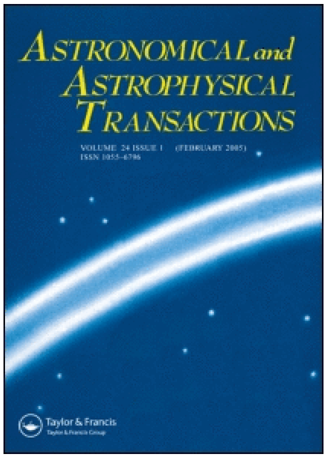

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A. Shukurov [a]
[a] Computing Center, Moskow University, Moscow, Russia

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TOPOLOGICAL PUMPING OF MAGNETIC FIELDS BY GALACTIC FOUNTAINS

A. SHUKUROV

Computing Center, Moskow University, Moscow 119899, Russia

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Topological pumping of the large-scale galactic magnetic field by the galactic fountain flow can be an important effect responsible for μG-strength magnetic fields in gaseous halos of spiral galaxies. The physical nature of this effect is discussed in application to spiral galaxies. In particular, we consider how topological pumping affects galactic dynamos and discuss specific properties of the large-scale galactic magnetic fields embedded in a turbulent flow of interstellar gas.

KEY WORDS **Spiral galaxies, interstellar magnetic fields, gaseous halos, galactic fountains**

1 INTRODUCTION

The effect of topological pumping of the large-scale magnetic field by convection was first suggested by Drobyshevski and Yuferev (1974) in application to the solar convective zone (see also Moffatt, 1978; Drobyshevski *et al.*, 1980). In Bénard convection, updrafts are isolated from each other, whereas downdrafts occupy a topologically connected region on a horizontal plane. As a result, a large-scale magnetic field can be trapped by the descending flows to be advected downwards. Thus, the topological structure of the flow leads to a unidirectional transport of the large-scale magnetic field, even though the streamlines are closed. The importance of this effect for spiral galaxies was first suggested by Brandenburg *et al.* (1995). In Section 2 we briefly discuss topological pumping in spiral galaxies.

It is important to realize that it is the *large-scale* field that is the subject of topological pumping, rather than the total magnetic field represented by both large- and small-scale components. The large-scale component of the total magnetic field can be defined in a natural manner as that whose scale exceeds the size of convection cells or, more generally, up- and down-drafts if the flow is not a "classical" convection but, say, a galactic fountain. In the galactic context, is this the field component that has a horizontal scale exceeding about 1 kpc and produces polarization of nonthermal emission as observed at a resolution of a few kiloparsecs. It is well known that large-scale magnetic fields embedded in a turbulent (or convection) flow behave in a non-trivial manner; in particular, they cannot be considered frozen into the flow even when the magnetic Reynolds number based on molecular magnetic diffusivity is large (see, e.g., Moffatt, 1978; Parker, 1979; Krause and Rädler, 1980; Zeldovich *et al.*, 1983; Ruzmaikin *et al.*, 1988b). Some distinct aspects of the behavior of large-scale magnetic fields in the interstellar medium are discussed in Section 3.

The results of Brandenburg *et al.* (1995) indicate that topological pumping may strongly affect evolution of magnetic fields in spiral galaxies; in Section 4 we discuss how topological pumping interacts with galactic dynamos. Finally, in Section 5 we consider a steady-state strength of magnetic field in galactic fountain.

2 MAGNETIC FIELD IN THE MULTI-PHASE INTERSTELLAR MEDIUM

The available theories of global magnetic patterns in spiral galaxies, based mainly on the mean-field dynamo theory, usually consider interstellar medium (ISM) as a single-phase electrically conducting gas neglecting the multi-phase structure of the ISM represented by dense clouds, warm intercloud medium and hot gas. The mean-field dynamo theory was never generalized to complicated multi-phase systems. Parameters of the idealized ISM rountinely adopted in analyses of galactic dynamos are close to those of the warm intercloud gas (Ruzmaikin *et al.*, 1988b). This choice is motivated as follows. First, Faraday rotation measurements, the main source of information on large-scale magnetic fields in the Milky Way and external galaxies (Wielebinski and Krause, 1993; Beck *et al.*, 1996), sample mainly regions occupied by the warm intercloud gas which make the dominant contribution into the integral $RM = \int n_e \mathbf{B}\, ds$ known as the Faraday rotation measure, with HI clouds being the second important contributor (here n_e is the thermal electron density, $\mathbf{B}$ is the magnetic field and integration is carried along the line of sight s) (Heiles, 1976; Ruzmaikin *et al.*, 1988b, Section III.6). Secondly, and this is more important, the warm intercloud gas is apparently the only phase in which the large-scale magnetic can be generated. Indeed, relatively dense interstellar gas clouds occupy a negligible fraction of the total volume in a galactic disk, so that they can hardly host the component of magnetic field whose scale is 1–2 kpc. The hot interstellar gas is too unsteady to generate the large-scale magnetic field *in the disk*: it leaves the disk within 10^6–10^7 yr to fill a hot gaseous halo. Since the latter time scale is much shorter than the mean-field dynamo time scale (10^8–10^9 yr in the disk), we conclude that the hot gas cannot be responsible for the maintenance of a large-scale magnetic field in the galactic disk.

