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# Diamagnetic pumping in a rotating convection zone

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**Abstract**

Solar dynamo models require some mechanism for magnetic field concentration near the base of the convection zone in order to generate super-kilogauss toroidal fields with sufficiently large ($\sim 10^{24}$ Mx) magnetic flux. We consider the downward diamagnetic pumping near the base of the convection zone as a possible concentration mechanism and derive the pumping velocities with allowance for the effect of rotation. Transport velocities for poloidal and toroidal fields differ in rotating fluid. The toroidal field is transported downward along the radius only but the pumping velocity for the poloidal field has an equatorward meridional component also. Previous results for cases of slow and rapid rotation are reproduced and the diamagnetic pumping expressions adapted for use in dynamo models are presented.


*Keywords:* Sun: magnetic fields; Magnetohydrodynamics (MHD); Dynamo; Turbulence

## 1. Introduction

Large-scale magnetic fields of turbulent fluids do not strictly follow the mean fluid motion. This is not only because the fields are subject to turbulent diffusion. Mean-field magnetohydrodynamics also predicts the effects of the large-scale field pumping with effective velocities which are not the actual velocities of fluid motion. The fields are expelled from the regions of relatively high turbulence intensity with the effective velocity $\boldsymbol{V}_{\mathrm{dia}} = -\boldsymbol{\nabla}\eta_{\mathrm{T}}/2$ ($\eta_{\mathrm{T}}$ is the eddy magnetic diffusivity; Krause and Rädler (1980)). Diamagnetic pumping was also found in 3D numerical experiments (Tobias et al., 1998; Tobias et al., 2001; Dorch and Nordlund, 2001; Ossendrijver et al., 2002; Ziegler and Rüdiger, 2003; Käpylä et al., 2006a) and in a laboratory experiment with liquid sodium (Spence et al., 2007).

Diamagnetic pumping is significant for the modelling of the solar dynamo. Käpylä et al. (2006b) and Guerrero and de Gouveia Dal Pino (2008) found that allowance for the pumping brings their models' results closer to observations. They in particular noticed that a horizontal component, which the pumping velocity may possess in addition to its (dominant) radial part, can be significant for latitudinal drift of magnetic fields. The observed equatorial drift of sunspot activity is believed to result primarily from a deep equatorward meridional flow (Choudhuri et al., 1995; Durney, 1995). However, horizontal turbulent pumping – if it exists – may also play a role.

Horizontal pumping can result from the influence of rotation on convective turbulence. The influence elongates convective eddies along the rotation axis to induce turbulence anisotropy. The resulting *anisotropic* pumping not only achieves a horizontal component but transports the poloidal and toroidal large-scale fields with different

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velocities. These circumstances were demonstrated in the case of effective transport due to stratification of density in turbulent fluid (Kichatinov, 1991) – a weaker effect compared to the diamagnetic pumping near the base of convection zone. Almost all effects of mean-field MHD for rotating turbulence were analysed in the nineties except diamagnetic pumping (cf., however, Pipin (2008)). This paper fills the gap.

We shall see that the diamagnetic pumping indeed attains a horizontal component in rotating fluids but only for poloidal fields which are transported with a different velocity compared to that of toroidal fields. The relative value of toroidal field transport (in relation to the turbulent diffusion) is enhanced by rotation. Pictorial interpretations can be given to all of these findings. Before deriving the diamagnetic pumping, however, it is worth discussing in more detail why can it be significant for the solar dynamo.

## 2. Significance of diamagnetic pumping

The region near the base of the convection zone has long been recognised as a favourable site for the solar dynamo (e.g., Galloway and Weiss (1981)). Diamagnetic pumping concentrates magnetic fields towards this site. The generation of super-kilogauss toroidal fields is hardly possible without this concentration.

