High Resolution Geodynamo Simulation by Yin-Yang Grid and its Visualizations

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The highest resolution simulation of geodynamo is performed. The base grid system is the Yin-Yang grid, a spherical overset grid with two congruent components each of which is a part of the usual spherical polar coordinates. High parallelization rate of the Yin-Yang geodynamo code has enabled us to perform the geodynamo simulation with the viscosity one order of magnitude smaller than the previoius calculations. The resulting flow and the generated magnetic field have fairly different structures compared with previous simulations. To analyze the three-dimensional structure of the new dynamo regime, we applied our original visualization tools, Armada and VFIVE. Armada is a software rendering program based on the ray-casting algorithm. Since Armada is parallelized with OpenMP and MPI and does not require any graphics hardware or OpenGL, it runs on general supercomputers. VFIVE is a virtual reality visualization software for CAVE-type virtual reality systems. Owing to the interactive, immersive, and three-dimensional visualization by VFIVE in the CAVE room, we have found an unpexpected structure of the electric current field.

1 Introduction

The compass points to the north since the Earth's surface is surrounded by its intrinsic magnetic field of the dipolar structure. The dipole field is generated by electric current in the Earth's core. The generation mechanism of the current, or the geodynamo, is one of the most important problems of the geoscience. The Earth is composed of two spherical layers (see Fig. 1); the mantle and the core. The outer part of the core is molten iron and the geomagnetic field is generated there by magnetohydrodynamic (MHD) dynamo process.

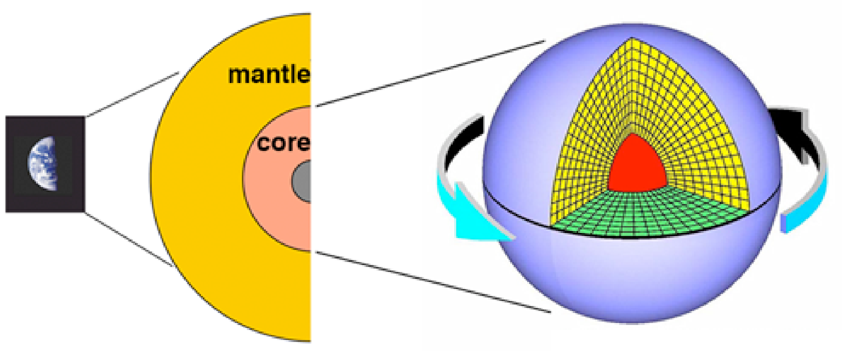

Fig. 1. Simulation model. The Earth's magnetic field is generated in the outer part of the iron core of the planet which is in the liquid state. The magnetohydrodynamic equation in a rotating spherical shell is solved by the geodynamo simulation.

The difficulty of the numerical simulation of geodynamo comes from extreme conditions of the liquid core as a rotating fluid system. A characteristic length in a rotating fluid system is thickness of the Ekman layer, which is given by $\delta = \sqrt{\nu/\Omega}$, where ν is viscosity and Ω is the system's rotation rate. For the Earth's outer core, δ is about 1 cm, that is much smaller than the radius R_o of the core, 3500 km.

A non-dimensional number defined from δ and R_o is the Ekman number $Ek \equiv \delta^2/R_o^2$, which stands for the ratio between the viscous force and the Coriolis force. The Ekman number of the Earth's outer core is $Ek = O(10^{-15})$. The smallness of this value is a symbol of the difficulty of direct numerical simulation (DNS) of the geodynamo.

We started the DNS approach to the geodynamo simulation in 1995 [1]. The value of Ek at that time was $O(10^{-4})$. Glatzmaier and Roberts [2] performed the geodynamo simulation almost at the same time in which dipole field generation and even its reversal were simulated, but they adopted eddy diffusivities in their simulation. In accordance with the development of the high performance computer (HPC), the Ek of the geodynamo DNS has being steadily, though slowly, descending.

Recently, we have performed a geodynamo simulation with Ek of $O(10^{-7})$, which is the smallest value ever achieved [3]. We made use of the Yin-Yang grid to make it possible to perform such a small Ek simulation. The resulting flow and the magnetic field were qualitatively different from those observed in previous simulations.

To analyze the three-dimensional structure of the flow and the magnetic field in this new dynamo regime, we needed to develop and customize our original visualization tools, since the total size of the output data for one simulation run reaches to more than 3 TB. In addition to its size, the spatial complexities of the simulated vector fields, including flow velocity, vorticity, magnetic field, and electric current field, prevent a straightforward visualization.

