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Japan Agency for Marine-Earth Science and Technology

New Generating Mechanism of Geomagnetic Field Found in the Highest-resolution Simulations Using Earth Simulator

1. Outline

Akira Kageyama, Takehiro Miyagoshi, Tetsuya Sato at Earth Simulator Center of Japan Agency for Marine-Earth Science and Technology found a new generation mechanism of geomagnetic field by performing large-scale computer simulations on the Earth Simulator with the help of advanced visualization based modern virtual reality technology.

The magnetic field in the Earth's outer core simulated this study is generated by sheet-like plumes convection which looks like curtains aligned along the axis of the Earth's rotation (Fig.1). These sheet-like flows stretch magnetic fields line and create the magnetic field. At the same time, the electric current is formed to run spirally around the magnetic field line (Fig.2, 3).

This achievement will be published on August 28th issue of the international journal of science "Nature".

Title: "Formation of current coils in geodynamo simulation"
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2. Background

The center of the Earth called "core" is made of electrically conducting iron. The high temperature of the Earth's interior melts the outer part of the core to be liquid. Since the Earth's surface is always cooled at the surface in space, the liquid iron of the outer core makes a spontaneous motion called "convection" (*1).

When an electric conductor moves in an ambient magnetic field, in general, the so-called 'electromagnetic induction' effect shows up and the electric current as well as the magnetic field are generated. This electric power generation process, or the dynamo process, is operating in the Earth's outer core, and called the "geodynamo".

The recent development of the super computer enables us to perform large-scale, high resolution computer simulation of the geodynamo, although the simulation with the real value of the viscosity of the outer core is still beyond the power of supercomputers in near future.

3. Summary of method

The Earth Simulator's 512 nodes (4,096 processors) were used for the geodynamo simulation for the highest resolution ever achieved. Such a large-

scale parallel computation was possible owing to originally-developed "Yin-Yang grid" (*2). The higher the resolution, the more realistic environment we can simulate.

In this simulation, the size of the output data is enormous, from several tens of giga bytes to several tera bytes. It is a challenge to grasp the three-dimensional structure and their mutual relationship of at least 4 vector fields (flow field, vorticity field, magnetic field, current field (*3)).

To resolve this, a three-dimensional virtual reality visualization was applied utilizing virtual reality visualization software "VFIVE" (*4) developed by Kageyama and his colleagues (Fig.4).

4. Summary of result

Through a large scale simulation on the Earth Simulator with the help of advanced visualization methods, new flow structures of velocity and current were found.

It is broadly accepted that a rotating system like the Earth's outer core is in a convection motion that is organized as a set of many columnar cells. Previous simulations with lower resolution actually confirmed the columnar convection in the outer core.

However, the form of outer core convection was substantially different in the high resolution simulation. Sheet plumes, rather than columns, are formed (Fig.1). This was the first computer simulation showed the sheet plume convection structure, while Prof. Sumita and colleagues at Kanazawa University had already showed it in their laboratory experiment using water.

It is also confirmed that this sheet plume convection is an effective dynamo that generates a strong magnetic field and electric currents in the outer core. These electric currents run spirally like coils (Fig.2, 3). This has been expected neither experimentally nor theoretically. Straight, elongated magnetic field lines are created in the center of electric current coil. That means the outer core's sheet plume convection stretch the magnetic field line and create straight long magnetic field. This is totally different dynamo mechanism from what had been reported before.

5. Future prospects and plans

Some creatures such as pigeons and sharks have a tiny magnet inside their body and sense directions by means of geomagnetic field. Geomagnetic field also serves as a barrier to protect the Earth from the shower of solar-wind and cosmic-ray (high energy charged particles from the space). Geomagnetic field plays important roles for our daily life in many ways.

Unfortunately, it is impossible to directly observe the flow or the electric current inside of the Earth's outer core. We are not able to confirm dynamo mechanism, sheet plume convection structure, and electric coil structure in the Earth's outer core under our feet. Still, this finding could pave the way to the fundamental study of geosciences that is to elucidate geomagnetic field. The data of this simulation will be analyzed in more detail to seek a connection between the simulation result and geomagnetic observation data.

Such a large-scale simulation using Earth Simulator shall contribute to not only geomagnetic simulations but also in various kinds of geoscience simulations.

*1: convection

The motion of a fluid in gravity when the bottom is warmed and the upper part is cooled. Heated portion of the fluid expands and thus becomes lighter

than the ambient fluid. Thus, the fluid spontaneously makes a flow called thermal convection.