However, the hot gas still produces profound effects on galactic magnetic fields, and topological pumping is one of them. The point is the hot gas can occupy connected regions spanning a few kiloparsecs within the disk. If so, the gas, when rising from the disk into the halo, can trap the interstellar large-scale magnetic field and carry it to the halo. The downward motion is represented by *isolated* clouds formed high above the galactic disk. This flow is known as the galactic fountain (Shapiro and Field, 1976). Since the clouds are isolated from each other, they cannot drag the *large-scale* magnetic field back to the disk but rather produce local indentations on its field lines and stretch them into local vertically extended loops that reconnect to become detached from the parent magnetic line. As a result, the large-scale magnetic field stays in the halo. Thus, the galactic fountain acts as a magnetic pump that continuously transfers the large-scale magnetic field from the disk into the halo.

A necessary condition for this effect to be efficient is that the hot gas in the galactic disk forms a connected region whose size is comparable with the scale of the regular magnetic field, that is, a few kiloparsecs. In terms of percolation theory (see, e.g., Feder, 1988; Vicsek, 1989), the hot phase should form a *percolating cluster*. The percolation threshold, i.e., the minimum volume filling factor at which percolation occurs is estimated from simulations of percolation on three-dimensional lattices as $f_{\rm cr} = 0.137$–0.428 depending on the geometry of the lattice (Nakayama *et al.*, 1994); this can be considered as an upper limit for $f_{\rm cr}$ in a continuous medium. This overlaps with the range of volume filling factors suggested for the hot phase of the ISM, $f \simeq 0.1$–0.7 (see, e.g., Cox, 1990; Spitzer, 1990). Among theories of the hot interstellar gas, the minimum volume filling factor is predicted by the chimney model as $f \approx 0.1$ (Norman and Ikeuchi, 1989). This value is just below the percolation threshold $f_{\rm cr}$ – indeed, the absence of percolation is merely another form of saying that the hot gas concentrates into *isolated* chimneys. However, other theories of the hot phase favor larger values of f reaching 0.5 at the midplane and even more. We thus conclude that it is quite plausible that the hot gas forms a percolating cluster already at the midplane thereby being able to act as a topological magnetic pump.

The filling factor of the hot gas must grow with height because it equals unity at the heights exceeding about 1 kpc where the disk ends – we known that galactic halos are filled with the hot gas! Thus, even if the filling factor of the hot gas is as low as, say, 0.1 at the midplane, there always exists a threshold height $z_{\rm cr}$ in the disk at which the hot gas becomes a percolating cluster. Then the topological pumping occurs above that height and the question is whether or not $z_{\rm cr}$ is small enough to ensure that the large-scale magnetic field is still significant there to make the pumping an important mechanism.

Let us estimate the height $z_{\rm cr}$ at which the hot phase is expected to form a percolating cluster even if it does not do that at the midplane of the galactic disk. The volume of a supernova remnant in pressure balance with its environment is inversely proportional to the density of ambient medium. Then the filling factor of the hot phase that represents merged supernova remnants is also in inverse proportion to the gas density, $f = f_0(\rho/\rho_0)^{-1}$ with f_0 and ρ_0 being the filling factor and gas density at $z = 0$. Since ρ decreases with height above the midplane, z, the filling factor is a growing function of z. Assuming that $f_0 = 0.1$ (this is probably a guaranteed lower estimate corresponding to the chimney model) and $\rho = \rho_0 \exp(-z/z_0)$, we have $f = 0.1 \exp(z/z_0)$, where z_0 is the scale height of the total interstellar gas density. For $z_0 = 100$ pc, we obtain $f = f_{\rm cr} \simeq 0.4$ at $z = z_{\rm cr} = 1.4 z_0 = 140$ pc. Since this is well within the layer containing the large-scale magnetic field (whose half thickness is 400–500 pc – see Ruzmaikin *et al.*, 1988b), we conclude that topological pumping is expected to be efficient in our Galaxy and other galaxies with at least similar supernova rate.

