Physics of the Earth and Planetary Interiors 247 (2015) 56–64

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

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

On core convection and the geodynamo: Effects of high electrical and thermal conductivity

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ARTICLE INFO

Article history:
Received 16 August 2014
Received in revised form 24 March 2015
Accepted 10 April 2015
Available online 6 May 2015

Keywords:
Earth's core
Geodynamo

ABSTRACT

Recent theory and experiment suggest the thermal and electrical conductivities of the Earth's core are 2–4 times higher than previously thought. This has important consequences for the core's thermal history and behaviour of the geodynamo. The conductivities increase with depth, with a discontinuous jump at the inner core boundary caused by the change in composition and phase change to a solid. Properties of putative core alloys are now sufficiently well known to make it worth exploring the effects of their variation with depth within the core. The magnetic decay times are increased to 58 kyr for the whole core, considerably longer than the advection time (the time it takes fluid to traverse the outer core), and 9 kyr for the solid inner core. Heat conducted down the adiabat through the core–mantle boundary is in excess of 15 TW, which is one third of the Earth's total heat loss and 2–3 times higher than most estimates. The core can be stirred by chemical convection against a stable thermal gradient, but at a cost that reduces the effective power available for generating magnetic field. We estimate the minimum heat flux required to sustain thermal dissipation alone to be 5–8 TW, but this is almost certainly a gross underestimate because it leaves nothing for convective or dynamo processes. Conduction gradients for cooling rates corresponding to these minimum heat fluxes are subadiabatic in the top 740 km of the core, which is also unlikely because geomagnetic secular variation requires upwelling somewhere near the core surface. Lateral variations in heat flux at the core–mantle boundary could easily be large enough to exceed the adiabatic value in some places, leading to mixing throughout the upper core. This not only reduces the total heat flux required to produce a well-mixed core, but also explains how mantle anomalies can exert a strong influence on core convection and the form of the geomagnetic field at the core surface. We propose a model of core convection that is vigorous in the lower part and very weak in the upper part.

1. Introduction

Until recently calculations of the core's thermal history and power supply for the geodynamo have been limited by poor knowledge of the material properties of likely core materials. The last decade has seen great improvements in both theoretical and experimental determinations of the properties of iron and iron alloys at high temperature and pressure, including density, seismic parameter, melting temperature, Grüneisen's parameter, material diffusivities, specific and latent heats, viscosity, and chemical potential. Studies of mixtures have extended to silicon, sulphur, oxygen, and carbon (Poirier, 1994; Alfè et al., 2002; Badro et al., 2014). Although some uncertainty remains, there is a remarkable degree of agreement between many studies.

Most recently, the all-important thermal and electrical diffusivities of Fe-Si alloys have been measured experimentally (Gomi et al., 2013) and calculated theoretically (de Koker et al., 2012; Pozzo et al., 2012; Pozzo et al., 2013; Pozzo et al., 2014) at core pressures and temperatures; they are found to be some 2–7 times higher than the widely-used estimates of Stacey and Anderson (2001) and Stacey and Loper (2007) rather than lower, as thought by some previous authors [e.g. Davies, 2007]. The higher values arise from a saturation that occurs when the mean free path between electron scattering events becomes comparable to the inter-atomic distance (Gunnarsson et al., 2003); the resistivity no longer follows the linear increase with temperature predicted by the Bloch–Grüneisen law but falls away at high temperature,

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http://dx.doi.org/10.1016/j.pepi.2015.04.002
0031-9201/

leading to an increase in conductivity (Wiesmann et al., 1977). This saturation effect had not been taken into account in previous estimates of the conductivities.

These very high values of thermal (k) and electrical (σ) conductivity have dramatic effects on the thermal history of the core and theory of the geodynamo. High k means an enormous amount of heat is conducted down the adiabat and is not available to drive the dynamo. High σ extends the magnetic diffusion time of the geomagnetic field, the time it would take the field to decay in the absence of any motion.

Core properties are now well enough known to reduce the uncertainties in core thermal history calculations dramatically. Furthermore, *ab initio* calculations give the depth-variation of most of these quantities accurately enough to make it worth discussing the depth-dependence of buoyancy forcing and dynamo driving. In this paper we therefore revisit estimates of present-day core heat flux, stratification, and dynamo power, including depth variations. We use a core model, described in Section 2, with an Fe–Si–O composition that matches the densities of the inner and outer cores. The crucial parameter is the density jump at the inner core boundary (ICB), most recently determined from normal mode eigenfrequencies as 0.8 ± 0.2 gm/cc (Masters and Gubbins, 2003). We use 3 compositions corresponding to 3 values of the jump, 0.6 (PREM), 0.8 and 1.0 gm/cc.

We first calculate the heat conducted down the adiabat for each density jump and a lower bound on the core cooling rate and heat flux required to mix the entire liquid outer core by thermo-chemical convection. The lower bound is less than that conducted down the adiabat at the core–mantle boundary (CMB) because compositional buoyancy acts against thermal buoyancy in places, driving heat downwards. In Section 4 we solve for the density profiles arising from the various sources of buoyancy as a guide to the convective stability as a function of depth within the core. In Section 5 we examine the effect of the electrical conductivity by calculating the magnetic decay modes for depth-varying conductivities and the effects of depth-variation of all the parameters on convection. We finish with a discussion of possible stable regions and conclusions for the true state of convection in the core. The whole discussion is restricted to the present-day core.

