Development of Advanced Simulation Methods for Solid Earth Simulations

Project Representative

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Numerical planet: We have developed the simulation code for the core formation process by solving the 3-D Stokes flow motion with the free surface under the self-gravitating field. Our simulation schemes are designed for the massively parallel/vector supercomputer system Earth Simulator 2(ES2). In this FY, in order to investigate the core formation with the impact of planetesimal, we implement the impact -differentiation melting model which is parameterized on the basis of a theoretical model. The simulation result suggests that the PP material could have survived impact events in the deep interior because of the thick mantle that formed before giant impacts. Geodynamo: We have done product runs by using newly developed magnetohydrodynamic dynamo code which can deal with length-of-day variation. We found there is a phase gap between length-of-day variation and geomagnetic field variation. In the long period case (20,000 years), amplitude of geomagnetic field variation is several ten percent, while short period case (200 years) it is about one percent. These trends match the observational geomagnetic field variation. Mantle convection: We are also developing a simulation code of mantle convection which includes the effect of two-phase flow, i.e., molten and solid phases. By properly adapting the solution techniques for advection by non-solenoidal and multi-dimensional flows, we successfully solved a coupled system with thermal convection and two-phase motion by permeable flow.

Keywords: Geodynamo simulation, Length-of-Day variation, Yin-Yang grid, Mantle convection, Core formation, Stokes flow, mixed precision arithmetic, Two-phase flow, Permeable flow

1. Development of numerical planet simulation code (Furuichi)

Development of the Stokes flow simulation code which can deal realistic mechanical boundary (surface) conditions is an interesting challenge for the field of computational geoscience, because such Stokes system is relevant to the long-time scale evolution of the planetary interior. Our new solution code named "Nplat", can solve the Stokes flow motion with free surface under a self-gravitation by using the sophisticated algorisms designed for ES2 [1-4]. Expressing the free surface motion, a stick air layer, which is the low viscosity layer surrounding the planetary surface, is assumed. An ill conditioned Stokes problem of the finite difference discretization on a staggered grid, is solved by iterative Stokes flow solver which is robust to large viscosity jumps by using a strong Schur complement preconditioner and mixed precision arithmetic utilizing the double-double method [3].

In this FY, with the simulation code developed in this project, we investigate the growing planet with the core formation by the impact of planetesimal. The formation of a metallic core is widely accepted as the major differentiation event during the planetary formation process. The early Earth hypothesis also suggested that the core formation process would be an important for understanding the initial condition (both thermal and chemical) of mantle convection.

Our simulation starts from the proto-planet (PP) with Martian size under the self-gravitating field. The core formation occurs when the planet experiences the large impact assumed with adding the mixture of silicate and metal rich materials to the planetary surface. This setup simplifies the differentiated melt fraction of the magma pond. The sinking metal layer in planetary interior and the post-impact rebound of planetary surface are captured with the deformable free surface with updating the gravity potential field.

Figures 1 (a)–(c) show temporal variations in the simulated core formation process caused by a number of impacts. The time interval of impacts is set as a constant δt = 0.01Ma, the size of impactor is set as 10% of the volume of the growing planet. Figure 1 (a) is a snapshot at the first impact. Figure 1 (b) shows that the metal-blob at the first impact sinking into the center when second impact occurs. After several impacts, the accumulated silicate mantle covers a planetary surface and the metal-rich material form the core at the center. At the end of the simulation, we find the presence of PP fractions above the metallic core in Fig. 1 (c). It implies that the dynamical change of the internal structure during core formation could lead to the remaining dense PP material on the CMB. This result indicates the new hypothetical scenario of the formation process of the primordial material layer suggested by geochemical and seismological studies.