*2: 'Yin-Yang' grid

A numerical grid system for the spherical geometry. By combining a two identical parts ("Yin" and "Yang") with partial overlap on their borders, one can solve numerical problems with mutual interpolations. It is similar to a seam curve of a baseball. Geodynamo simulation code using the Yin-Yang grid won the Gordon Bell Prize in 2004.

*3: flow field, vorticity field, magnetic field, current field

Electromagnetic induction inside of the outer core is electric current generation occurred by interaction between the flow field of the liquid iron and magnetic field in the outer core. For a system of strong rotation such as the outer core, it is known that a useful field for the flow is the vorticity, which is local rotational component in flow field. Thus, to understand the geodynamo mechanism, analyses of 4 vector fields (flow field, vorticity field, magnetic field, current field) are necessary.

*4: VFIVE

VFIVE stands for 'Vector Fields Interactive Visualization Environment' developed by Akira Kageyama and Nobuaki Ohno at JAMSTEC. VFIVE is an interactive, three-dimensional data visualization software for CAVE-type virtual reality (VR) system. It was designed to make the best use of CAVE's highly immersive environment of virtual reality. The source code of VFIVE can be downloaded from JAMSTEC's website. Some universities and institutes had already installed it to their CAVE system.

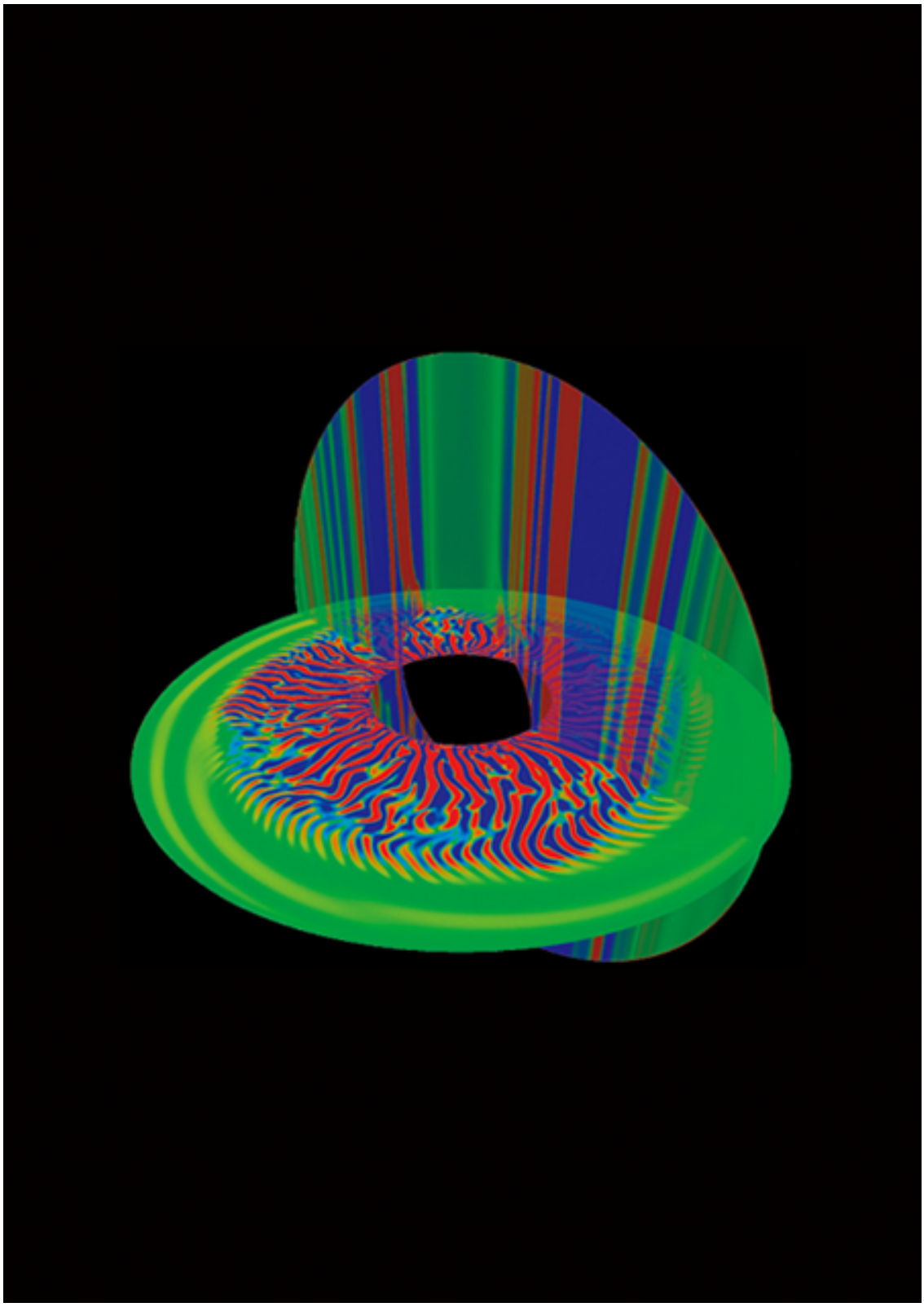

Fig.1: Sheet plume convection structure in the Earth's outer core. Vorticity on equatorial and meridional cross-section shows in colors. On meridional cross-section, vorticity or flow field is likely to be distributed uniformly toward the earth rotating direction. On the other hand, on equatorial cross-section, vorticity or flow field have elongated structure. This sheet plume flow structure was simulated on the computer for the first time, although it already has been confirmed by the water experiment. This is the snap shot obtained from Yin-Yang Movie Maker, the data visualization software on Yin-Yang grid developed by Nobuaki Ohno at JAMSTEC.

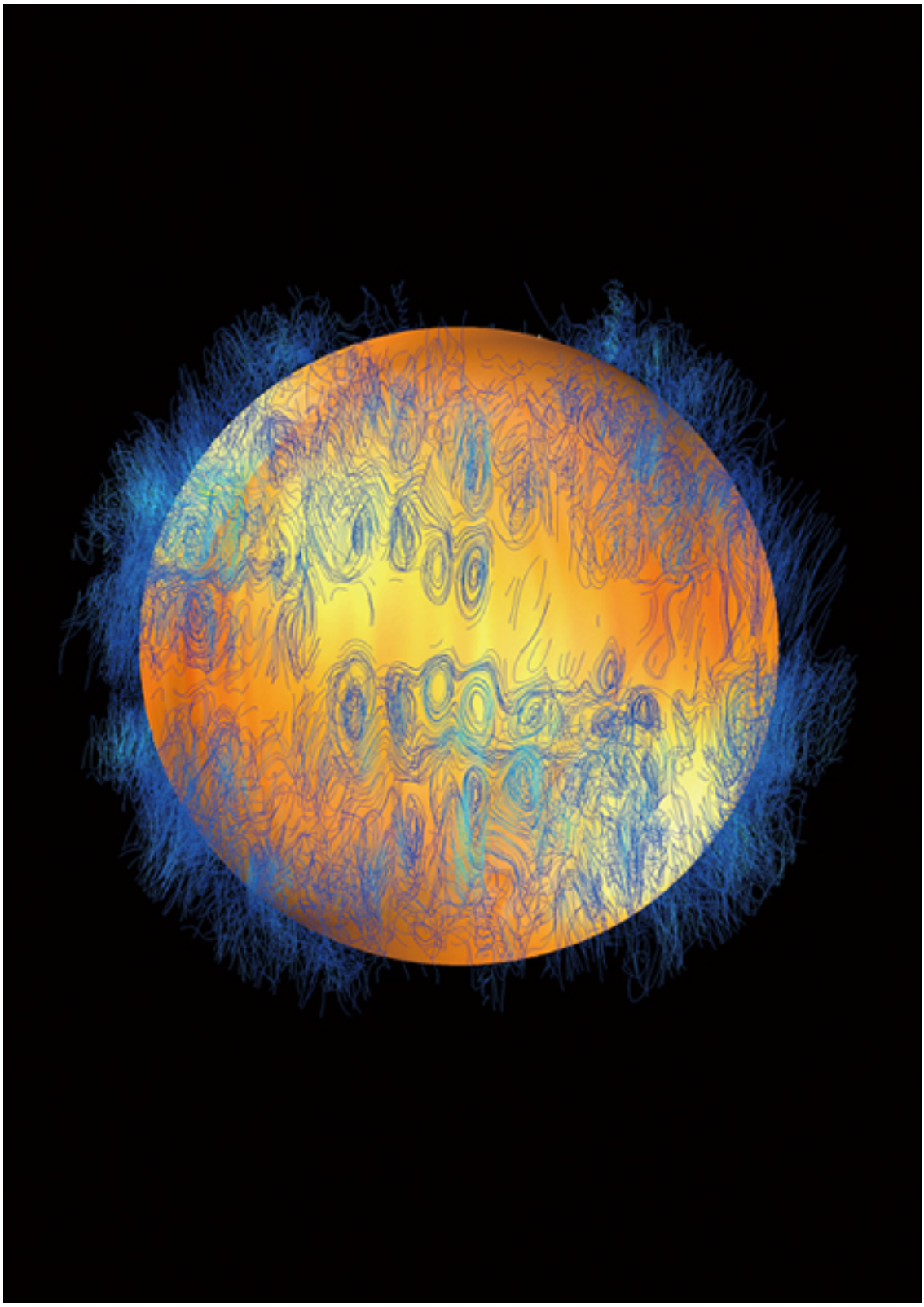

Fig.2: It is found that effective dynamo induced by sheet plume outer core convection has resulted to generate electric current of unique coil structure.

