News Release

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Chiba University
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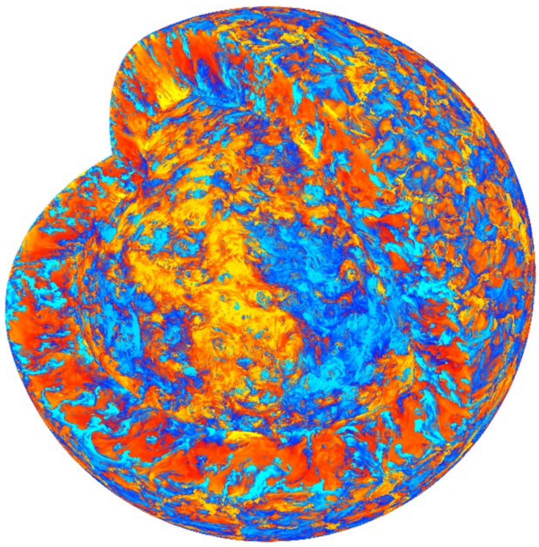
Solar mystery about differential rotation was solved with supercomputer “Fugaku”

The solar differential rotation was reproduced for the first time with the highest-resolution simulation

Associate Professor Hideyuki Hotta (Graduate School of Science, Chiba University) and Professor Kanya Kusano (Institute for Space-Earth Environmental Research, Nagoya University) succeeded to precisely reproduce the thermal convection and the magnetic field in the solar interior in the super high-resolution calculation on supercomputer “Fugaku”*1. As a result, the basic structure of the solar differential rotation, that is, the equator region rotates faster than the polar region, was also reproduced without any artificial manipulation.
The calculation ability of “Fugaku” enabled us to reproduce the sun on the computer. We continue carrying out higher-resolution calculations. Our effort will be a big step towards solving the biggest solar mystery, the 11-year solar cycle*2.
This research was published in Nature Astronomy (13 September 2021).

■ Introduction: Convective conundrum

While the earth rotates rigidly, the sun has different rotation periods in different latitudes, called differential rotation*3. This fact has been known since 1630. Currently, we know that the solar equatorial regions rotate faster than the polar regions; the former rotates with a period of 25 days, and the latter with a period of 30 days. The differential rotation is thought to have essential roles in the sunspot formation and the solar activity cycle.
The solar interior is filled with turbulent*4 thermal convection*5. The energy generated by the nuclear fusion around the solar center is transported by the radiation in the radiation zone (70% of the solar radius). In the convection zone, which is the outer 30% of the sun, thermal convection transports the energy. This turbulent motion is expected to construct and maintain the solar differential rotation.



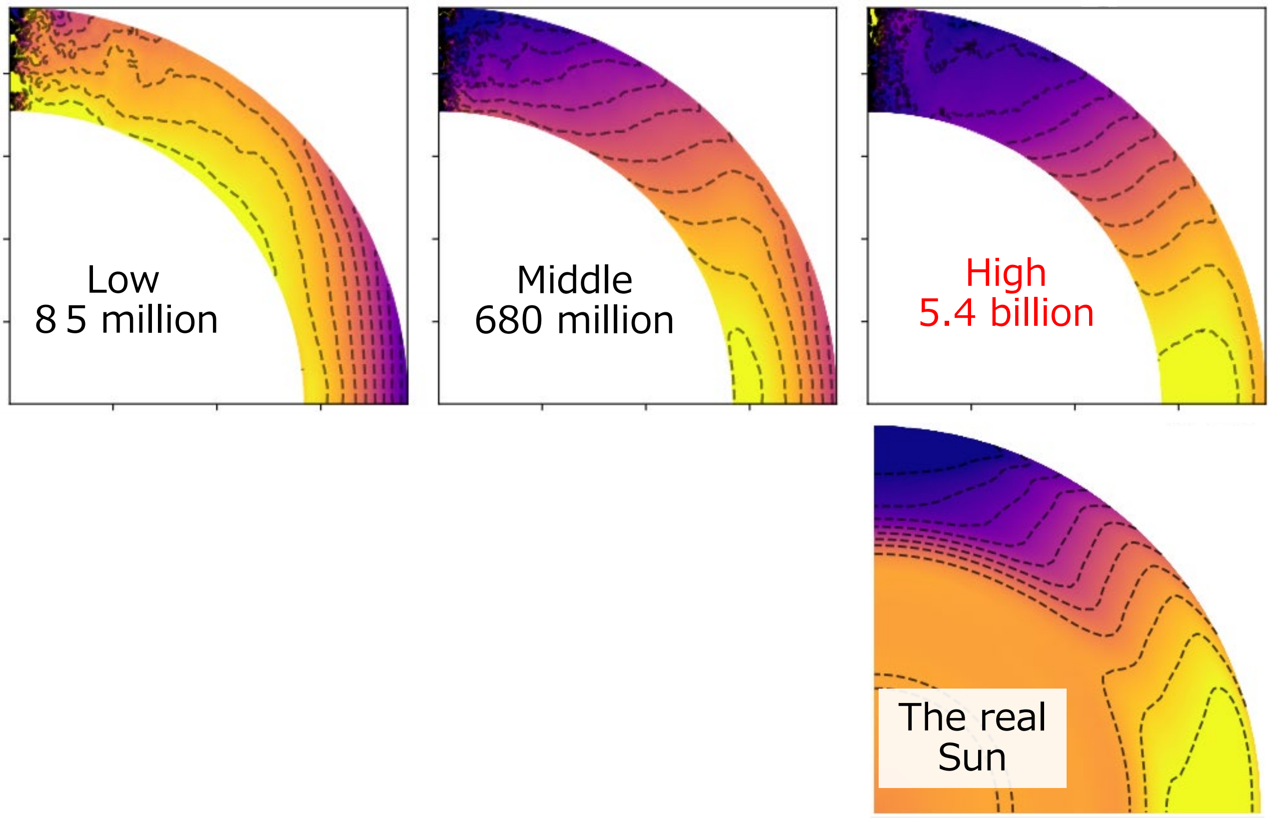
The solar internal convection structure reproduced in Fugaku. The entropy, which is suitable to describe the thermal convection is shown. Orange and blue regions correspond to the warm and cool, respectively.

