Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

SIT003-01 Room:101 Time:May 26 08:30-08:50

Dynamics of the Earth and planetary dynamos revealed by numerical dynamo simulations

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It is generally believed that dynamo action working in its fluid core is the origin of the planetary magnetic field. Fluid flow is driven mainly by thermal and compositional buoyancy, sources of which are ascribed to secular cooling of the core, heat source due to radioactivity, latent heat and light element release duo to inner core nucleation. Essentially these buoyancy sources are related to the core-mantle boundary (CMB) and inner-core boundary (ICB). Thus, physical and dynamical states of the outer core and its dynamo are strongly related with these boundaries.

By taking effects of the boundaries into account in dynamo simulations, many dynamo modelers have tried to explain characteristics of the magnetic field of each planet. As to the geodynamo, it is found that changes in polarity reversal frequency are governed by CMB heat flux distributions. For the ancient Martian dynamo, the hemispherically biased CMB heat flux (degree-1 pattern) imposed possibly due to mantle convection or giant impact can yield hemispherical dynamo consistent with north-south dichotomy of crustal magnetic field of Mars. The Mercurian extremely weak magnetic field may be explained by stable stratification of the upper part of the core due to sub-adiabatic thermal structure of the Mercury's core, or by iron-snow zone located midway of the core, which is the result of sulfur concentration and pressure condition of Mercury. In this talk, we review such progress and recent topics of dynamo simulation and discuss future prospects of numerical dynamo modeling.

Keywords: dynamo, core, convection, CMB, stratification

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SIT003-02 Room:101 Time:May 26 08:50-09:10

Outermost core Vp derived from analyzing SmKS waves observed at large scale arrays

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The Earth's core is composed primarily of iron with several per cents by weight of lighter elements. The lighter elements are thought to be progressively enriched in the outer liquid core as the core cools and the inner core crystallizes. In this study we present evidence for compositional layering in the outermost part of the core based on the analyses of travel times and wave forms of SmKS multiple. Large scale broadband seismometer array data of SmKS waves with m up to 5 are analyzed to investigate the depth profile of P wave speed (Vp) of the outermost core. We apply a tau-p inversion to the SmKS data and show that Vp is 0.35% slower at the CMB than PREM and the lower Vp anomaly gradually diminishes to zero at 300 km below the CMB. The SmKS differential travel times clearly indicates that there must be a significant difference in the radial gradient of Vp between the outermost 300 km of the core and the deeper part of the core, but the obtained Vp anomaly is less pronounced than the 1 to 2 % reductions in a thinner layer suggested by previous seismological studies. The evaluation of Bullen's parameter for the obtained Vp profile shows that adiabatic self compression of a homogeneous material cannot explain the observation and that some form of compositional anomaly is required. The compositional layering at the outermost outer core may indicate the presence of sub-adiabatic temperature gradients, which means that the thermal effects on density are augmented by compositional effects.

Keywords: outer core, stable stratification, SmKS wave, broadband seismometer array, compositional inhomogeneity

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SIT003-03 Room:101 Time:May 26 09:10-09:25

Filtering of polarity reversals in MHD dynamo simulations with a stably stratified layer in a rotating spherical shell

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The structure of the outer core in the Earth would have a stably stratified region ranging 70 to 300 km below the core-mantle boundary inferred from seismological data analyses [Tanaka, 2007; Helffrich and Kaneshima, 2010]. Regarding with numerical dynamo simulations, a stably stratified region near the outer boundary works as the filter of small-scale structures of radial magnetic field [Christensen, 2006; Christensen and Wicht, 2006]. The important mechanism for understanding such an effect is that the zonal flow induced by thermal wind balance and power caused by Coriolis and Lorentz force cannot penetrate into the stratified region [Nakagawa, submitted].

There are many numerical dynamo simulations with polarity reversals [Olson et al., 2007; Driscoll and Olson, 2009; Takahashi et al., 2007]. Their models have not investigated how the stably stratified region works in the situation of polarity reversals. Here we show a couple of examples for numerical dynamo simulations with a stably stratified region under physical parameters occurring the polarity reversals. The main result is that the time-scale of polarity reversals is very different between unstratified and stratified cases. The stratified case would have much longer time-scale of polarity reversals than for the unstratified case or no reversals. The filtering effect caused by a stably stratified region near the outer boundary would work to avoid occurring the polarity reversals as well as the smaller-scale of magnetic field changes into the dipolar field.