We applied our original visualization software, Aramda, to analyze the geodymo data. Armada is a software rendering tool, meaning that it requires no graphics hardware (graphics board) to generate images. The speed up of the image generation in Armada is realized by the parallelization with OpenMP and MPI. Details of Armada and its applications to geodynamo simulation is described in section 4.

The virtual reality (VR) technology is rapidly growing these years. Among various paradigms of VR, a room-sized, projector-based, immersive display system called CAVE produces the highest quality of VR. We have been developing a VR visualization software for the CAVE system for a decade. The software, named VFIVE, played a key role to grasp the three-dimensional structure of the flow and magnetic field in our geodynamo simulation. We will describe the VR visualization by VFIVE in section 5.

2 Simulation Model

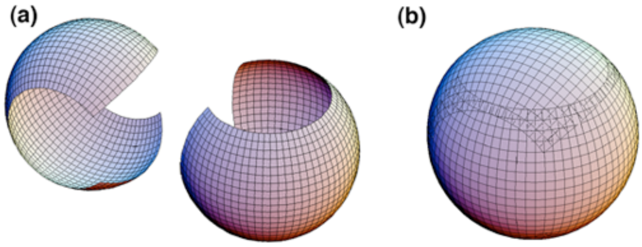

Fig. 2. Yin-Yang grid. Two congruent grids are combined in a complemental way to cover a spherical surface. Each grid is a low latitude part of a spherical polar coordinates.

The liquid iron in the Earth's outer core is believed to be in a convection motion. Since the driving mechanism of the convection is still unknown, here we simply suppose a thermal drive. Our simulation model is as follows: Modeling the outer core, we consider a spherical shell region between two co-centric and co-rotating spheres with radius $r = r_i$ and $r = r_o$. The inner sphere of radius r_i is the boundary between the inner solid core and the outer liquid core. The outer sphere of radius r_o is the boundary between the outer core and the mantle. The temperatures of the spheres are fixed; hot at $r = r_i$ and cold at $r = r_o$. An electrically conducting fluid is confined in the spherical shell region. The inward central gravity causes thermal convection if the temperature difference between the spheres is large enough. We numerically solve the time development of the MHD equations in the spherical shell. We put random perturbations of the temperature and the magnetic field at the beginning of the simulation. The thermal convection of the MHD fluid amplifies the seed magnetic field.

We applied a spherical grid system named Yin-Yang grid [4, 5] to this geodynamo simulation. The Yin-Yang grid is a kind of overset grid [6], applied to the spherical geometry. Two congruent grids, Yin-grid and Yang-grid, are combined in a complemental way with partial overlap to cover the full spherical shell region, see Fig. 2.

The grid size in this simulation is 511 (in r) $\times$ 514 (in θ) $\times$ $1,538$ (in ϕ) $\times$ 2 (Yin and Yang) with r radius ($0.3 \leq r \leq 1.0$), θ colatitude ($\pi/4 \leq \theta \leq 3\pi/4$), and ϕ longitude ($-3\pi/4 \leq \phi \leq 3\pi/4$). For this simulation, we have used 512 nodes or 4096 processors of the Earth Simulator, which is the maximum size allowed for a calculation. The speed is about 15 TFLOPS, which is about 46% of the theoretical peak performance.

3 Simulation Results

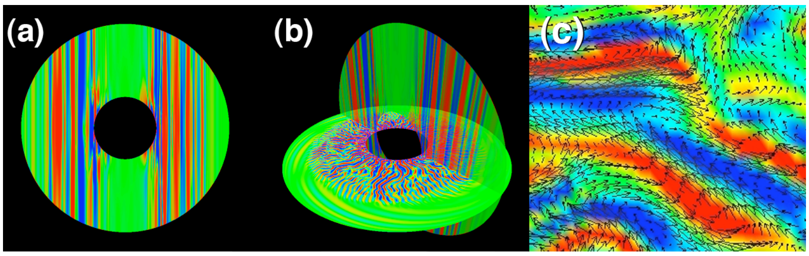

Fig. 3. Convection structure of the outer core in the high resolution geodynamo simulation. (a) The vorticity component parallel to the rotation axis, ω_z, in the meridian plane. (b) ω_z in the meridian and equatorial planes. (c) An amplified view of ω_z in the equatorial plane near the inner core with velocity arrows.

When Ek is relatively large, the convection flow in a rapidly rotating spherical shell is organized as a set of columnar convection cells [7]. Sumita and Olson [8] showed by laboratory convection experiments of water in a hemispherical shell that the convection motion is organized as a set of thin jet sheets or sheet plumes, rather than columns, when Ek is small enough.