However, previous numerical simulations*6 could not reproduce the solar differential rotation. Even with the high-resolution calculation on K-computer (~100 million grid points), it simulated that the poles rotate faster than the equator, contrary to the actual solar profile. This phenomenon occurred because the simulations could not precisely calculate turbulent thermal convection. The problem is called “the **convective conundrum**,” a long-term mystery in solar physics.

■ Research achievement

We carried out **an unprecedentedly high-resolution simulation, which is** only achievable with "Fugaku," to solve the convective conundrum. As the high turbulent solar interior investigation requires a substantial numerical resource, we used 5.4 billion points to simulate the solar convection zone. As a result, we succeeded in reproducing the solar-like differential rotation; the fast equator and the slow pole.

The previous calculations have shown that the magnetic energy was smaller than the turbulent energy in the solar convection zone. The magnetic field, therefore, had been thought to have minor roles. The calculation in this study shows that the energy of strong magnetic fields is more than twice the turbulent energy. Our view on the solar interior is significantly changed. Also, we found that the magnetic field has essential roles in the construction and the maintenance of the solar differential rotation.



The longitudinally averaged differential rotation on the meridional plane reproduced in the numerical simulations. The color indicates the angular velocity. The yellow corresponds to the faster rotation.

■ Future perspective

The solar differential rotation has an essential role in the origin of the solar magnetic field. Understanding the solar differential rotation is a vital step in solving the biggest solar mystery, the 11-year solar activity cycle.

Although we found that the high-resolution simulations could reproduce the solar interior, we have not used the full abilities of "Fugaku" yet. We will continue carrying out higher-resolution simulations to challenge the 11-year cycle mystery.

■ Researcher's comment (Assoc. prof. Hideyuki Hotta)

Since we expected it would take a longer time to solve the problem, we are surprised and happy

to obtain the result.
The solar differential rotation is closely related to the biggest solar mystery, the 11-year cycle. We are excited to continue the research for the next goal.

■ Glossary

***1) Supercomputer Fugaku:** A supercomputer settled in RIKEN as a successor of the K-computer. The computer has obtained the first place in four categories of the supercomputer ranking for three consecutive terms from June 2020 to June 2021. Currently, Fugaku is the world's fastest supercomputer. The main operation started on 9 March 2021.

***2) 11-year solar cycle:** The number of sunspots cycles every 11 years. The mechanism has not been understood yet.

***3) Differential rotation:** There are different rotation periods in different latitudes. Like the earth, the rotation which does not depend on the latitude is called rigid rotation.

***4) Turbulence:** A chaotic and uneven movement in a liquid or gas. The antonym is the laminar flow which indicates the ordered flow.

***5) Thermal convection:** Phenomena in which the heated substances such as air or water rise and cool air/water descend, which occurs in hot water in a bus tab. In the solar interior, the energy generated by the nuclear fusion warms the convection zone from the bottom, and the thermal convection occurs permanently.

***6) Numerical simulation:** Equations that are thought to describe the solar interior are solved numerically. A tremendous amount of calculation is needed to reproduce the solar situation, and high-performance computers are required.

■ Research team

- Associate Professor Hideyuki Hotta, Graduate School of Science Chiba University
- Professor/Manager Kanya Kusano Institute for Space-Earth Environmental Research, Nagoya University

■ Project

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Movies and figures are available on the website.
http://www.astro.phys.s.chiba-u.ac.jp/~hotta/press/2021/

Contact information
Hideyuki Hotta, Graduate School of Science, Chiba University
TEL: +81 432902749 Email: hotta@chiba-u.jp