様　式　C－１９、F－１９－１、Z－１９　(共通)

科学研究費助成事業　　研究成果報告書

令和　４ 年　７ 月　４ 日現在

機関番号： １２６０８
研究種目： 基盤研究(C)（一般）
研究期間： 2019～2021
課題番号： １９Ｋ０４０３５

研究課題名（和文） Partial Melting of the Inner Core

研究課題名（英文） Partial Melting of the Inner Core

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交付決定額（研究期間全体）：（直接経費）　　1,800,000円

研究成果の概要（和文）：鉄分を多く含む地球の核はほとんどが液体だが、固体の内核は固化して直径2,442 kmまで成長している。内核がどのように結晶化するかはまだ解明されておらず、内核を通過する地震波によって、単純な固化過程では説明できない非常に複雑な内部構造が明らかになっている。近年、固体の内核が再び溶けて液体になる可能性が考えられており、それによって観測結果が説明できる可能性があります。この研究で明らかになったのは、内核の融解は、少量の液体が生成され、多孔質の流れによって表面に移動する部分融解として起こるはずだということです。これは、内核の化学組成に敏感であり、地球科学の大きな未解決問題である。

研究成果の学術的意義や社会的意義
地球の核は、初期の太陽系や地球の形成過程、化学組成などに関する重要な情報を蓄えている。また、地球の水の起源であり、地磁気の発生場所でもあります。この研究は、内核の構造、成長と進化、内核の化学組成と地磁気を発生させる駆動力との関係について、いくつかの重要な問題を提起している。また、この情報は、他の惑星や月のコアの進化や、惑星表面を保護し居住可能にする鍵と考えられている内部磁場を発生させる可能性の理解にも役立つと思われます。この研究で得られた情報は、地球の化学組成や磁場の年代などのモデルにも反映される。

研究成果の概要（英文）：The iron-rich core of the Earth is mostly liquid, but the solid inner core is solidifying and growing to a diameter of 2,442 km. How the inner core crystallizes is still unknown, and seismic waves passing through the inner core reveal a very complex internal structure that cannot be explained by a simple freezing process. Recently, it has been considered that the solid inner core may melt again to become liquid, which may explain the observations. What this study reveals is that the melting of the inner core should occur as partial melting, where a small amount of liquid is produced and transferred to the surface by the porous flow. It is sensitive to the chemical composition of the inner core, which is a major unsolved problem in geoscience.

研究分野： 地球物理学

キーワード： コア　地磁気　地球構成　地球進化論

１．研究開始当初の背景

Key scientific question: Does the interior of the inner core partially melt? If so, what are the consequences for inner core dynamics, seismic structure, composition, and long-term evolution?
Background: Earth's solid inner core freezes (on average) as the core is cooled by loss of heat to the surrounding mantle. But it should not cool at a uniform rate everywhere. Variations in freezing rates arise owing to lateral heat flux variations in the surrounding convecting liquid outer core, caused by Earth's rotation and variable heat flux in the mantle (figure 1). Yoshida et al. (1996) proposed faster cooling and freezing at the equator due to outer core rotation, which deforms the inner core and can explain its axial seismic anisotropy. Alboussiere et al. (2010) and Monnereau et al. (2010) suggested that the inner core could preferentially freeze in one hemisphere and perhaps melt in the opposite hemisphere, causing "inner core translation" that may explain east-west hemisphere differences in seismic structure.

Motivation: Inner core models have considered very simplistic descriptions of melting, with freezing/melting only at the inner core surface. However, incongruent partial melting inside the inner core is often invoked to explain the low seismic shear velocity of the inner core, and could fundamentally alter the dynamics of these processes. Partial melting involves production and expulsion of eutectic melts while creating a refractory solid residue. Melt and residue have distinct composition and density, and migrate according to different physical processes (e.g., percolation vs. viscous compaction and deformation). Partial melt-induced density/buoyancy changes can induce non-linear dynamical feedbacks with translation, deformation, and/or convective overturn.

２．研究の目的

Purpose: This proposed project aims to (1) understand the evolution of the inner core with more realistic melting behavior than considered in the past, (2) assess the range of permissible core evolution scenarios within the present range of uncertainties in external factors (such as heat flow, intrinsic variables such as chemical composition, and physical properties such as viscosity, conductivity, etc.), and (3) build a modeling framework that connects different inner core dynamical states to seismic observations in order to facilitate hypothesis testing. **Scientific Significance:** The inner core is an important target for research because its structure reflects the evolution of the Earth's deep interior, and is sensitive to (1) thermal evolution and (2) chemical composition. Furthermore, the inner core (3) plays a role in the generation of Earth's magnetic field because its growth helps to fuel outer core convection, and melting/freezing processes are fundamental to this driving force. And (4) it is important to understand the evolution of Earth's core as a foundation for considering the cores of other planets (both in our solar system as well as super-Earth) and their magnetic history. Finally (5) the physical properties (e.g., thermal conductivity, viscosity) of the inner core are controversial, and different predictions are expected to produce different dynamical states, hence generating distinguishable seismic structures.