We also note that the filling factor of the hot gas probably grows with star formation activity, so that topological pumping is most probable to occur in galaxies with high star formation rate.

3 LARGE-SCALE MAGNETIC FIELD IN A GALACTIC FOUNTAIN FLOW

Evolution of magnetic field embedded in a flow of electrically conducting fluid (plasma) is described by the induction equation

$$\frac{\partial \mathbf{H}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{H}) + \nu_m \nabla^2 \mathbf{H}, \tag{1}$$

where $\mathbf{H}$ is the magnetic field, $\mathbf{v}$ is the velocity field and ν_m is the molecular magnetic diffusivity. Effects similar to topological pumping arise when $\mathbf{v}$ is a small-scale velocity field, and they can be studied via averaging the induction equation over scales exceeding that of $\mathbf{v}$. The result of the averaging is the following equation (see, e.g., Moffatt, 1978; Krause and Rädler, 1980):

$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \nabla \times (\hat{\alpha} \cdot \langle \mathbf{B} \rangle) - \nabla \times (\beta \nabla \times \langle \mathbf{B} \rangle), \tag{2}$$

where $\langle \mathbf{B} \rangle$ is the mean magnetic field, β is the effective magnetic diffusivity, and $\hat{\alpha}$ is a tensor that describes averaged induction effects of the small-scale velocity field:

$$\hat{\alpha} = \begin{pmatrix} \alpha_0 & V_z & V_y \\ -V_z & \alpha_0 & -V_x \\ -V_y & V_x & \alpha_0 \end{pmatrix}, \tag{3}$$

where diagonal elements are responsible for the mean-field dynamo action and off-diagonal elements describe advection of the mean magnetic field: this can be easily seen from equality $\hat{\alpha} \cdot \langle \mathbf{B} \rangle \equiv \alpha_0 \langle \mathbf{B} \rangle + \mathbf{V} \times \langle \mathbf{B} \rangle$ with $\mathbf{V} = (V_x, V_y, V_z)$ being a certain mean velocity field written here in Cartesian coordinates.

As we can see by comparing Eqs. (1) and (2), the large-scale magnetic field $\langle \mathbf{B} \rangle$ embedded in a small-scale flow (say, turbulence, convection or galactic fountain) behaves quite differently from the total magnetic field $\mathbf{H}$. The latter, represented as a superposition of the large-scale and small-scale components, may be (almost) frozen into the flow provided that $\nu_m \to 0$, i.e., electrical conductivity is large. However, the large-scale field is detached from the streamlines and does not follow the gas flow first because the effective magnetic diffusivity β (determined by the scale and r.m.s. velocity of the small-scale flow) may be large and, secondly, because the form of Eq. (2) directly indicates that the flux of the mean magnetic field is *not* conserved even for $\beta \to 0$ provided that $\alpha_0 \neq 0$ (when the mean-field dynamo action occurs – see below).

The off-diagonal elements of the tensor $\hat{\alpha}$ describe, in particular, the vertical transport of the mean magnetic field by galactic fountain at a velocity V_z. As argued above, this peculiar behavior is due to the topological properties of the flow with downward motions being disconnected from each other, so that they cannot carry the large-scale magnetic field back towards the midplane and the net effect is an upward transport. Another important effect which contributes to V_z is the vertical transport of $\langle \mathbf{B} \rangle$ associated with variation of β with z, known as turbulent diamagnetism. This is discussed in Section 5.

As topological pumping is associated with advection of magnetic fields by plasma flow, it is clear that induction effects must dominate over magnetic diffusion for this effect to be important. This can be conveniently expressed in terms of the turbulent magnetic Reynolds number R_T defined as $R_T = V_{z*}L/\beta$ with V_{z*} a characteristic value of V_z and L the horizontal scale of the fountain flow. According to Arter (1983) and Brandenburg *et al.* (1995), topological pumping is efficient provided $R_T \geq 50$. Estimates of Brandenburg *et al.* (1995) show that the turbulent magnetic Reynolds number in the disks and halos of spiral galaxies can reach 100–500, so that topological pumping can be efficient.