2. Geodynamo simulation (Miyagoshi)

The length-of-day variation of the Earth probably affects outer core convection and geomagnetic field. For example, Hamano (1992) pointed out relation between geomagnetic field variation and length-of-day variation associated with Milankovitch cycle [5]. However, there are no geodynamo models which can deal with length-of-day variation effect. We developed magnetohydrodynamic geodynamo code which deals with the length-of-day variation in the last fiscal year and have done product runs by the code in this fiscal year. The Yin-Yang dynamo model [6, 7] was developed for this purpose.

From geomagnetic field observation, during last eighty thousand years, geomagnetic field intensity varies in the period of tens of thousands years. The amplitude of its variation is several tens of percent [8]. On the other hand, in shorter time scale (recent one hundred years), geomagnetic field intensity variation is also seen. The period of variation is several decades, and the amplitude is about one percent [9]. Between long and short time scales, the amplitude of variation is very different. So we have investigated geomagnetic field variation in both long and short period case.

We have done numerical simulations in both long and short period cases. The model parameters are as follows. The Ekman number, Rayleigh number, Prandtl and magnetic Prandtl numbers are 1.9E-5 and 1.5E8, unity and unity respectively. The rotational speed variation is given as a sine function depending on time with amplitude of two percent.

In the long period case, the period is the same as the magnetic diffusion time. It corresponds to twenty thousand years in the Earth. This also corresponds to one of the Milankovitch cycle. Numerical simulation results show the length-of-day variation causes variation of magnetic energy in the outer core, kinetic energy of convection, and magnetic dipole moment. The amplitude of magnetic energy and dipole moment variation is about thirty percent, which is much larger than the amplitude of the rotational speed variation (two percent). We found the phase of magnetic energy variation is not the same as the phase of the rotational speed variation. The phase difference between magnetic energy and rotational speed is pi over two. In addition, the phase difference between magnetic energy and time difference of rotational speed is pi. The phase of magnetic dipole moment is the same as that of magnetic energy. On the other hand, the phase difference between magnetic energy and convection kinetic energy variation is pi.

In the shorter period case, the period is given by 1 percent of the magnetic diffusion time. It corresponds to two hundred years in the Earth. In this case, magnetic dipole moment and convection kinetic energy varies although magnetic energy does not vary. The amplitude of magnetic dipole moment variation is about one percent, which is much smaller than the long period case. This tendency matches the observational geomagnetic field variation.

The variation depends on the Ekman number. We calculated

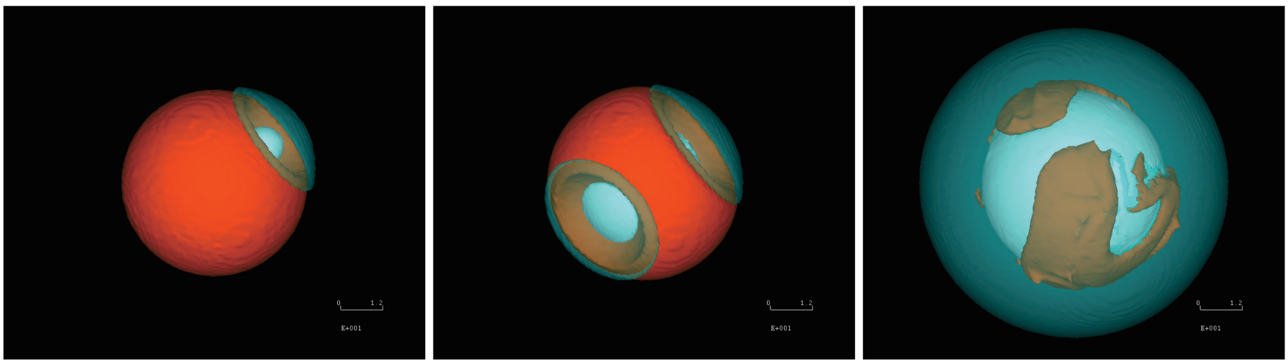

Fig. 1 Snapshot of the simulated evolution of the planet with core formation by the impact (a) initial state with first impact; (b) intermediate state with second impact; (c) final state with a radius r = 0.8 Re. The white and orange isosurface represent metal-rich and PP materials respectively. The semi-transparent green iso-surface indicates the silicate rich material. In this simulation viscosity of metal-rich, PP and silicate-rich materials are 10^{20} [Pa.s], 10^{22} [Pa.s] and 10^{19} [Pa.s] respectively.

