Physics of the Earth and Planetary Interiors 223 (2013) 2–7

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

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

Causes and consequences of outer core stratification

George Helffrich [a],*, Satoshi Kaneshima [b]

[a] Earth Sciences, University of Bristol, Wills Mem. Bldg., Queen's Road, Bristol BS8 1RJ, UK
[b] Earth and Planetary Sciences, University of Kyushu, 6-10-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan

ARTICLE INFO

Article history:
Available online 27 July 2013
Edited by M. Jellinek

Keywords:
Core
Seismology
Geomagnetism
Geodynamo

ABSTRACT

The Earth's outer core appears to be compositionally layered. Exotic mechanisms such as an original chemically layered core preserved from the Earth's accretionary period, or compositionally different core material delivered by a Moon-creating impactor are conceivable, but require a core whose outermost part has been stratified throughout core history, relying on unknowable processes to achieve. Barodiffusion and core-mantle reaction lead to layers significantly thinner than observed. We show that a balance of mass transferred from the inner core to the top of the outer core is possible, and that the stratification could arise as a byproduct of light element accumulation. However, if a subadiabatic thermal gradient at the top of the outer core exists that quells radial flow, it could serve as a witness of light element accumulation by preventing mixing with the convecting part of the core. The temperature difference through a subadiabatic layer could be 80–300 K and carry heat fluxes through the core-mantle boundary of 0.5–23 TW, given uncertainty in core properties.

1. Introduction

Birch (1952) used finite strain theory and velocity–density systematics of various cosmochemically abundant materials to show that the Earth's core is iron alloyed with perhaps 10% by weight of lighter elements. The amount seems negligibly minor, given the typical uncertainties encountered in geophysical investigations, yet it exerts a major influence on the dynamics, evolution and structure of the core. This is because the Earth cools over time and the liquid alloy crystallizes due to the higher interior pressures. Unequal partitioning of any light element between the solid and the remaining core liquid enriches the liquid, over time, in a less dense light element component (Poirier, 1994). Considerable gravitational potential energy is released by the process (Fearn and Loper, 1981; Stacey and Stacey, 1999), providing a long-term power source to drive the geodynamo. In addition, many elements that alloy with iron develop immiscibility in their liquid state, where an iron-enriched metallic liquid coexists with a light-element enriched ionic liquid, a phenomenon exploited by metallurgists to smelt ores and to make high-quality steels. In the final phases of the evolution of planetary cores, continual light element enrichment will inevitably drive liquids towards immiscibility. This could lead to core stratification; Helffrich and Kaneshima (2004) unsuccessfully sought the signal of liquid immiscibility in the Earth's core, provoking experimental study of the extent of immiscibility in some alloying systems (Tsuno et al., 2007; Corgne et al., 2008; Morard and Katsura, 2010). More subtly, incomplete mixing of light-element enriched fluid liberated by crystallization at the base of the core could lead to a light-element enriched layer at the top of the core. Detection of such a layer is a key step in testing the viability of the light element enrichment process.

The top of the outer core has a long history of study, and virtually all workers find that this region has a different radial velocity gradient with respect to the deeper outer core (Lay and Young, 1990; Tanaka and Hamaguchi, 1993; Garnero et al., 1993; Tanaka, 2004, 2007; Eaton and Kendall, 2006; Alexandrakis and Eaton, 2010; Helffrich and Kaneshima, 2010; Kaneshima and Helffrich, 2013). Helffrich and Kaneshima (2010) and Kaneshima and Helffrich (2013) interpreted their observed gradient to be due to compositionally different material to the remainder of the outer core and proposed it to be a non-convecting zone that evolves gradually from the convecting, well-mixed deeper interior. Here, we examine various ways that compositional layering might arise and be preserved, motivated by their potential effects upon core's dynamical behavior.