Unfortunately, it is difficult to offer a convenient parametrization of topological pumping for a flow of general type (that is, to express V_z in terms of the flow parameters), particularly because it is difficult to quantify topological properties of the flow in a convenient manner. Therefore, the only option available now is to specify a certain velocity field having required topological properties and to study the evolution of magnetic field embedded in this flow by solving a properly averaged induction equation (1). Brandenburg *et al.* (1995) suggested such a velocity field which is expected to be an adequate qualitative model of the galactic fountain flow with allowance for mass conservation and density stratification.

Since interstellar medium in both disks and halos of spiral galaxies is involved in turbulent motions whose scale ($l \simeq 100$ pc in the disk) is smaller than that of galactic fountains ($L \simeq 1$ kpc for the horizontal scale), it is expedient to average Eq. (1) over the turbulent velocity field. This yields

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B}) - \nabla \times \left(\frac{1}{2}\nabla\eta \times \mathbf{B}\right) - \nabla \times (\eta\nabla \times \mathbf{B}), \tag{4}$$

where $\mathbf{B}$ is the magnetic field averaged over the ensemble of turbulent motions, $\mathbf{U}$ is the velocity field associated with the galactic fountain (similarly averaged), η is the turbulent magnetic diffusivity ($\eta = \frac{1}{3}lv$ with l and v being the turbulent scale and velocity, respectively), and we have allowed for the spatial variation of η.

Altogether, the physical meaning of Eqs. (1), (2) and (4) is as follows. Equation (1) is the induction equation involving the total magnetic field $\mathbf{H}$ and molecular magnetic diffusivity ν_m. Equation (4) is a result of averaging of Eq. (1) over the turbulent velocity field; it involves the turbulent magnetic diffusivity η and the averaged magnetic field $\mathbf{B}$ whose scale is larger than the scale of turbulent motions l, but smaller that the horizontal scale of the fountain flow, L. Finally, Eq. (2) is a result of spatial averaging of Eq. (4) over scales exceeding L; this involves magnetic

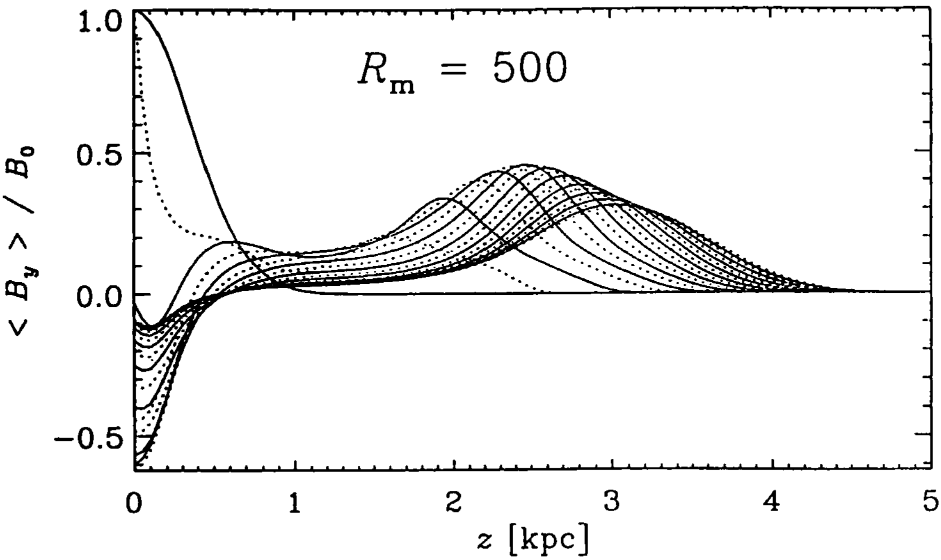

Figure 1 The dependence, on the vertical coordinate z, of the horizontal magnetic field averaged over horizontal planes z = const is shown for $R_m = 500$ at different times, starting from $t = 0$ to $t = 1$ Gyr with an interval of 0.05 Gyr. The initial field is shown by the solid line, which is the uppermost at $z = 0$ (from Brandenburg *et al.*, 1995). Presented are solutions of the indiction equation for a density-stratified layer with a scale height 1 kpc. The velocity field is devised to model the galactic fountain flow with connected updrafts and disconnected downdrafts. The turbulent magnetic diffusivity η is assumed to be uniform in these simulations in order to isolate the topological pumping.

field $\langle \mathbf{B} \rangle$ which has the largest possible scale (comparable with the size of the parent galaxy) and the effective magnetic diffusivity β that incorporates diffusive action of all the components of the velocity field whose scales are smaller than or equal to L.