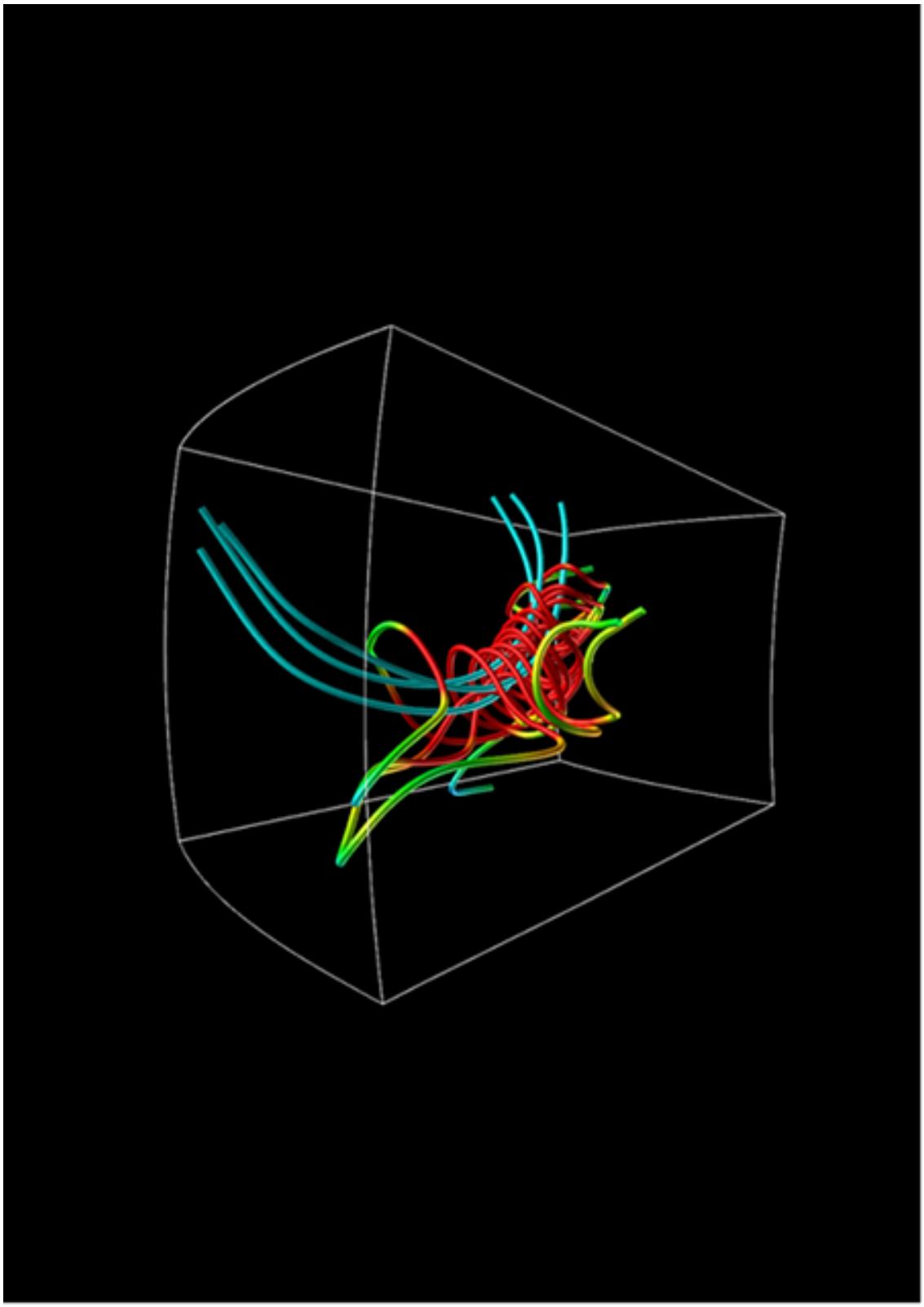

Fig.3: Enlargement of a part of current coils in Fig.2. Current coil structure (red indicates rather strong and weakened gradually yellow to green) and magnetic field line (blue).