Originality: This will be the first study to consider partial melting inside the inner core, including its non-linear feedbacks with dynamical processes such as convective over-turn, deformation, and/or translation. In the past the driving force for these kinds of inner core-shaping processes have been limited to buoyancy induced by temperature (or heat flux) and chemical composition variations. All of these fields are strongly affected by partial melting, and the buoyancy of the interstitial melt (in a mushy state) itself will also be assessed.

３．研究の方法

Objective 1. What are the necessary conditions for partial melting of the inner core to occur?
(a) Growth history: How does the proclivity for partial melting depend on inner core growth rate?
(b) Core alloy composition: Which potential alloys promote or suppress partial melting, and how do these

affect the nature of the melting process?
(c) Induction of melting: What perturbations (e.g., inner core translation) induce partial melting?

Objective 2. What are the dynamical feedbacks between partial melting and inner core deformation and motion?

- (a) Density changes: What are the density changes in the inner core induced by partial melting?
- (b) Melting Instabilities: Do density changes caused by melting have feedback that drives inner core
  motions? What is the pattern and timing of these instabilities in the inner core?
- (c) Marginal stability: What are the key parameters controlling stability/instability of partial melting?
- (d) Physical properties: Which key physical properties are important (e.g., viscosity, permeability)?

Objective 3. How do partial melting and related instabilities affect the seismological structure of the inner core? (a) Presence of partial melt: How much can be supported to explain a low shear modulus? (b) Deformation fabric: Could seismic anisotropy be explained by partial melt-driven dynamics?

Methods for Objective 1: Develop one-dimensional (radial) time-dependent inner core growth model of viscous solid-liquid compaction and include the effects of and melting/freezing as source terms in the governing equations, constrained by imposed phase diagrams for various alloy compositions (e.g., O, Si, S, C, H, etc.). Compaction models will be benchmarked against previously published results (e.g., Sumita et al., 1996). The influence of perturbations (e.g., upwelling) will be considered by varying all input parameters systematically.

Methods for Objective 2: A previous code (Hernlund & Jellinek, 2010) has already been modified for 2D axisymmetric geometry to model the dynamics of compaction, liquid percolation, and buoyancy-driven flow in the inner core (see figure 2). It employs a standard finite volume solver for the Stokes equations with strongly variable viscosity, and melt-solid separation dynamics are modeled using an alternating-direction implicit solver. When coupled with a thermodynamical model (inherited from objective 1) and phase diagram, this model will enable us to explore the outcome of perturbations in a 2D geometry, and to study the presence/absence of any instabilities that might arise as a consequence of partial melting of the inner core.

Methods for Objective 3. Results from objective 2 can be directly applied to make predictions for the seismic structure effects, by assuming relations for dependence of seismic velocity on melt fraction (3a) and modeling the strain of the inner core and comparing it to models for development of deformation fabrics (3b).

４．研究成果

Results: It was found that there are two modes of melting in the inner core:

(I) Dynamic Equilibrium Melting: Thermodynamic equilibrium between two phases describes the equality of the movement of chemical components and heat between those phases. Thus the inner and outer core can exchange matter even at equilibrium, and this allows the interface between the solid and liquid to migrate so long as the net exchange of material is negligible. This kind of melting is relevant to the surface of the inner core, and may accommodate inner core translation.

(II) Incongruent Partial Melting: The inner core may partially melt to produce a melt having a different composition than the solid. There are several varieties of partial melting that depend on the mode of inner core formation and pressure-dependent changes in the phase diagram through the inner core pressure range (~330-360 GPa). This is most relevant to melting that takes place in the interior of the inner core.

An important finding is that if the phase diagram normalized to the melting temperature of pure iron does not vary over the pressure range of the inner core, then mode (II) produces a melt having the same composition as the one that froze to produce the original solid material. However, if the present day inner core is crystallizing from liquid that is enriched in alloys owing to fractionation, then there is no possibility for completely frozen inner core to partially melt in the canonical scenario of inner core growth. In this case, partial melting can only occur if the the inner core remained partially molten owing to melt retention, or if it originally froze in a different manner. Both of these possibilities have been explored in detail.