Brandenburg *et al.* (1995) solved numerically the Cauchy problem for Eq. (4) with the velocity field U specified to possess connected updrafts and disconnected downdrafts. Their model includes density stratification similar to that observed in spiral galaxies (with an exponential scale height of 1 kpc).

In Figure 1 we show the time evolution of the large-scale magnetic field averaged over the horizontal coordinates x and y, denoted as $\langle B_y \rangle$, as a function of the vertical coordinate z. The effective turnover time of the model flow is $\tau = h/U \approx 2.510^7$ yr, where $h = 0.5$ kpc is the scale height of the velocity field and $U \approx 20$ km s^{-1} is the r.m.s. z-component of the velocity (with its maximum value adopted as $U_{\max} = 100$ km s^{-1}). Initially, magnetic field is assumed to be uniform on any plane z = const, directed along the y-axis and distributed along the z-axis as a Gaussian with the scale height 0.5 kpc. The initial magnetic field is shown by a solid line which is uppermost at $z < 1$ kpc. The vertical distributions of magnetic field are shown at an interval of 5×10^7 yr by alternating solid and dashed lines. As we can see, already after two turnover times (the uppermost dashed line at $z < 1$ kpc) there appears a secondary maximum of the horizontal magnetic field at $z \approx 1.5$ kpc; this maximum becomes higher with time and simultaneously drifts upwards until a maximum of $\langle B_y \rangle$ equal to about 0.4 of the initial field at $z = 0$ is reached at $z \approx 2.5$ kpc, $t \approx 5 \times 10^8$ yr. After that moment, the field maximum slowly decays while drifting upwards.

It is remarkable that the transfer of the large-scale magnetic field occurring at a time scale of a few turnover times is unidirectional, although the streamlines of the velocity field are closed. Since this transport is not due to magnetic diffusion (this effect can only smear the initial maximum of the field, so that the field would always be monotonically decreasing with z), we see again that topological pumping involves induction effects. It is then important to realize that the *large-scale* magnetic field is *not* frozen into the flow, even though the magnetic Reynolds number is as high as 500 in the simulations presented in Figure 1.

Another important example of such "autonomous" behavior of the large-scale magnetic field is the mean-field dynamo. Streamlines of the regular gas flow in spiral galaxies (represented by differential rotation, $V_y(x)$ in Eq. (2)) are closed circles but the field lines of the large-scale magnetic field are *spirals* which are *not* closed in the galactic disk (they close in the halo) (see Ruzmaikin *et al.*, 1988a, b; Beck *et al.*, 1996). This implies again that the large-scale magnetic field is not frozen into the flow, even though the molecular magnetic diffusivity in the ISM is so small that $R_m = vl/\nu_m \simeq 10^6$ (Ruzmaikin *et al.*, 1988b, Section VII.13). In this case this happens because of the dynamo action associated with the diagonal elements of the tensor $\hat{\alpha}$. Interstellar turbulence continuously tangles the large-scale magnetic field thereby reducing its strength at an exponential rate. This process is balanced by the dynamo action which regenerates the large-scale magnetic field. The configuration of the regenerated field is determined by the physical nature of the regeneration mechanism (the dynamo). Any kind of regeneration requires that magnetic field has at least two vector components. In the galactic disk, where differential rotation plays an important role in the dynamo action, these are the azimuthal and radial components: the former is produced from the latter by diffential rotation, while the inverse process occurs owing to the mean helicity of interstellar turbulence; the diagonal elements of $\hat{\alpha}$ are proportional to the mean helicity of interstellar turbulence. A combined action of differential rotation and turbulence thus explains the maintenance of magnetic field against the turbulent diffusion because these two magnetic field components can feed each other thus ensuring self-excitation of the total magnetic field. Therefore, the field lines of the large-scale magnetic field are necessarily spirals. A purely azimuthal magnetic field aligned with the streamlines of the regular velocity field can only decay under the action of turbulent magnetic diffusivity because it cannot reproduce a radial field via the action of differential rotation; the time scale of this decay is as short as $h^2/\beta_0 \simeq 5 \times 10^8$ yr with $h \approx 400$ pc the half-thickness of the magnetic field distribution and $\beta_0 = 10^{26}\ \mathrm{cm^2\ s^{-1}}$ the turbulent magnetic diffusivity within the disk.