2. The core model

We assume a Fe–Si–O core with compositions that fit the seismic density values with a variable inner core boundary density jump, using the results from Alfè et al. (2002) and Alfè et al. (2007). S and Si partition almost equally between the liquid and solid phases, while O remains almost entirely in the liquid. Only Si is used here since S behaves in a closely similar fashion (Alfè et al., 2000)—replacing Si with S should make little difference. The seismic density jump determines the O content of the liquid core while the Si content adjusts to preserve the density of the inner core at values somewhat lower than those of pure iron. The density profiles for the outer core were calculated as described in Pozzo et al. (2013) and for the inner core in Pozzo et al. (2014).

Impurities lower the melting point, in the case of the core by many hundreds of degrees below the melting point of pure iron. The temperature at the ICB therefore varies with concentration, being lower for higher concentrations of light elements and therefore higher density jumps at the ICB. The adiabatic temperature is calculated by the usual integral

$$T_a(r) = T_o \exp\left\{\int_r^{r_o} \frac{g\gamma}{\phi} dr\right\} = T_i \exp\left\{-\int_{r_i}^{r} \frac{g\gamma}{\phi} dr\right\} \tag{1}$$

which leads to the ratio

$$\frac{T'_a}{T_a} = -\frac{g\gamma}{\phi}, \tag{2}$$

where prime denotes differentiation with respect to radius, r, T_o is the CMB temperature, T_i the ICB temperature, and r_o the CMB radius. Acceleration due to gravity, g, and the seismic parameter, ϕ, are well determined by seismology. The thermodynamic Grüneisen parameter, γ, has been found from first principles calculations to be close to 1.5 throughout the core. The main uncertainty in $T_a(r)$ is T_i, the melting temperature at the ICB; its gradient is proportional to T_i and is therefore shallower for the lower ICB temperatures associated with larger ICB density jumps, which in turn require higher concentrations of the impurity that lowers the melting point. The adiabat decreases significantly with depth in the core because of the decrease in g/ϕ.

Another useful formula follows from the time derivative of (1). The right hand side depends only on physical properties of the core, and while the temperature may change by as much as 10%, the exponent changes by a much smaller amount, of order $\alpha_T\gamma T$ or less than 1%. Differentiating with respect to time and ignoring any secular change in $g\gamma/\phi$ gives

$$\frac{1}{T_a}\frac{dT_a}{dt} = \frac{1}{T_o}\frac{dT_o}{dt}, \tag{3}$$

which allows us to refer the cooling rate at any depth in the core to that at the CMB.

The thermal expansion coefficient is related to the Grüneisen parameter by its thermodynamic definition:

$$\alpha_T = \frac{\gamma C_p}{\phi}. \tag{4}$$

Both γ and the specific heat C_p vary little across the core so α_T varies inversely as the seismic parameter: it decreases with pressure. The effect is substantial but has so far not received much attention in the context of core convection. A decrease in α_T with depth means a decrease in thermal buoyancy deep in the core, and a corresponding decrease in fluid flow and magnetic induction.

Mathematical variables and their values are given in Table 1. Variables that are model dependent are given in Table 2. Thermal and electrical conductivities are shown as a function of pressure in Fig. 1. Both increase with depth, the thermal by some 50%, the electrical less so because of the rising temperature (the Wiedemann–Franz law predicts $k \propto \sigma T$). Both are substantially

Table 1
Mathematical quantities and their numerical values where they are independent of radius and inner core density jump. Ranges are from bottom to top of the core.

c	Concentration of light material	m^{-3}
T_a	Adiabatic temperature	K
T_{co}	Cotemperature	K
$\partial T_m/\partial P$	Melting gradient at ICB	9.0 K GPa^{-1}
g	Acceleration due to gravity	ms^{-2}
q	Heat source per unit volume (generic)	W m^{-3}
s	Mass source per unit volume (generic)	kg m^{-3} s^{-1}
r_i	Inner core radius	1.221×10^6 m
r_o	Outer core radius	3.485×10^6 m
V_{oc}	Volume of outer core	1.70×10^{20} m^3
M_{oc}	Mass of outer core	1.85×10^{24} kg
M_c	Mass of whole core	1.9477×10^{24} kg
C_P	Specific heat at constant pressure	715 J $kg^{-1}K^{-1}$
L	Latent heat of outer core liquid	0.75×10^6 J kg^{-1}
α_{c_O}	Compositional expansion coefficient of oxygen	1.10
γ	Grüneisen's constant	1.5
$\bar{\eta}_c$	Volume-averaged magnetic diffusivity, whole core	0.6746 m^2 s^{-1}
$\bar{\eta}_i$	Volume-averaged magnetic diffusivity, inner core	0.5219 m^2 s^{-1}