Our simulations have confirmed the sheet plume structure in low Ek regime for the first time. Fig. 3(a) shows the distribution of the axial component of the vorticity, ω_z, in the meridian plane. Fig. 3(b) shows ω_z in the equatorial and meridian planes. The flow is composed of many plumes elongated in s direction, where we use the cylindrical coordinates (s, ϕ, z). The plume structure is composed of jet flow in positive s-direction and negative s-direction, side by side as shown in the amplified view of colored ω_z with velocity arrows in Fig. 3(c).

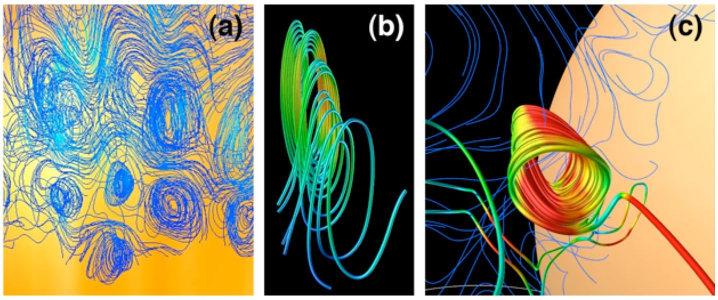

Fig. 4. Spontaneously generated spring coil structure of electric current. The magnetic energy is generated when straight magnetic field lines threading through these spring coils are stretched by hot, upwelling flows in the sheet-like plumes.

The sheet plume convection is an effective dynamo. The total magnetic energy becomes more than 4 times larger than the total convection energy. The magnetic energy is generated by upwelling ($v_s > 0$) plume flows. The flow is accelerating in positive s direction after a plume leaves from the inner hot boundary. The magnetic field lines imbedded in the upwelling plume are stretched in the parallel direction by this acceleration. A stretched magnetic field line means the formation of a current coil around the line. Fig. 4(a) to (c) show the spring coil structure of the electric current observed in our simulation.

4 Visualization with Armada on Yin-Yang Grid

The output data size of the geodynamo simulation amounts to 50 GB in total for just one time step. This data size, which is common in large scale simulations on Earth Simulator, is beyond the power of commonly used visualization tools for CFD data. Therefore, we are developing a visualization software for large scale data visualization, named Armada.

We take a purely software-based approach to the visualization in the development of Armada. We have adopted the ray casting as the basic algorithm for various visualization methods including volume rendering, isosurface, stream lines, ortho-sicers, and so on. To accelerate the ray casting, we have parallelized the code with OpenMP and MPI. Since Armada does not need any graphics hardware and graphics API such as OpenGL, it runs on massively parallel supercomputers such as Earth Simulator.

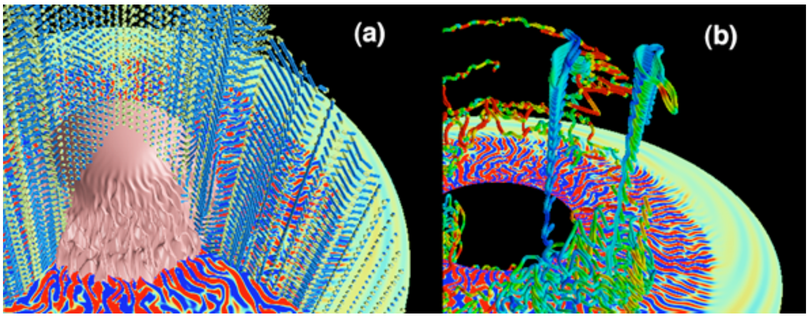

Fig. 5. Sample visualizations by Aramda, a parallel rendering software tool to visualize large scale simulation data. Since Armada is a parallelized visualization tool with OpenMP and MPI and requires no graphics hardware, it runs on general supercomputers. Vector arrows in the panel (a) as well as stream tubes in the panel (b) are generated by the software cay-casting.

We are developing three different versions of Armada that adopt (i) Cartesian coordinates data, (ii) spherical coordinates data, and (iii) Yin-Yang grid data. We applied the Yin-Yang version of Armada for the visualization of the geodynamo simulation. The images of Fig. 3(a) & (b) and Fig. 5(a) & (b) are generated by the Yin-Yang version of Armada. As Fig. 5 shows, Armada generates vector arrows as well as stream tubes. We have found that Armada is a powerful tool for visualization of large scale simulation such as the Yin-Yang geodynamo simulation.