4 TOPOLOGICAL PUMPING AND GALACTIC DYNAMOS

The time scale of topological pumping by galactic fountains is given by the turnover time of the fountain flow, $\tau_{\rm GF} \simeq 3 \times 10^7$ yr. The fountain flow removes the large-scale magnetic field from the disk at this time scale. Since $\tau_{\rm GF}$ is much shorter than the galactic dynamo time scale $\tau_{\rm dyn} = 10^8$–10^9 yr (see Beck *et al.*, 1996 and references therein), it is only natural to ask whether or not galactic fountains can destroy dynamos in galactic disks. We argue in this section that the answer is negative.

The point is that galactic fountains can carry away from the disk only that part of the field which happens to belong to the hot gas. Meanwhile, as we have discussed above, the dynamo action occurs in the warm intercloud gas. Let us estimate the rate at which the large-scale magnetic flux is removed from the disk by the fountain flow.

Consider first the strength of the large-scale magnetic field in the hot phase of the ISM. As argued by Kahn and Brett (1993) (see also Kahn, 1991), the radius of a supernova remnant is $R_1 \simeq 70$ pc when it merges with other remnants to form a superbubble. The mass of the gas in this volume is about $200M_\odot$ (this is mainly a warm interstellar gas heated by the supernova explosion), and the radius of the region initially occupied by this gas at a number density 1 cm^{-3} is $R_0 \simeq 13$ pc. Assuming that the large-scale magnetic field in the warm interstellar gas is $B \simeq 2\ \mu$G, we obtain the magnetic field strength in the hot gas from flux conservation as $B_{\rm hot} \simeq B(R_0/R_1)^2 \approx B/30 \approx 6 \times 10^{-8}$ G.

The rate at which the flux of the large-scale magnetic field (assumed to be horizontal) is removed from the disk by the fountain flow is estimated as

$$\dot{\Phi}_- \simeq \frac{B_{\rm hot}(h - z_{\rm cr})}{\tau_{\rm GF}}, \tag{5}$$

where $B_{\rm hot}(h - z_{\rm cr})$ is magnetic flux per unit radial distance through the region $h - z_{\rm cr}$ where topological pumping is efficient, and h is the equivalent half-thickness of the magnetic field distribution. The dynamo action regenerates the flux at the rate

$$\dot{\Phi}_+ \simeq \frac{Bh}{\tau_{\rm dyn}}.$$

Thus we obtain

$$\frac{\dot{\Phi}_-}{\dot{\Phi}_+} \simeq \frac{B_{\rm hot}}{B}\frac{\tau_{\rm dyn}}{\tau_{\rm GF}}\left(1 - \frac{z_{\rm cr}}{h}\right) \approx 0.05 - 0.5,$$

where we have adopted $B/B_{\rm hot} \simeq 30$, $\tau_{\rm GF} = 3 \times 10^7$ yr, $\tau_{\rm dyn} = 10^8$–10^9 yr, $z_{\rm cr} = 140$ pc and $h = 400$ pc. This estimate implies that topological pumping hardly might be dangerous for galactic dynamos, except possibly for the weakest ones where the dynamo time scale is about 10^9 yr. We note, however, that the Milky Way and the Andromeda nebula host such weak dynamos (Ruzmaikin *et al.*, 1988a, b; Poezd *et al.*, 1993).

Thus, in should be expected that galactic fountains may have an important effect on galactic dynamos, even though they hardly can destroy them completely. Of course, a conclusive assessment of the role of galactic fountain flows in galactic dynamos should be based on extensive models that incorporate both galactic disk and halo (cf. Brandenburg *et al.*, 1992, 1993) and consistently allow for their dynamic connection.

