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# The effect of thermal boundary conditions on dynamos driven by internal heating

K. Hori*, J. Wicht, U.R. Christensen

*Max-Planck Institute for Solar System Research, Max-Planck-Strasse 2, 37191 Katlenburg-Lindau, Germany*

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ABSTRACT

The early dynamos of Mars and Earth probably operated without an inner core being present. They were thus exclusively driven by secular cooling and radiogenic heating which can both be modeled by homogeneously distributed heat sources. Some previous dynamo simulations that explored this driving mode found dipole dominated magnetic fields, while other reported multipolar configurations. Since these models differed both in the employed outer thermal boundary conditions and in the size of the inner core, which was still retained for practical reasons, the cause for the variation in field geometry remained unclear. Here we investigate this issue and find that strong dipole dominated fields are preferred for fixed heat flux conditions whereas weaker multipolar fields are typical for fixed temperature conditions. The size of the inner core, on the other hand, proved to be of minor influence. The stronger dipolar fields for fixed heat flux conditions promote larger convective structures. Since the mantle of the terrestrial planets controls the heat flux rather than the temperature at the core-mantle boundary, our results suggest that the early dynamos of Mars and Earth would have produced dipole dominated magnetic fields.



## 1. Introduction

According to thermal evolution models, Earth had no solid inner core until about 1–2 billion years ago (Labrosse, 2003; Nimmo, 2007). When an inner core is absent, a dynamo must be driven by volumetric secular cooling and possibly radiogenic internal heating, whereas the present geodynamo is thought to be largely driven by a buoyancy flux from below, arising from the release of latent heat and the compositional enrichment associated with inner core freezing (e.g. Stevenson et al., 1983; Labrosse, 2003; Nimmo, 2007). The early Martian dynamo probably also operated without an inner core and was driven by secular cooling (e.g. Stevenson, 2001). If a growing inner core had been present, it is difficult to understand why the Martian dynamo stopped to operate approximately 4.1 billion years ago (Lillis et al., 2008). In the absence of an inner core the dynamo could have stopped because the declining heat-flow has led to a subadiabatic temperature gradient in the fluid core.

The presence or absence of an inner core affects the dynamo in various ways—through its electrical conductivity, through its influence on the geometry of the flow in the outer core and by its role as a buoyancy source. Inner core conductivity has been proposed as being essential for stabilizing the dipole field against too frequent reversals (e.g. Hollerbach and Jones, 1993). Numerical simulations comparing cases with a conducting and an insulating inner core (Wicht, 2002) and with or without an inner core (Sakuraba and Kono, 1999) suggest that the differences for the observable field outside the core are small.

The geometrical effect arises because the inner core represents an obstacle to the preferred pattern of convection, which consists of nearly geostrophic convection columns aligned with the rotation axis (e.g. Busse, 2002). This effect occurs also for non-magnetic convection. Dormy et al. (2004) investigated the onset of thermal convection with homogeneous heat sources in the inner and outer core. They find that the structure of convection at onset hardly depends on the inner core radius, provided it is less than approximately 45% of the core radius (so-called thick shell regime), and that the convection is similar to that in a full sphere.

Perhaps the most profound difference between dynamos with and without an inner core comes from the different distribution of buoyancy sources. In the absence of an inner core, the lack of the buoyancy flux associated with its growth implies that convection is weaker and Ohmic dissipation lower than for the present Earth's core. Furthermore, the different distribution of sources and sinks of buoyancy flux may lead to different morphologies of the magnetic field. Here we separate the question of the existence of an inner core from that of the mode of driving convection in the fluid core. We focus on dynamos in a thick shell where the buoyancy sources are volumetrically distributed and where the outer boundary represents the sink for the buoyancy flux. This represents convection that

* Corresponding author. Tel.: +49 5556 979 379; fax: +49 5556 979 240.
*E-mail address:* hori@mps.mpg.de (K. Hori).

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is driven by internal heat sources or secular cooling or a combination of both. Hereafter we refer to this scenario as internal heating and we use the term basal heating when the buoyancy source is located at the inner core boundary.

Previous dynamo simulations proposed that dynamos driven by significant degrees of internal heating produce different field properties, compared to those with no internal heating. Busse and co-workers (e.g. Grote et al., 2000; Busse, 2002) studied the field morphology for dynamos driven by a combination of internal heating and basal heating, mostly with stress-free mechanical boundary conditions. Depending on the various control parameters, they found a diversity of field morphologies, comprising dipolar and non-dipolar solutions with various field geometries. Dynamos with dipole-dominated fields are more commonly found with pure basal heating and no-slip mechanical condition (e.g. Christensen et al., 1999). Directly comparing cases of internal heating, of basal heating and of compositional convection (where buoyancy sources at the inner boundary are balanced by volumetric sinks) for the case of no-slip conditions, Kutzner and Christensen (2000, 2002) found that internal heating favours solutions with non-dipolar magnetic fields at the same control parameter values where dipolar dynamos prevail for the other modes of driving convection.