In the case where the inner core never completely freezes, any decompression of the material will produce melt (i.e., decompression melting). This excess melt will produce buoyancy, and cause the material to rise, promoting more decompression, more melting, in a positive feedback. This is a new kind of inner core instability that would result in internal deformation and convective overturn. My numerical models as well as a linear stability analysis revealed that there is a critical threshold for instability, and I computed the critical "Rayleigh number" for this process.

We also re-visited the mode of freezing of the inner core, since it was found to be essential for understanding the later possibility of melting the inner core. In particular, models for a dense outer core fluid "F layer" surrounding the inner core allow the bulk outer core to be on either the iron liquidus or an alloy-rich phase liquidus. With mineral physics colleagues, my students and I compiled a large database relating to relevant thermodynamic criteria, and we found that the inner core probably freezes on the alloy-rich liquidus (the inner core boundary itself is at a cotectic). This resurrects a model first proposed by Braginsky (1962) that explains seismological observations of the F layer and also the flux of light alloys to the outer core to power the dynamo without disrupting/mixing the stratified fluid layer surrounding the inner core.

All of these studies dovetailed with and/or motivated other results, and helped to support a variety of publications which are already listed in the final report. This work also helped to support and motivate a portion of the research of two Ph.D. students at the Tokyo Institute of Technology, Dr. Irene Bonati and Dr. Kang Wei Lim. Both of them included this material in their doctoral dissertations and published papers. We are presently following up one of our most exciting results and preparing a publication to submit this year. It was obtained using models of freezing/melting to connect the core composition to thermal evolution constraints: We find that only a limited number of alloy combinations yields plausible heat flows, significantly narrowing our search for the Earth's plausible core composition, one of the greatest unsolved questions of Earth science.

５．主な発表論文等

〔雑誌論文〕　計6件（うち査読付論文　1件／うち国際共著　0件／うちオープンアクセス　1件）

１．著者名 Irene Bonati	４．巻 None
２．論文標題 The evolution and diversity of rocky planets: From the core to the atmosphere...	５．発行年 2021年
３．雑誌名 Ph.D. Dissertation, Tokyo Institute of Technology	６．最初と最後の頁 N/A
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

１．著者名 Lim Kang Wei、Bonati Irene、Hernlund John W.	４．巻 48
２．論文標題 A Hybrid Mechanism for Enhanced Core‐Mantle Boundary Chemical Interaction	５．発行年 2021年
３．雑誌名 Geophysical Research Letters	６．最初と最後の頁 N/A
掲載論文のDOI（デジタルオブジェクト識別子） 10.1029/2021GL094456	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

１．著者名 Shephard Grace E.、Houser Christine、Hernlund John W.、Valencia-Cardona Juan J.、Tr?nnes Reidar G.、Wentzcovitch Renata M.	４．巻 12
２．論文標題 Seismological expression of the iron spin crossover in ferropericlase in the Earth’s lower mantle	５．発行年 2021年
３．雑誌名 Nature Communications	６．最初と最後の頁 N/A
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41467-021-26115-z	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

１．著者名 Tagawa Shoh、Sakamoto Naoya、Hirose Kei、Yokoo Shunpei、Hernlund John、Ohishi Yasuo、Yurimoto Hisayoshi	４．巻 12
２．論文標題 Experimental evidence for hydrogen incorporation into Earth’s core	５．発行年 2021年
３．雑誌名 Nature Communications	６．最初と最後の頁 N/A
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41467-021-22035-0	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

1．著者名 Houser C.、Hernlund J.W.、Valencia-Cardona J.、Wentzcovitch R.M.	**4．巻** 308
2．論文標題 Discriminating lower mantle composition	**5．発行年** 2020年
3．雑誌名 Physics of the Earth and Planetary Interiors	**6．最初と最後の頁** 106552～106552
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.pepi.2020.106552	**査読の有無** 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	**国際共著** -

1．著者名 Hernlund John William、Bonati Irene	**4．巻** 124
2．論文標題 Modeling Ultralow Velocity Zones as a Thin Chemically Distinct Dense Layer at the Core‐Mantle Boundary	**5．発行年** 2019年
3．雑誌名 Journal of Geophysical Research: Solid Earth	**6．最初と最後の頁** 7902～7917
掲載論文のDOI（デジタルオブジェクト識別子） 10.1029/2018JB017218	**査読の有無** 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	**国際共著** -

〔学会発表〕　計0件

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関