5 A STEADY STATE OF MAGNETIC FIELD IN THE FOUNTAIN FLOW

As can be seen from the simple model presented in Figure 1, the maximum of the large-scale magnetic field slowly drifts upwards and ultimately leaves the halo. Even though this process is very slow (the total duration of the evolution shown in Figure 1 is 10^9 yr), it is important to clarify whether there are mechanisms that can prevent such a leakage of magnetic field through the upper boundary. As argued by Brandenburg *et al.* (1995), such a mechanism might be associated with turbulent diamagnetism of interstellar turbulence. The physical nature of turbulent diamagnetism, discovered by Zeldovich (1956), is associated with the tangling of large-scale magnetic field lines by turbulent motions. Insofar as this tangling is stronger at positions where turbulent intensity is higher (more precisely, what matters is the turbulent diffusivity $\eta \approx \frac{1}{3}lv$ with l and v the turbulent scale and velocity), the large-scale magnetic field is expelled from regions with stronger turbulence. However, turbulent diamagnetism is not a purely diffusive effect, so that it can be described as advection of magnetic field at velocity (see, e.g., Vainshtein and Zeldovich, 1972)

$$\mathbf{V}_{\mathrm{TD}} \simeq -\frac{1}{2}\nabla\eta, \tag{6}$$

explicitly included in Eq. (4). As argued by Sokoloff and Shukurov (1990) and Poezd *et al.* (1993), turbulent magnetic diffusivity grows with height above the galactic disk from about $\eta_0 \approx 10^{26}$ cm^2 s^{-1} in the disk to about 5×10^{27} cm^2 s^{-1} in the halo owing to the growth in both v and l. As can be seen from Eq. (6), turbulent diamagnetism pumps the large-scale magnetic field downwards since η grows with z. Thus, this effect opposes topological pumping and it can lead to a steady state with a finite magnetic field at a height of several kiloparsecs. Brandenburg *et al.* (1995) estimate the typical velocity of the upward advection of magnetic field by the fountain flow as $V_{\mathrm{GF}} = 0.5$–1 km s^{-1} at a height 2–3 kpc. A steady state is achieved when the large-scale magnetic field has a maximum at that height where $V_z = V_{\mathrm{TD}} + V_{\mathrm{GF}} = 0$. Assuming for simplicity that $\eta = \eta_0[1 + (z/1\ \mathrm{kpc})^2]$, we obtain the height at which the magnetic field concentrates as $z_{\max} \simeq V_{\mathrm{GF}}/\eta_0 \simeq 2$–5 kpc. Numerical simulations of Brandenburg *et al.* (1995) with allowance for both topological and diamagnetic pumping mechanisms confirm these estimates. As can be seen from Figure 2, the vertical drift of the mean magnetic field slows down and halts at $z = 2$–3 kpc when the diamagnetic effects is incorporated into the model (that is, the vertical variation of η as shown in Eq. (4) is taken into account).

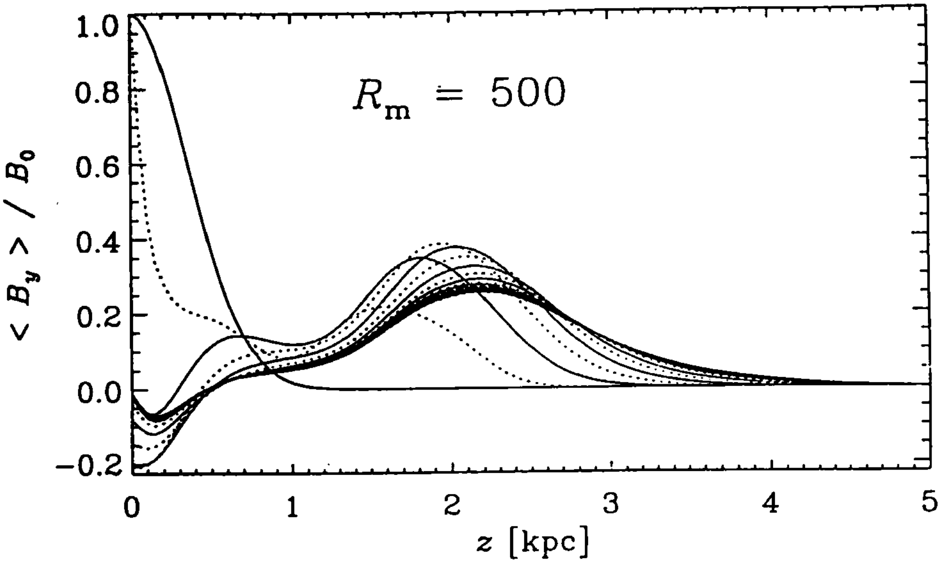

Figure 2 The same as in Figure 1, but with allowance for the growth of turbulent magnetic diffusivity η with z, as expected for spiral galaxies. The associated turbulent diamagnetic effect opposes the upward advection of the mean magnetic field $\langle B_y \rangle$ by the velocity field $\mathbf{U}$ and results in a quasi-stationary state with a maximum of $\langle B_y \rangle$ at $z = 2$–3 kpc.