It is generally acknowledged that toroidal fields ($B_\phi$) are wound from poloidal ones ($\boldsymbol{B}^{\mathrm{p}}$) by differential rotation. The winding process is accounted for by the following term,

$$\frac{\partial B_\phi}{\partial t} = r\sin\theta(\boldsymbol{B}^{\mathrm{p}}\cdot\boldsymbol{\nabla})\Omega + \ldots, \quad (1)$$

on the right-hand side of the toroidal field induction equation. In this equation, $\Omega$ is the angular velocity, $r$ is the heliocentric radius and $\theta$ is the co-latitude. The upper bound for the amplitude of the toroidal field, which can be wound in the course of a solar cycle, can be estimated as $B_\phi = CB^{\mathrm{p}}$, where $B^{\mathrm{p}}$ is the (local) amplitude of the poloidal field and the conversion factor $C$ reads

$$C = r\sin\theta|\boldsymbol{\nabla}\Omega|P_{\mathrm{cyc}}, \quad (2)$$

with $P_{\mathrm{cyc}} = 11$ years as a cycle period. The angular velocity gradients in the solar interior were detected seismologically by Antia et al. (2008). The conversion factor of Eq. (2) estimated using their data (GONG data averaged over the 23rd solar cycle) is shown in Fig. 1.

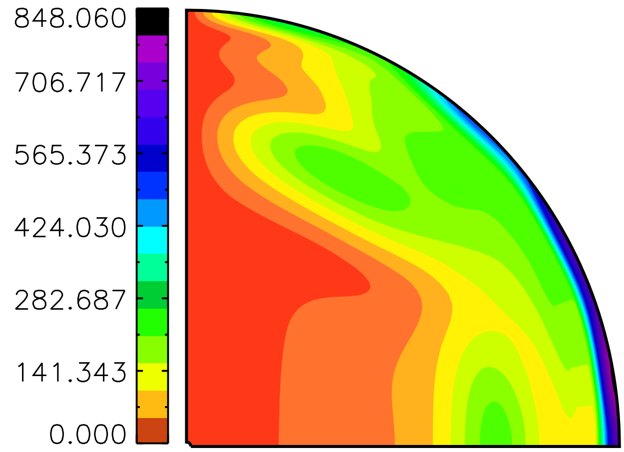


Fig. 1. The poloidal-to-toroidal field conversion factor of Eq. (2) estimated from the helioseismological data on the gradients of rotation rate of Antia et al. (2008).

Helioseismology may underestimate the radial gradient of rotation in the tachocline region. However, the radial gradient shears the radial field, which should be small in the tachocline region. Otherwise it is a relic field penetrating from the radiative interior. The conversion factor of Eq. (2) is an upper bound, which can be reached only if the poloidal field and rotation gradient are perfectly aligned. Also taking $P_{\mathrm{cyc}}$ as the winding time overestimates the conversion factor. The toroidal field is amplified only on the rise phase of an activity cycle, before the poloidal field inversion. However, even the upper bounds of the conversion factor of Fig. 1 are too small for producing super-kilogauss toroidal fields with distributed dynamo models.

Galloway and Weiss (1981) estimated the total magnetic flux of the active regions of a solar cycle to exceed $10^{24}$ Mx. Their estimations also suggest that a comparable or perhaps slightly smaller toroidal flux should be stored near the bottom of the convection zone at the activity maxima. Assuming the latitudinal extend of the storage region of about 30° and its radial extend $< 0.1R_\odot$, we find the low bound for the toroidal field strength of about 4000 Gs. Cameron and Schüssler (2015) found that the net toroidal flux does not depend on how the poloidal field is distributed inside the convection zone. The flux is uniquely defined by the surface radial field and differential rotation. The observed surface fields correspond to the peak values of toroidal flux of about $5 \times 10^{23}$ Mx in the recent solar cycles 22 and 23 (Cameron and Schüssler, 2015). If the surface active regions emerge from near the base of the convection zone, super-kilogauss toroidal fields should be present in the near-base region.

The large-scale poloidal field on the solar surface is of the order of 1 Gauss (Stenflo, 1988; Obridko et al., 2006). If the field is distributed smoothly inside the convection zone, toroidal fields well below one kilogauss are produced near its base (Fig. 1). It may be argued that this refers to the mean or large-scale field only. The field in convectively-unstable fluids fragments in a fibril state with a much stronger field in the fibrils compared to its mean value (Parker, 1984). However, the magnetic flux of a sub-kilogauss *mean* toroidal field in the near-bottom region is too small ($< 10^{24}$ Mx) to feed active regions of a solar cycle.

The problem can be resolved by downward diamagnetic pumping. The meridional field pumped to the base of convection zone can be two orders of magnitude stronger compared to the surface poloidal field (Kitchatinov and Olemskoy, 2012). The conversion factors of Fig. 1 then

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