Physics of the Earth and Planetary Interiors 181 (2010) 42–53

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

journal homepage: www.elsevier.com/locate/pepi

Effects of a radially varying electrical conductivity on 3D numerical dynamos

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ARTICLE INFO

Article history:
Received 30 May 2009
Received in revised form 21 February 2010
Accepted 10 March 2010

Edited by: K. Zhang.

Keywords:
Variable electrical conductivity
Numerical dynamos
Geodynamo
Mercury

ABSTRACT

The transition from liquid metal to silicate rock in the cores of the terrestrial planets is likely to be accompanied by a gradient in the composition of the outer core liquid. The electrical conductivity of a volatile-enriched liquid alloy can be substantially lower than a light-element-depleted fluid found close to the inner core boundary. In this paper, we investigate the effect of radially variable electrical conductivity on planetary dynamo action using an electrical conductivity that decreases exponentially as a function of radius. We find that numerical solutions with continuous, radially outward decreasing electrical conductivity profiles result in strongly modified flow and magnetic field dynamics, compared to solutions with homogeneous electrical conductivity. The force balances at the top of the simulated fluid determine the overall character of the flow. The relationship between Coriolis, and Lorentz forces near the outer core boundary controls the flow and magnetic field intensity and morphology of the system. Our results imply that a low conductivity layer near the top of Mercury's liquid outer core is consistent with its weak magnetic field.

1. Introduction

Variations in the physical properties of fluids in planetary dynamos define the character of the observed intrinsic magnetic field (e.g., strength, geometry and time variability). Changes in the electrical conductivity of the fluid as a function of depth may become relevant in the context of terrestrial and gas giant planets. In this paper we explore (with a focus on the terrestrial planets) how the radial variation of electrical conductivity in planetary cores, may result in changes to dynamo-generated magnetic fields.

1.1. Terrestrial planets

The cores of the terrestrial planets are composed principally of iron, with minor but significant amounts of nickel and lighter elements. It has long been known that an iron–nickel core would have too high a density to be compatible with Earth's moment of inertia and seismic data (e.g., Birch, 1952; Poirier, 1994). A compatible Earth core density model can result from the inclusion of about 8% by weight of one or more light elements. Detailed models of core composition are based primarily on the constraints of seismology, mineral physics, geochemistry, metallurgy, and cosmochemisty. Silicon, sulphur, and oxygen are the primary candidates for the light elements. Sulphur is likely to be a significant component; but the depletion of light elements in the process of accretion in the inner solar system limits sulphur to about 2 wt% in the core.

Recent reviews of core differentiation and composition distinguish between models considering silicon versus those considering oxygen as the primary light element. Composition models give weight percents of Fe $\simeq$ 85–88%, Ni $\simeq$ 5% Si $\simeq$ 0–7%, O $\simeq$ 0–4%, and S $\simeq$ 2% (e.g. McDonough, 2003; Wood et al., 2006). Solidification of a more or less pure iron–nickel inner core may exclude the lighter elements, which would then be enriched in the outer core. The ratio of the inner core radius (1221 km) to the core radius (3480 km) is 0.35, and the mass of the inner core is only about 5% of the total core mass. So the bulk composition of the outer core is only slightly different from that of the whole core.

Convection in the liquid outer core is driven by a combination of compositional and/or thermal buoyancy. Thermal buoyancy available to drive convection and dynamo action originates primarily from the latent heat of solidification at the inner core boundary (ICB) and possibly from cooling at the core–mantle boundary (CMB). Secular cooling at the CMB does not guarantee a source of convective instability since heat can be conducted through a stably stratified layer (a super-adiabatic heat flux is needed). Compositional buoyancy originates at the ICB due to light-element enrichment in the residual liquid associated with inner core solidification. A source of compositional buoyancy near the CMB could come from precipitation from a silicate-enriched layer at the top

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0031-9201/$ – see front matter
doi:10.1016/j.pepi.2010.03.006

of the core, leaving a light-element depleted, heavy residual liquid and a silicate sediment layer at the CMB (Buffett et al., 2000).

Temperature and pressure dependence of electrical conductivity may lead to sizable variations with depth (Stacey and Anderson, 2001). Assuming a well-mixed outer core and a Si concentration of $X_{Si} = 0.25$ in a dual species alloy, the authors found that the most extreme variation in the fluid core of Earth results in a factor of 1/2 difference for the electrical conductivity and about 3/4 for the thermal conductivity from the ICB to the CMB. Although the effects of different impurities in the alloy have not been explored experimentally, Stacey and Anderson (2001) argue that the effects of impurities other than Si do not significantly change their estimates. A later revision (Stacey and Loper, 2007) found that the variation in electrical and thermal conductivities had been overestimated due to the assumption of treating Fe as an electronically simple metal. Their later results predict a difference in the electrical conductivity of a factor of 0.78 between that near the CMB when compared to the ICB. Those estimates were made under the assumption of a well-mixed outer core. However, gradients in material properties would be amplified in a compositionally stratified layer.