2. Methods used to investigate outermost core structure

We provide a brief summary of data sources and methods for outer core study. The travel times of *SmKS*, an arrival that reflects $m-1$ times from the core side of the CMB before ascending to the surface as a shear wave provide the basic data (Fig. 1). As Tanaka and Hamaguchi (1993) summarized the studies prior to theirs, *SmKS* is widely observed after earthquakes and provides a good source of data about the outer core, provided structure near the

---

* Corresponding author. Tel.: +44 1179545400.
E-mail address: george.helffrich@bris.ac.uk (G. Helffrich).

0031-9201/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.pepi.2013.07.005

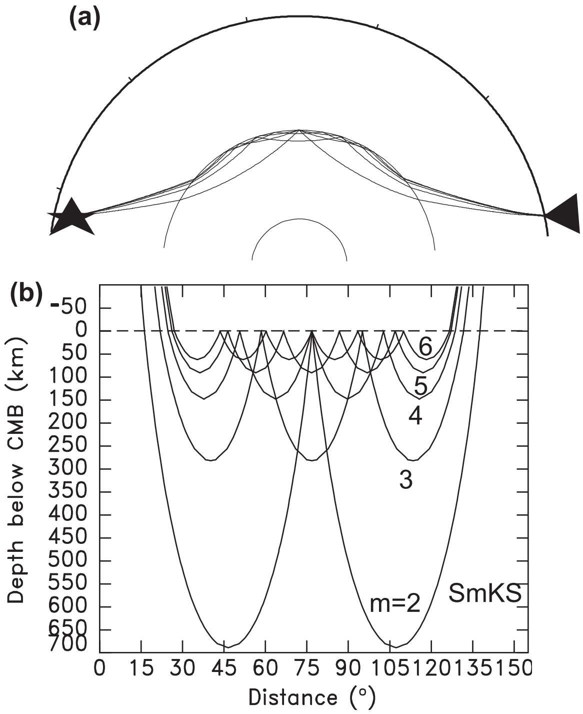

Fig. 1. (a) Ray paths for *SmKS* ($2 \leqslant m \leqslant 6$) for a source (star) 550 km deep to a station (triangle) at 155°. (b) Core legs of ray path. As multiples in core increase, bottoming depth in core decreases. *S6KS* bottoms at ~60 km below the CMB, whereas *S2KS* bottoms ~700 below the CMB.

source, receiver, and near the CMB is properly accounted for. This is typically accomplished by using travel time differences between $S(m+1)KS$ and $SmKS$, with $2 \leqslant m \leqslant 4$. These arrival pairs are sensitive to structure in the topmost 80–700 km of the core, with differences involving larger m sensitive to shallower levels (Fig. 1).

Availability of data from large-scale regional seismic arrays enabled exploration geophysics methods to be applied to deep-Earth investigation. Weak, later arrivals from earthquake sources may be recognized and measured with small formal errors using the higher spatial sampling density of the seismic wavefield of individual events. Helffrich and Kaneshima (2010) and Kaneshima and Helffrich (2013) applied this to *SmKS* and placed strong constraints on wavespeeds and their gradients under the CMB. The observational uncertainties are significantly improved compared to traditional, pseudo-record section techniques (Tanaka and Hamaguchi, 1993; Alexandrakis and Eaton, 2010), as Fig. 2 shows.

The wavespeed profiles in the outermost core may be fit by a finite strain profile to assess whether it represents self-compression of a homogeneous material. Fits of the Birch–Murnaghan (or other finite strain model) to the velocity profile typically yield smooth variations in wavespeed near the top of the outer core. Indeed, PREM (Dziewonski and Anderson, 1981) closely approximates homogeneous self-compression (Fig. 2). A change in outer core velocity gradient beyond the uncertainty limits of the data requires compositional change in the outer core. Fig. 2 shows two recent core wavespeed models compared to PREM. KHOCQ (Helffrich and Kaneshima, 2010) clearly indicates that the outermost core's composition differs from the deeper parts, while AE09 (Alexandrakis and Eaton, 2010) does not. The IASP91 and AK135 models (Kennett and Engdahl, 1991; Kennett et al., 1995) suggest a compositional difference as well, but the models were developed by fitting body wave travel time data and thus lack density constraints (IASP91) or simultaneous solution of body wave and density models (AK135; see Montagner and Kennett (1996)), making the self-compression test harder to quantitatively assess.