Keywords: stably stratified layer, polarity reversals, dynamo, Earth’s core

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SIT003-04 Room:101 Time:May 26 09:25-09:40

The influence of heat flux boundary conditions on convection and dynamo in a rapidly rotating sphere

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Present geodynamo is driven by a mixture of secular cooling and of latent heat and light core constituents emanating from a growing inner core. The early dynamos of Earth and Mars, however, functioned without an inner core were thus exclusively driven by secular cooling. Dynamo simulations model secular cooling by internal heat sources and the inner core-related driving by bottom sources. We explore how the different combination of thermal (compositional) boundary conditions and source distributions affects non-magnetic convection and dynamo simulations.

The impact of the outer boundary condition is only large when the convection is mainly driven by internal sources. When bottom sources dominate, the lower boundary condition becomes more important. In both cases, a fixed flux condition promotes larger convective scales than a fixed temperature (composition) condition. A magnetic field can further increase the flow scale in the dynamo cases. The roll of magnetic field in the effect of the boundary conditions is understood from a linear stability analysis of magnetoconvection. The result suggests that the thermal outer boundary condition plays an important role for the early dynamos in Earth and Mars more than for the present geodynamo.

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SIT003-05 Room:101 Time:May 26 09:40-09:55

Density and structure of molten iron under pressure

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Physical properties of molten iron, such as density, are fundamental to understand the dynamics of the core of the terrestrial planets. Structures of molten iron alloys at high pressures are interested, because the physical properties of melts are strongly related to those structures. Therefore, we have investigated the density and the structure of molten iron alloys at high-pressures by using synchrotron radiation. Here we report the results of density measurements and the X-ray diffraction analysis of molten iron under pressure. The density is determined up to 3 GPa by X-ray absorption technique at BL22XU, SPring-8, and the structure is investigated up to 7 GPa by using energy dispersive X-ray diffraction analysis at PF-AR NE5C, Photon Factory. Combined density data with diffraction data, we derived the coordination number of Fe melt at high pressures. We will discuss how the structure of molten iron responds to pressure.

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SIT003-06 Room:101 Time:May 26 09:55-10:10

Melting relation of Fe-O-S alloy at the outer core condition

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The Earth's core consists of the liquid outer core and the solid inner core, which suggests that the temperature at a boundary of the inner/outer core (ICB) corresponds to the melting temperature of the core material. Thus, the melting temperature of the Fe-alloy under high pressure is important in order to clarify the thermal structure of the Earth's core. However, solidus and liquidus temperatures of Fe-alloys have never yet been measured simultaneously in the megabar pressure range.

In this study, the solidus and liquidus temperatures of the Fe75O5S20 alloy are determined up to 157 GPa using a laser-heated diamond anvil cell combined with in situ X-ray diffraction technique.

The liquidus temperature is 260-670 K lower than the melting temperature of pure Fe because of the alloying effect of S and O on the melting temperature of Fe. Based on our results, we estimated the temperatures at the core/mantle boundary and at the boundary of the inner/outer core.

Keywords: Liquidus, Solidus, Earth's core, high pressure

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SIT003-07 Room:101 Time:May 26 10:10-10:30

Spontaneous flow reversals observed in a magnetoconvection of liquid metal

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We report a finding of spontaneous flow reversals of roll-like patterns in liquid gallium Rayleigh-Benard convection under the influence of an applied magnetic field. Thermal convection in liquid metals with an external magnetic field is a basic problem in considering the flow of the outer core. Especially, to clarify the relation between a mean flow structure and turbulence under magnetic fields is important. The flow of liquid iron in the outer core of the Earth may be turbulent because of its large scale, and the characteristics of the turbulence may be controlled by the geomagnetic field.

The vessel we used has a square geometry with aspect ratio five, and a uniform horizontal magnetic field is applied to the whole vessel. The flow patterns were visualized by ultrasonic velocity measurements, and the time variation of convective flow structure including the processes of reversals of the flow direction was clearly observed. The basic flow pattern in the vessel is a four-roll structure with its axis parallel to the magnetic field. Our experiment whose duration was much longer than the thermal diffusion time for the fluid layer displayed several reversals of the flow pattern. Emergence of a new circulation at a corner of the vessel caused flow reversal by inducing reorganization of the whole pattern. For most of the duration, the basic four-roll structure is dominant and the flow keeps its two-dimensionality, while three-dimensionality of the flow accompanied by the new circulation plays an important role at the timing of reversals. The process of reversals is over in a relatively short time, which is comparable to the circulation time for a roll. The reversals of the flow occur randomly with the typical time interval between reversals much longer than the circulation time. The observed phenomena are flow reversals, but these features are analogous to the reversals of the geomagnetic field. The study of this flow reversal can provide a key for the mechanism of geomagnetic field reversals.