5 Visualization by CAVE VR system with VFIVE

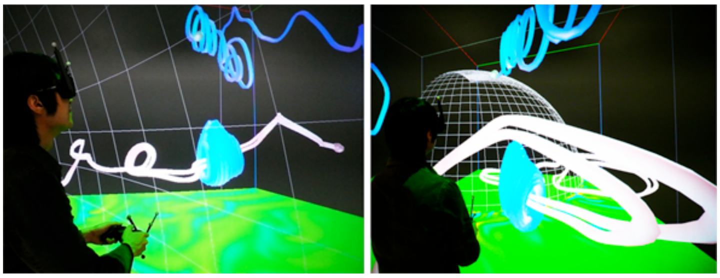

Fig. 6. Virtual reality visualization with VFIVE in the CAVE virtual reality room. When one presses a button on a portable controller, a new stream line is seeded from the tip of a virtual beam. We have found a torus cell structure of the electric current by this virtual reality visualization.

It is generally difficult to grasp three-dimensional structure of a vector field such as the convection velocity or magnetic field. We are using a virtual reality (VR) technology to visualize highly complicated structure in three-dimensional VR space. Among various VR systems, CAVE [9] provides the most powerful VR environment.

The CAVE is a room-sized, projector-based, and immersive-type VR system. The arena of the CAVE is a cubic room surrounded by four screens (three wall screens and a floor screen). The position and angle of the viewer's head in the CAVE room is tracked in real time. Stereo images on the screens are refreshed with the proper perspective of the viewer's eyes.

We have been developing an interactive visualization software called VFIVE [10, 11, 12] for CAVE systems. Various visualization methods are implemented in VFIVE, including isosurface, global slice planes, local slice planes, volume rendering, etc. for scalar field data, and particle tracer, stream lines & tubes, local 3-D arrows, thousands of tracer particles in a spot light, line-integral-convolution, etc. for vector field data.

Since the spatial resolution of the geodynamo simulation is too fine for the straightforward visualization in the CAVE, we made use of the region-of-interest (ROI) function that is recently implemented in VFIVE. A user can visualize the data with finer and finer resolution as he or she specifies smaller and smaller ROI. The ROI can be intuitively specified in the CAVE room by a hand motion.

Among various visualization methods, the stream line and the stream tube are very useful to visualize the magnetic and current fields, see Fig. 6. Pressing a button of the wand, a portable controller in the CAVE, generates a short beam from the wand tip. The beam points the seeding position of the stream line tracing. When the button is released, a particle that denotes the stream line's tip starts moving following the vector field. The particle flies in the CAVE room in front of the user's eyes. Repeated clickings of the wand button generate a sequence of new stream lines.

The electric current is basically organized as a set of spring-coils as we described above. By this VFIVE visualization in the CAVE, we have found that some of the current coils have an intriguing structure—in those coils a string of the electric current line makes a closed surface of a torus. The finding of this torus cell of the current field would have been difficult, if possible, by other visualization methods.

6 Summary

We have developed a new geodynamo simulation code based on the Yin-Yang grid whose speed reaches more than 15 TFLOPS on 4096 processors on Earth Simulator. This speed has enabled us to perform highest resolution simulation of the geodynamo.

We have found that the convection structure of the outer core is fairly different from other simulations performed so far in which the Ekman number was roughly one order of magnitude larger. The convection was organized as a set of sheet-like plume structures, in contrast to the columnar structure observed so far.

A strong magnetic field is generated by the sheet plume convection. The magnetic energy is generated when magnetic field lines are stretched out in the upwelling part of the sheet plumes. The stretched straight magnetic lines are surrounded by helical-shaped electric current lines. The plume sheets and the helical currents were analyzed in detail by our original visualization tools, Armada and VFIVE.

Armada is a parallelized visualization program that is developed as a general purpose visualization for large scale simulation data. Since Armada requires no graphics hardware or OpenGL, it runs on general HPCs. Among various versions of Armada we have used the Yin-Yang version that accepts data defined on the Yin-Yang grid. Since the Yin-Yang grid is applied in various fields these days, the Yin-Yang version of Armada will be useful for those simulations, too.

VFIVE is a virtual reality visualization software for the CAVE-type VR system. The interactive, immersive, and three-dimensional visualization provided by VFIVE was the key to grasp the characteristic structure of the magnetic field and the electric field in our geodynamo simulation. We conclude that the virtual reality technology is a very powerful, almost indispensable, tool when we analyze highly complicated structure of vector fields in three-dimentional space.

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