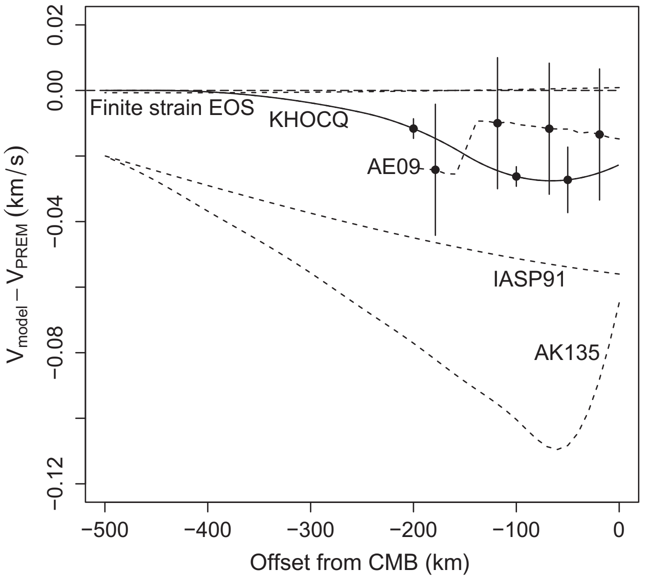

Fig. 2. Two recent outer core wavespeed models compared to PREM in the outermost core. The models are from Helffrich and Kaneshima (2010) (KHOCQ) and from Alexandrakis and Eaton (2010) (AE09), along with their reported 2σ errors. A comparison of two recent whole-earth models AK135 (Kennett et al., 1995) and IASP91 (Kennett and Engdahl, 1991) with PREM is also shown. The short-dashed line that closely follows the zero reference line is a representative Birch–Murnaghan finite strain profile (Birch, 1952) fit to PREM densities and wavespeeds in the outer core (zero pressure ρ 8699.7 kg m^{-3}, isothermal bulk modulus K378.30 GPa, dK/dP 4.08, T_{CMB} 4300 K, Gruneisen parameter γ1.52, and pressure-dependent thermal expansivity α ranges from 5×10^{-6} at CMB to 3×10^{-6} at 1700 km below CMB). The self-compression wavespeed profile is indistinguishable from PREM, within the uncertainty of AE09, but is contradicted by KHOCQ.

3. Discussion of the consequences of layering

3.1. Origin of the layer

The comparisons with the data show the KHOCQ observations to be incompatible with a constant-composition outer core. A layer might form from reaction with the core-mantle boundary, where oxygen from the silicate mantle alloys with the liquid iron of the core (Lay and Young, 1990; Asahara et al., 2007; Buffett and Seagle, 2010). A simple model that we can test is whether diffusion of a buoyant light element introduced at the top of the core can develop a layer via a diffusion profile into the core, assuming that the outermost core is not convecting radially. Fig. 3 shows calculated diffusion profiles for various anion diffusivities in the core. Diffusion is so slow that it is impossible to develop a layer as thick as the one we observe over the lifetime of the Earth.

If the lighter material is advected downwards, some mechanism must prevent entrainment into the rest of the convecting outer core in order to preserve its seismic signature. A thermohaline staircase (Merryfield, 2000) might mix solute downward at rates faster than diffusion, but because the compositional and thermal gradients are anti-parallel, the configuration appears to be in the diffusive regime for double-diffusive convection and more strongly controlled by diffusion rather than advection in fingers, and akin to thermochemical convection (Kelley, 2001).

Another possibility is that the layer is relict from the accretion of the Earth. Models of the early Earth invoke a multi-stage core-formation process (Wood et al., 2006), separated by a Moon-forming giant impact by a Mars-sized impactor that exchanged material with the Earth (Canup and Asphaug, 2001). If layering arose before this event, a mechanism must be invoked to preserve it despite addition of new core material. The mass of the outermost 250 km