We should stress that the strength of the large-scale magnetic field at its maximum in the halo is comparable to or exceeds that at the base of the fountain flow (see Figures 1 and 2), even though the gas density at the height of 3 kpc was adopted to be 20 times smaller than at $z = 0$. This happens because the fountain acts as a pump continuously replenishing the large-scale magnetic field in the halo. This is in a striking contrast with behavior of a frozen-in magnetic field advected from the disk by, say, galactic wind. In the latter case, the field strength scales with the gas density as $\rho^{-2/3}$ for a spherically symmetric expansion, so that one would expect a large-scale field of only 2×10^{-8} G for $B = 2 \times 10^{-6}$ G and $\rho = 1.7 \times 10^{-24}$ g cm^{-3} in the disk and $\rho = 1.7 \times 10^{-27}$ g cm^{-3} in the halo. Such fields are by far weak in comparison with those observed in the halos of spiral galaxies where μG-strength large-scale magnetic fields seem to be typical (e.g. Beck *et al.*, 1994). The strength of the large scale magnetic field can be somewhat enhanced by the action of velocity shear and dynamo in the halo (Bradenburg *et al.*, 1992, 1993) but this enhancement is not sufficient. Elstner *et al.* (1995) invoke a strong shearing flow associated with the hot gas rising from the disk to the halo to explain μG-strong magnetic field. However, such a strong shear may be present not farther than 1–2 kpc from the disk plane, whereas μG-strength magnetic fields are observed at least twice that height; moreover, this could explain only vertical magnetic fields with *zero* mean value.

Topological pumping provides an attractive way to explain relatively strong horizontal magnetic fields at heights 2–5 kpc above the disks of spiral galaxies. The steady-state strength of the large-scale magnetic field pumped by the galactic fountain is expected to follow from equipartition of magnetic energy density and kinetic energy density of the flow which yields $B_{\rm halo} \simeq (4\pi\rho U_{\rm max}^2)^{1/2} \approx 10^{-6}$ G, where $\rho \approx 1.7 \times 10^{-27}$ g cm^{-3} is the gas density in the halo and $U_{\rm max} \approx 100$ km s^{-1} is the maximum velocity in the fountain flow.

The time required to reach this strength can be estimated using Eq. (5) as

$$T \simeq \frac{B_{\rm halo} H}{\Phi_-} = \tau_{\rm GF} \frac{B_{\rm halo}}{B_{\rm hot}} \frac{H}{h - z_{\rm cr}},$$

where $H \simeq 5$ kpc is the vertical extent of the halo. This yields $T \simeq 300\tau_{\rm GF} \approx 10^{10}$ yr, implying that topological pumping can produce μG-strength magnetic fields at $z \simeq 5$ kpc within galactic lifetime.

We stress that the large-scale field produced in the halo by the fountain flow has the same configuration and symmetry as that in the disk, i.e., it is predominantly horizontal and has even parity with respect to the galactic midplane. Horizontal large-scale magnetic fields are observed in the halos of three spiral galaxies (NGC 891 – Hummel *et al.*, 1991; Sukumar and Allen, 1991; NGC 4565 – Sukumar and Allen, 1991; and NGC 253 – Beck *et al.*, 1994) out of the four detections available (in the fourth case, NGC 4631, magnetic field is predominantly poloidal in the halo – Hummel *et al.*, 1988; Golla and Hummel, 1994). Moreover, recent observations of NGC 253 indicate an even parity of the magnetic field in the halo (Beck *et al.*, 1994). A dynamo acting in the halo would produce an odd magnetic field insofar as the halo is quasi-spherical unless the dynamo in the disk, where an even parity dominate, is very strong to dominate over the dynamo in the halo (Brandenburg *et al.*, 1992). We conclude that topological pumping by the galactic fountain flow might be the dominant mechanism for generation of magnetic fields in the halos of spiral galaxies.

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