the case with high Ekman number (O(10E-4)) and rotational speed variation amplitude 6.7%. In this case, magnetic energy as well as convection kinetic energy does not vary although the amplitude is larger than the previous low Ekman number (O(10E-5)) case. The Ekman number represents the intensity of rotational effect. So it can be intuitively understood that larger amplitude is needed in high Ekman number cases. In the Earth's outer core, the Ekman number (O(10E-15)) is much smaller than that of our model (and today's all geodynamo models). So the geomagnetic variation by length-of-day variation is expected to easily occur because necessary amplitude becomes small.

3. Development of mantle convection simulation code (Kameyama)

In this project, we are developing a new simulation code of mantle convection, based on our code named "ACuTEMan" [10-12], which includes the effect of two-phase flow, i.e., the presence and/or migration of molten materials in a solid mantle. Through the temporal evolution of the terrestrial planets, two-phase flow is considered to play crucial roles in the development of thermal and chemical structures of the interior by, for example, an intrusion of molten liquid iron into an unmolten (silicate) protocore in the earliest stage of the planets. Therefore, it is one of the most important directions of solid Earth sciences to establish numerical techniques of large-scale simulations of mantle convection incorporating the effects of two-phase flow.

In this FY, we concentrated our effort to (i) an adaptation to ES2 of the routine for solving the creeping flow of solid phase, and (ii) an improvement of the numerical techniques of material transport in two-phase system. The former task includes an enhancement of vectorization of loops which calculate the flow fields of (truncated) anelastic fluid, and that of conformance with Fortran 90 standards. The latter task, on the other hand, includes developments of solution routines for (a) an advection equation based on FCT (Flux-Corrected Transport) method, (b) a relative motion between the solid and liquid phases based on Darcy's law of permeable flow, and (c) a coupled flow between the thermal convection and two-phase motion. By conducting several preliminary calculations with moderate problem sizes, we confirmed that our technique successfully calculates the coupled system with thermal convection and two-phase motion by permeable flow (Fig. 2). Our experiences suggest that an appropriate choice of solution techniques is quite important in solving the advection in multi-dimensions when the flow fields are not solenoidal (i.e., associated with source and/or sink terms). In particular, by the help of "flux limiter", one can avoid spurious concentration or rarefaction of advected quantities.