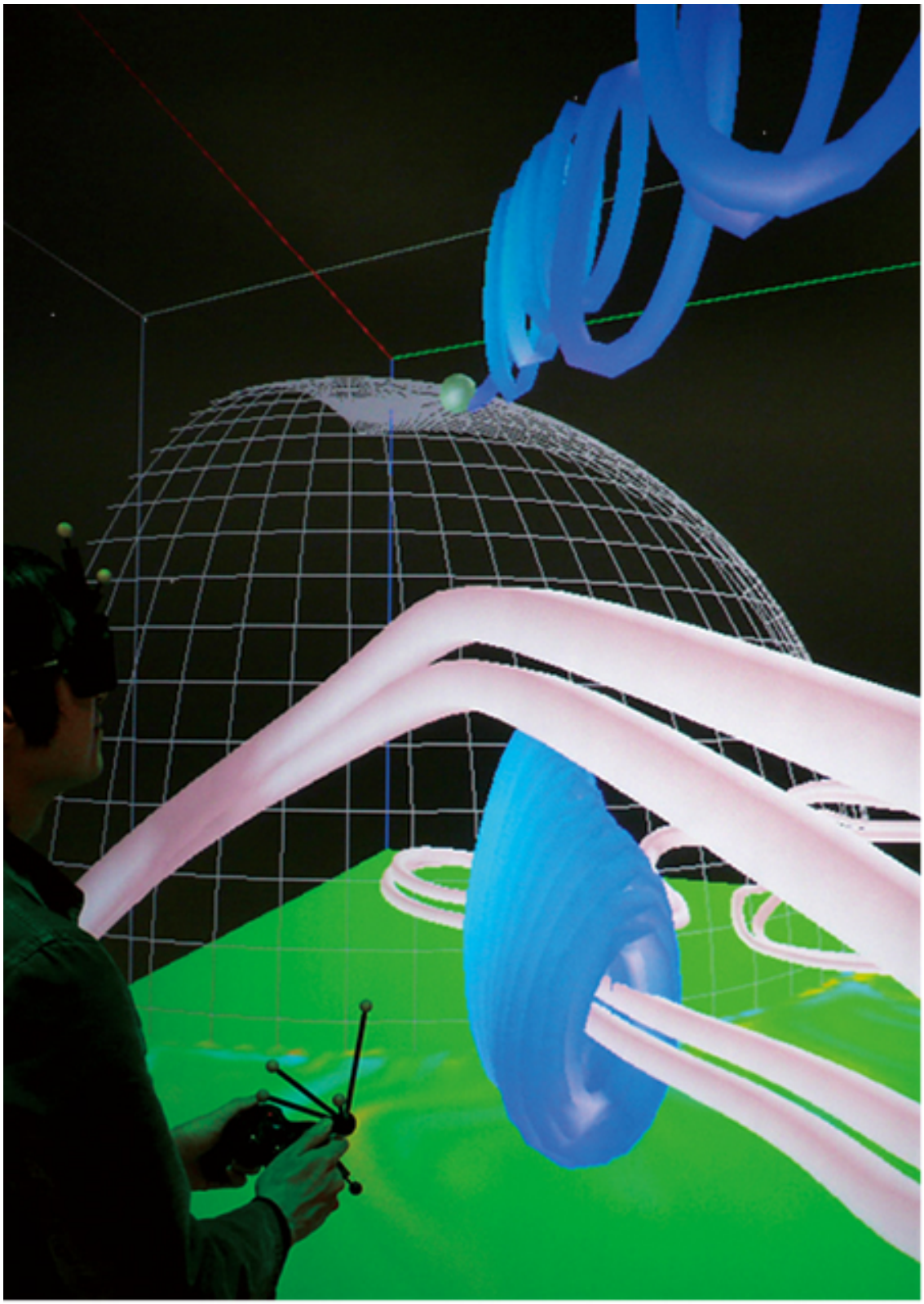

Fig.4: Three-dimensional visualization of simulation results is possible by using CAVE-type virtual reality (VR) system. This figure is the snap shot of analysis of magnetic field (pink) and current field (blue) in interactive and three dimension way using CAVE-type visualization software, VFIVE. Torus current in the figure has been found during the data analysis in VR system. VFIVE's features that can enlarge specific area automatically and draw magnetic line in tube shape have been developed by Nobuaki Ohno at JAMSTEC.

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