For dynamos with an imposed temperature contrast Christensen and Aubert (2006) found that a local Rossby number, which is a measure for the ratio between inertial and Coriolis forces, controls the field structure. At low values the solution is dipolar and at high values (approximately >0.12) the field at the outer boundary of the dynamo is dominated by higher multipoles. Olson and Christensen (2006) showed that the dipolar-multipolar transitions as a function of the local Rossby number is less sharp for internally heated dynamos than it is for models with fixed temperature contrast and that non-dipolar solutions persist to lower values of the local Rossby number. The dipole moment was found to be generally weaker at the same value of the buoyancy flux in the internally heated case.

In contrast to these earlier results, Aubert et al. (2009) found in recent dynamo simulations relatively small differences, at a given value of the convective power, in terms of the magnetic field strength and of the relative dipole contribution to the field at the outer boundary between dynamos with internal heating, basal heating or compositional convection. Their models for internally heated dynamos differed in two respects from earlier ones. Previous models employed a condition of fixed temperature on the outer boundary, whereas Aubert et al. (2009) impose a fixed homogeneous heat flux, which is a more natural condition for dynamos in terrestrial planets. The difference in the thermal boundary condition can have a significant influence on the pattern of convection and the properties of the magnetic field (Sakuraba and Roberts, 2009). Furthermore, most earlier studies used the present radius of the Earth's inner core, 35% of the core radius, whereas Aubert et al. (2009) reduced the inner core size to 1–5%. Most internally heated models retained a passive inner core, because the current spectral dynamo codes usually only allow to simulate a spherical shell but not a full sphere. The differences between the results of Aubert et al. (2009) and those of Kutzner and Christensen (2000, 2002) and Olson and Christensen (2006) could be caused by the thermal boundary condition or by the difference in inner core size.

Roberts and Glatzmaier (2001) explored three models related to the past, present and future geodynamo with different sizes of the inner core, using heat flux conditions on the boundaries. In their model with a small inner core the dipole was found to be more dominant than in the other cases. However, even their model with a small inner core was mainly driven by basal heating, because the smaller surface area of the inner core was balanced by a much faster growth in radius than at present. For this reason there is a strong difference between the situation without an inner core and that with even a small inner core. The influence of the inner core size on the dynamo onset in the case of bottom heated convection was also studied by Heimpel et al. (2005).

In most MHD dynamo simulations fixed temperature conditions have been the standard (e.g. Kageyama and Sato, 1995; Olson et al., 1999; Takahashi et al., 2008a). Others used a heat flux boundary condition, but in many cases the emphasis was on exploring the influence of various pattern of heterogeneous heat flux distribution at the core-mantle boundary (e.g. Glatzmaier et al., 1999; Olson and Christensen, 2002; Christensen and Olson, 2003; Takahashi et al., 2008b). Stanley et al. (2008) proposed that a strong hemispherical dichotomy of the heat flux out of the early Martian core has led to a dynamo operating only in one hemisphere. This could explain the observed uneven distribution in the magnetization on the Martian crust observed by Mars Global Surveyor. The question whether the nature of the thermal boundary condition, fixed flux or fixed temperature, makes a fundamental differences has been addressed in a few studies only. For non-magnetic rotating convection the heat flux boundary condition favours larger scales of convection than the temperature condition near the onset of convection (Takehiro et al., 2002). Comparing dynamo models with different thermal boundary conditions, Busse and Simitev (2006) reported no major qualitative differences. Recently, Sakuraba and Roberts (2009) compared the effect of the boundary condition for a rapidly rotating dynamo model (low Ekman number). They found that the heat flux condition promotes stronger magnetic fields and larger scales in the velocity and magnetic field.

The purpose of this paper is to clarify the influence of thermal boundary conditions and the size of the inner core on dynamos driven by internal heating. The inner core is kept only for technical reasons and is made passive in the sense that it is not a source of buoyancy nor is it electrically conducting. By varying its size we want to determine if its kinematic influence on the dynamo is significant. We compare dynamos with uniform temperature and uniform heat flux, respectively, for otherwise identical sets of control parameters. The model setup and the diagnostic parameters that we use to compare the results are described in Section 2. In Section 3 we demonstrate that the thermal boundary condition rather than the inner core size has a major role on the field morphology and in Section 4 we discuss the implications for the early geodynamo and the Martian dynamo.

## 2. Formulation

We model a rotating spherical shell with inner core radius $r_i$ and outer radius $r_o$ that is filled with an electrically conducting fluid. Convection is driven by homogeneously distributed volumetric heat sources. We solve the following dimensionless equations in the Bousinesq approximation: the heat transport equation (1), the Navier-Stokes equation (2), the induction equation (3), and the conditions for incompressible fluid and solenoidal field (4):

$$\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \frac{1}{Pr} \nabla^2 T + 1, \quad (1)$$

$$Ek \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) + 2\hat{\mathbf{e}}_z \times \mathbf{u} = -\nabla P + Ra' T \frac{\mathbf{r}}{r_o} + Ek \nabla^2 \mathbf{u} + \frac{1}{Pm} (\nabla \times \mathbf{B}) \times \mathbf{B}, \quad (2)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \frac{1}{Pm} \nabla^2 \mathbf{B}, \quad (3)$$

$$\nabla \cdot \mathbf{u} = 0, \quad \nabla \cdot \mathbf{B} = 0, \quad (4)$$