Keywords: flow reversal, liquid metal, magnetoconvection, velocity measurement

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SIT003-08 Room:101 Time:May 26 10:45-11:05

Inner core growth and its effect on the structure and dynamics of the core

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Earth's inner core is growing due to the cooling of the Earth. Crystallization of molten iron alloy on the inner core boundary (ICB) is responsible for the structure of the inner core and for the energy supply to the geodynamo.

The small-scale features of the ICB seem to be well established theoretically and experimentally. A constitutional super cooling by the advance of the solid-liquid interface of the core iron alloy at ICB condition will almost certainly cause morphological instability of the surface, and the instability create a mushy layer at the ICB from which buoyant materials are ejected to supply a driving energy of the geodynamo.

Global inner core growth models are necessary to discuss the structure of the inner core's interior. It is widely believed that the near surface structure of the inner core has asymmetry between the eastern and western hemispheres, and the deep interior of it has a seismic anisotropy. Existence of convection in the inner core seems to play a role on determining the structure, but it is not clear whether a type of convection can explain the observed asymmetry and anisotropy at once. Also, the convection might have influence of the thermal history of the Earth and might alter the estimate of the inner core age.

In this review talk, present status of the understanding of the inner core growth is summarized and possible improvements on the inner core growth models are discussed.

Keywords: inner core

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SIT003-09 Room:101 Time:May 26 11:05-11:20

Thermo-chemical convection in the inner core

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The dynamics of the Earth inner core depends criticaly on whether it is stably stratified or unstably stratified. Solidification-induced partitioning of the light elements may induce a stable density stratification within the inner core. Whether the thermal field is stabilizing or destabilizing depends on the inner core solidification rate, on the thermal diffusivity of iron at inner core conditions, and on the ratio of the Clapeyron slope to the adiabatic gradient in the inner core. The temperature field within the inner core can be destabilizing - and could drive convection - if the growth rate of the inner core is large enough. While this possibility has often been thought implausible, the young inner core age predicted by the most recent core thermal evolution models and the low thermal conductivity value proposed recently (Stacey and Davis, 2009) leave this possibility open.We focus here on this case, taking into account a possible stabilizing effect of a compositionnal profile in addition to the destabilizing thermal field. We developed a numerical model of thermo-chemical convection in a growing inner core, coupling the thermal evolution of the inner core with a model of thermal and compositional evolution of the outer core. Melting and crystallization associated with deformation of the ICB would be of importance for the style of convection if the viscosity is large, but we focus here on the case of low viscosity ($< 10^{19}$ Pa.s) for which phase change associated with dynamic topography at the ICB is expected to play a secondary role. If a stabilizing compositional stratification is present, we show that convection develops in a regime close to the "diffusive" regime of double-diffusive convection. A particularly interesting feature of the regime we found is that the convective flow can be confined to the deep inner core. The radius of this inner convective region depends essentially on the relative effects of thermal and compositionnal fields, and is found to be similar to the seismically determined radius of the innermost inner core for plausible parameters. The thermal forcing generaly decreases as the inner core grows because the cooling rate at the ICB decreases. A second possible explanation for the origin of the innermost inner core is that the inner core has been convecting during its early history but is now quiescent.

Keywords: inner core, geodynamics, anisotropy, thermal convection

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SIT003-10 Room:101 Time:May 26 11:20-11:35

Depth Variation of Inner Core Hemisphericity from PKP(DF) and PKP(Cdiff): P-Wave Velocity and Attenuation Structures