The existence of a thermally and/or compositionally stably stratified layer near the top of the Earth's core has been both suggested and argued (Jacobs, 1975; Fearn and Loper, 1981; Lister and Buffett, 1998; Braginsky, 1993, 2007). Here we will focus on the possibility of a compositionally stratified layer near the top of the core, since the electrical conductivity in such a layer would decrease with radius (due to the higher light-element concentration when compared to the bottom of the fluid core). Two mechanisms by which a compositionally stratified layer can grow are by chemical diffusion from the mantle directly to the top of the core (Lister and Buffett, 1998), and by buoyant transport of light-element enriched residual liquid from inner core solidification (Moffatt and Loper, 1994). Chemical diffusion is a slow process and would not result in a layer thickness greater than about 10 km (Lister and Buffett, 1998). On the other hand, buoyant rise of light-element rich residual liquid could be an efficient process to build a layer of greater thickness. A thick layer with a significantly anomalous density would likely be detected as a seismically fast layer. Seismological constraints have been so far inconclusive. However, recent seismological results using outermost core waveforms seem to be consistent with the existence of a low density layer of about 100 km thickness (Alexandrakis and Eaton, 2007; Tanaka, 2007).

It has been confirmed that Mercury has a liquid iron core (Margot et al., 2007). Furthermore, it is likely that Mercury's weak intrinsic magnetic field is generated by a dynamo in its liquid outer core. Neither the details of Mercury's core composition nor the size of its inner core is known (Hauck et al., 2004; Solomon et al., 2008; Heimpel and Kabin, 2008). Observations of Mercury's contractional lobate scarps imply a planetary radial contraction of about 3 km, small compared to an estimated 17 km of contraction that would result from a completely solidified core. This implies that Mercury may have a relatively large outer core, perhaps earth-like proportion. For a thick-shell outer core to exist in Mercury, given its small size, Hauck et al. (2004) estimated that the light elements (such as S or Si) in the core are present in relatively high concentration. This suggests the possibility of a large and stratified Hermean outer core with a thick, and stably stratified outermost layer. Such a layer would be compositionally stratified (in contrast to thermally stratified models previously proposed, e.g., Christensen, 2006) with a radial increase in the proportion of a light elements and a radial decrease in electrical conductivity.

1.2. Gas giant planets

The magnetic field in the gas giants is generated within a metallic hydrogen region. Experimental results indicate that the transition from metallic to molecular hydrogen yields a wide range of pressures where the electrical conductivity is non-negligible and thus varies slowly with depth in planetary interiors (Nellis, 2000). The internal structure has been deduced to first order from measurements of the moment of inertia and total mass of each planet (e.g., Guillot, 2005). However, constraints on hydrogen and helium mixtures at high pressures need to be found in order to better determine the internal structure of the gas giants. The additional effect of helium may complicate further the underdetermined internal layering of gas giants (e.g., Stevenson, 2008). The metallic to molecular hydrogen transition is of particular interest from the point of view of the internal dynamics. The depth and radial extent of this transition are important for magnetic field generation and in understanding the observable magnetic field morphology. This is a task for future investigation.

In this paper, we present results from a numerical dynamo model with radially varying electrical conductivity (Gómez-Pérez, 2007). To implement the radially variable conductivity, we modified an existent numerical code (originally MagIC 2.0, Wicht, 2002), that uses the Boussinesq approximation. We focus this study on the effect of the varying conductivity on the dynamo action, and on the generated magnetic field. With this new implementation we performed a set of tests to analyze the model's consistency with previously published work. In Section 2 we include a review of numerical models that included stratified liquids. In Section 3 we present the necessary modification to the dynamo equations, and to the numerical code. The parameters explored for twenty runs studied in this paper are included in Section 4. We present the results in Section 5, and the discussion and conclusions are found in Sections 6 and 7, respectively. We also included a table of symbols in Appendix A.

2. Stratified planetary interiors in numerical simulations

The study of planetary and solar dynamos has evolved rapidly in the past two decades due to code development and the accessibility to powerful computers used to solve numerically the equations of motion of rotating fluids. Solutions of numerical dynamos share characteristics with Earth's dynamo with respect to temporal variability, evolution, and mean geometry (e.g., Kageyama et al., 1993; Glatzmaier and Roberts, 1995; Kuang and Bloxham, 1997; Christensen et al., 1998). More recently, numerical models have been successful in reproducing non-dipolar and weak fields such as those observed for the ice giants (e.g., Gómez-Pérez and Heimpel, 2007; Stanley and Bloxham, 2006). Nevertheless, these models of planetary dynamos rely on strong assumptions that do not necessarily represent realistic physical conditions expected for planetary interiors. For example, due to hardware limitations, numerical models cannot simultaneously resolve planetary- and small-scale flow, both of which are prevalent for low viscosity fluids such as liquid iron or metallic hydrogen in a planetary setting.

2.1. Buoyancy stratification

Christensen and Wicht (2008) and Christensen (2006) implemented a stably stratified (non-convecting) layer at the top of the electrically conductive fluid in planetary dynamo models. They showed that small-scale magnetic fields may be generated in the deep interior of the electrically conductive fluid, shielded by a stably stratified layer. This outer layer acts as a filter that mainly damps the rapidly varying small scale components by the magnetic skin effect. They concluded that the axisymmetric field of Saturn and the relatively weak field of Mercury may be explained by a stably stratified layer at the top of the dynamo region.