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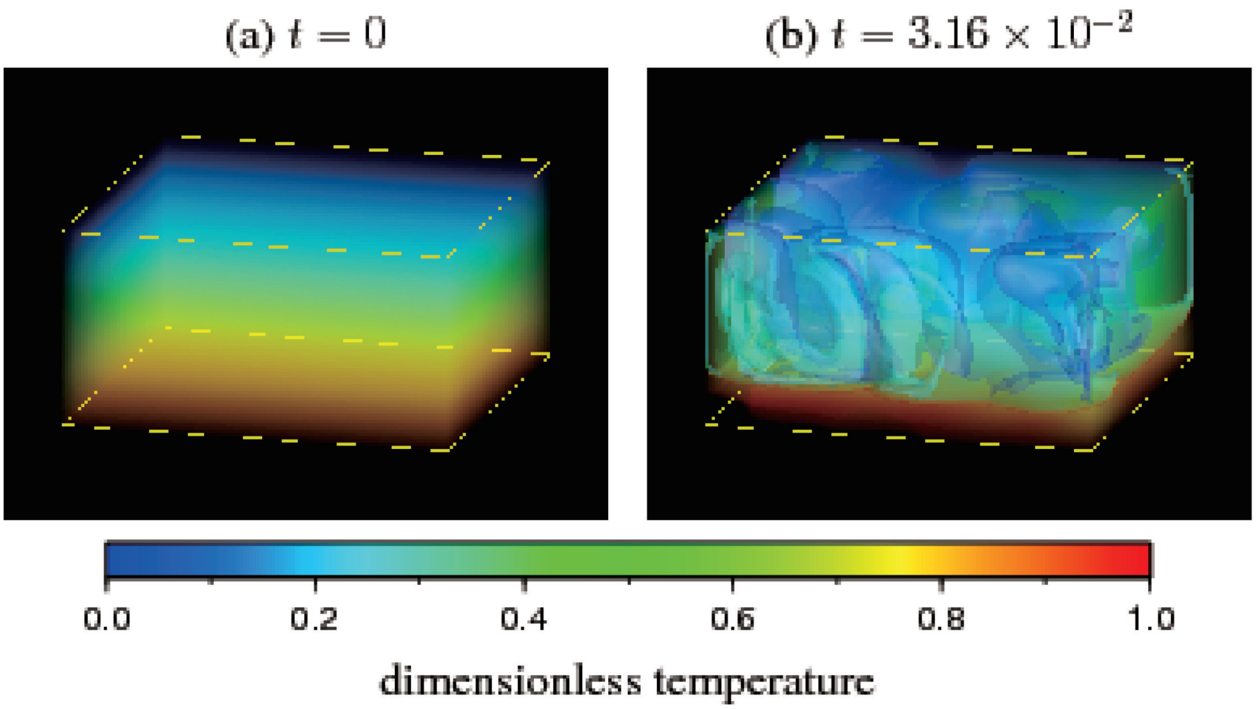

Fig. 2 Snapshots of distributions of temperature and liquid phase obtained by the thermal convection of two-phase motion by permeable flow at the elapsed times indicated in the figure. Shown in colors are the distributions of dimensionless temperature, while indicated by isosurfaces are those of volume fraction of liquid. In this calculations, the liquid phase, whose density is assumed to be larger than that of solid, is not only migrated downward by the permeable flow but also driven upward by the overall thermal convection.

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先端的固体地球科学シミュレーションコードの開発

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我々は、惑星の形成過程から地球ダイナモの生成並びにマントル対流の駆動といった固体地球科学ダイナミクスの諸問題に包括的に取り組むために、地球シミュレータ２の特徴を生かした先端的なシミュレーションコードを開発し、その応用を行っている。

数値惑星：前年度までに開発した、自己重力下での自由境界表面を伴う３次元地球中心核形成シミュレーションコードに、新たに惑星衝突のモデルを実装すること成功した。そして、幅広い衝突パラメータ空間においけるシミュレーションによって、惑星衝突によるコア形成時に地球内部に不均質な層が構築されることを見出した。このような結果は、地球深部にその存在が示唆されている始原物質層の形成過程の新しい仮説を導くものである。

ダイナモ：昨年度開発した地球自転速度変動の効果を考慮した地球ダイナモシミュレーションコードを用いてプロダクトランを行った。変動周期が磁場散逸時間（地球では２万年に相当）の場合、磁場のダイポール成分が約 30％変動したが、その 1/100 の周期（同 200 年）では約 1％の変動であった。これらは観測されているそれぞれの時間スケールでの磁場変動の振幅と傾向が合っている事が分かった。

マントル：固液２相系のマントル対流シミュレーションにあたり、(i) 固体の流動を計算する機能の ES2 向け改良、及び (ii) 物質の移動を計算する機能の構築、の２つを集中的に行った。中規模モデルによるテスト計算により、浸透流による２相の相対運動と熱対流運動のカップリングの取り扱いができることを確認した。

キーワード: 地球ダイナモ, インヤン格子, 地球回転変動, マントル対流, コア形成, ストークス流れ, 2相流, 浸透流