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The hypothesis of inner core hemisphericity is supported by both observations of body waves and free oscillations. However, its fine structure is controversial. Here I examine the depth variation through the travel times and amplitudes of PKP(DF) with respect to PKP(Cdiff) in the distance range from 150 to 160 degrees. The use of PKP(Cdiff) as a reference phase makes it possible to extend the available depth of PKP(DF) from the inner core boundary (ICB) with high accuracy. As PKP(Cdiff) can not be properly treated with the ray theory, the reflectivity method is used for the comparison. I have measured differential travel times and amplitude ratios in short-period (1-5 Hz) using the cross-correlation method, then collected 583 data (229 and 354 for Eastern and Western hemispheres, respectively). Global averages of PKP(Cdiff)-PKP(DF) times and PKP(DF)/PKP(Cdiff) amplitude ratios are well explained by AK135, the geographical pattern of the data scatter is consistent with the hemispherical distribution. Forward modelling suggests the inner core P-wave velocity in Eastern hemisphere is 0.5 % faster than AK135 at the ICB and gradually closes to AK135 with the transition thickness of 500~600 km. On the other hand, P-wave velocity at ICB in Western hemisphere is 0.5 % slower and the transition thickness is about 200 km. The apparent Q values in Western hemisphere are approximately 400 and almost constant in the concerned distance range. However, those in Eastern hemisphere are approximately 270 around 151 degrees and 400 in the distance greater than 154 degrees.

Keywords: the inner core, hemisphericity, PKP(DF), PKP(Cdiff)

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SIT003-11 Room:101 Time:May 26 11:35-11:55

The crystal structure of iron at the inner core

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The Earth's solid inner core is mainly composed of iron. Thus the crystal structure of iron is of prime importance for understanding the nature of solid inner core. Despite many efforts to investigate phase relations of iron have by dynamic and static compression, and theoretical calculation, consensus on the stable phase at the inner core condition has never been achieved. While hcp-Fe can persist to core pressures at 300 K, a phase transition at elevated temperature is a possibility. Both theory and experiments proposed different forms of iron at simultaneously high P-T conditions, which include bcc, face-centered-cubic (fcc), and hcp structures. The structure of iron has never been examined experimentally at the inner core P-T conditions (>330 GPa and >5000 K), because such extreme conditions could only be achieved by shock-wave compression experiments.

Based on static compression experiments in a laser-heated diamond-anvil cell (DAC), we determined the structure of iron up to 377 GPa and 5700 K. Iron powder and thermal insulation layers of SiO2 glass were loaded into a hole of a pre-indented rhenium gasket placed in the For experiments beyond 300 GPa, the double-beveled diamond anvils with 40-microns culets were used, and accordingly the sample size was limited to about 20 microns. Heating was performed from both sides of the sample by employing two single mode, Yb fiber lasers with output power up to 100 W each with flat-top beam shaping optics to minimize temperature gradient across the sample. Angle-dispersive x-ray diffraction measurements were conducted at BL10XU of SPring-8.

Six separate sets of experiments were conducted in a wide P-T range from 135 GPa and 2690 K to 377 GPa and 5700 K. We observed crystal growth and hence the stability of hcp-Fe at these P-T conditions with no evidence for a phase transition to bcc nor fcc iron phases. The c/a axial ratio of hcp-Fe at high temperature was also studied, which has significant effect on the nature of the elastic anisotropy. We found that c/a ratio at 330 GPa is substantially lower than the ideal value of 1.6299 for hcp structure with small temperature dependence, which is contrary to the theoretical studies. These observations suggest the should be elastically anisotropic even at the high temperature conditions of the inner core.

Keywords: core, iron, DAC

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SIT003-12 Room:101 Time:May 26 11:55-12:10

Phase relation of Fe-Ni-Si alloy up to 3 Mbar

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The seismic observation reveals the anisotropic structure of the Earth's inner core [Woodhouse et al., 1986;Morelli et al., 1986]. The anisotropy of the inner core could be explained by the preferred orientation of the hexagonal close-packed (hcp) phase of iron, but its direction of orientation and the stability of hcp structure are still under debate. Stixrude and Cohen (1995) suggested that the orientation with the c-axis parallel to the Earth's rotation axis. On the other hand, Steinle-Neumann et al. (2001) reported the strong temperature dependence of the axial ratio (c/a) of hcp iron and its elasticity based on theoretical calculation and suggested that the basal planes of the hcp structure are partially aligned with the rotation axis.

