Pure exponential growth of a weak magnetic field. The curves from bottom to top show $t = 0.2$ Gyr, $t = 0.4$ Gyr, and $t = 0.6$ Gyr.

(CMB) makes it impossible to detect magnetic fields with total strengths below $3.3\,(1+z)^2$ μG[4]. Large-scale fields can also be detected via the Faraday rotation of polarized background sources. Since the rotation angle increases with the thermal electron density, the line-of-sight component of the regular field, and the square of the observation wavelength, low-frequency telescopes are particularly well suited to measuring Faraday rotation in weak fields. A regular field of 0.1 μG with a coherence length of 1 kpc and an electron density of 10^{-3} cm^{-3} results in a Faraday rotation angle of about 0.3 rad at 150 MHz (2 m wavelength). Even regular fields or electron densities that are lower by factors of 3 still generate a measurable amount of Faraday rotation. However, the main limitation comes from Faraday rotation in the Galactic foreground which has to be subtracted (Oppermann et al. 2012). A sufficiently large number of background sources is needed, which restricts the observations to galaxies with a large angular size on the sky.

The galaxies that possess extended HI discs (e.g. Sanders & Noordermeer 2007; Lelli et al. 2010) or UV discs (Thilker et al. 2007), which spread far beyond the conventionally defined optical borders, are of special interest. Star formation currently taking place in the outer UV discs guarantees the presence of relativistic electrons and ionized gas. As the radio brightness is expected to be low in the extended discs, modern low-frequency arrays such as LOFAR, MWA, and the planned SKA may be suitable for determining the radii of the outer limits of magnetic fields generated in differentially rotating galactic discs.

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