The crystal structure of pure iron at the inner core condition is likely to be hcp [Tateno et al., 2010]. But the inner core is not pure iron, but it should contain about 5 wt.% of nickel [Allegre et al., 1995; MacDonough and Sun, 1995] and some amount of light elements such as silicon [Birch, 1952]. Recently the phase transition of Fe-10at.%Ni from an hcp structure to a body-centered cubic (bcc) was observed at 225 GPa and 3400 K [Dubrovinsky et al., 2007]. Moreover, it is considered that silicon is one of the most plausible candidate of the light element in the core based on the cosmochemical arguments [Allegre et al., 1995] and the chemical reactions between mantle and core [Sakai et al., 2006; Takafuji et al., 2005]. Since Fe-FeSi system shows a solid solution at Fe-rich side, the solid inner core can contain some amount of silicon in its structure [Kuwayama and Hirose, 2004]. Several reports on the phase relation of Fe-Si alloy at high pressure revealed that silicon drastically expands the stability field of the fcc phase [Asanuma et al., 2008; Lin et al., 2002]. Therefore, the effect of nickel and silicon is important to consider the crystal structure of the inner core.

Here we report the phase stability of hcp phase and the axial ratio (c/a) of $Fe_{87.9}Ni_{4.4}Si_{7.7}$ up to 307 GPa and 2780 K. We used a symmetric-type diamond anvil cell with the beveled diamond anvils of inner culet size of 30-40 ?m for high pressure generation. The crystal structure of the sample was determined by the synchrotron X-ray diffraction experiment at SPring-8 BL10XU. We did not observe other phases such as a body-centered cubic (bcc) structure. The axial ratio (c/a) of $Fe_{87.9}Ni_{4.4}Si_{7.7}$ at 300 GPa shows almost a constant value of 1.59-1.60 against temperature. The weak temperature dependency of the axial ratio of hcp Fe-Ni-Si alloy could explain the seismic wave anisotropy of the inner core with the c-axis parallel to the Earth's rotation axis.

Keywords: phase relation, anisotropy of the inner core, Laser-heated diamond anvil cell

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SIT003-13 Room:101 Time:May 26 12:10-12:25

Experimental Insights into the Light Element(s) in Earth's Inner Core from in situ Elastic Wave Velocity Measurements

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Understanding the composition of the Earth's core is integral to answering many questions in the Earth Sciences, including the conditions, mechanisms, and timing of core formation, as well as the interactions between the core and the mantle, which also has important implications for the composition of the Earth's mantle. Because of the remote nature of the core, seismic profiles of the Earth's interior must be relied upon to determine the velocity and density structure of the deep Earth, and these profiles must then be compared with experimental data on candidate core phases at extreme conditions. The work presented here will show the results of recent synchrotron-based ultrasonic interferometry experiments on iron/light-element alloy (ILEA) compounds at high pressures and temperatures; specifically compounds containing Si, S, and P. These experimental data were extrapolated to pressures and temperatures relevant to the Earth's inner core for direct comparison with seismic profiles.

A density-velocity-compositional model was constructed for the solid inner core by accommodating for the recent evidence from these ultrasonic experiments that iron minerals may not follow a linear "Birch's Law" density-velocity relationship. By accounting for this non-linearity, the first model that is in good agreement with all aspects of the Preliminary Reference Earth Model (PREM) in the inner core, including shear velocities, has been generated. In addition, this model was then compared to existing cosmochemical and experimental data, as well as element partitioning studies, to form a more comprehensive model of the Earth's inner and outer cores. The results of this model are also in excellent agreement with geochemical constraints on light-element content of the core, and can begin to reconcile the density deficits observed in the liquid outer core. This is the first model to have good agreement with all the parameters of PREM in the inner core, including density, bulk sound speed, V_P, V_S, K_S, and G, and it also resolves most of the density deficit in the liquid outer core.

Keywords: core, mineral physics, experimental, ultrasonic interferometry, elasticity, high pressure

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SIT003-14 Room:101 Time:May 26 12:25-12:45

Ab initio study on the high-P,T phase relations and elasticity of iron and iron-light element systems

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The Earth's core is thought to consist of iron with some light elements (O, Si, S, C, etc). But the phase relations and physical properties of those systems are still underdetermined primarily due to experimental difficulty. The ab initio computation method is instead a strong technique to investigate materials under ultrahigh-pressure and temperature conditions. In this talk, I briefly summarize the current status of the computations of some core materials and discuss thermochemical properties of the Earth's core, including new findings related in particular to the large entropic effects likely expected at high core temperatures.

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Keywords: iron and iron-light elements system, high-pressure, stability and elesticity, ab initio method, Earth's core