2nd Asia-Pacific Conference on Plasma Physics, 12-17,11.2018, Kanazawa, Japan

MHD relaxation and dynamo in a sphere

Akira Kageyama
[1] Department of Computational Science, Kobe University
kage@port.kobe-u.ac.jp

The Earth's magnetic field is a manifestation of magnetohydrodynamics (MHD) inside the planet. The kinetic (flow) energy of the MHD fluid in the planetary core is converted into the magnetic energy through the so-called MHD dynamo process. It is well known that the dominant component of the dynamo-generated geomagnetic field is the dipole. The fact that the dipole field is the simplest structure of the magnetic field in nature suggests that the geodynamo process could be understood as a kind of MHD relaxation process.

We have performed large-scale computer simulations of geodynamo and found various structures and dynamics in the flow and magnetic fields, including columnar convection cells [1], dipole magnetic field [2], its reversals [3], helical currents [4], and sheet-plumes [5]. It would be natural to try to understand those coherent structures as results of relaxation processes in a spherical MHD system. However, the most successful relaxation theory for the MHD relaxation, i.e., Woltjer-Taylor theory, is not applicable to the geodynamo system, because the flow energy in the relaxed state is supposed to be absent in the theory.

Trying to find a hint for a theory of MHD relaxation in which the fluid in the relaxed state has both the flow and magnetic energies, we have performed a computer simulation MHD relaxations in an idealized system: An MHD fluid with low dissipation rates is confined in a perfectly conducting sphericalc boundary. The stress-free boundary condition is assumed for the flow.

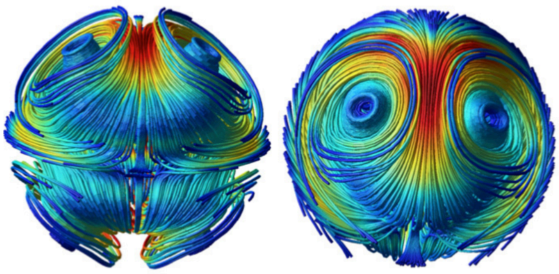

Fig.1: Symmetric vortices (flow lines) in a relaxed state, started from an unstable, ring-shaped magnetic field without flow. The magnetic field lines are aligned to the flow lines. The vortices are located on the four vertices of a regular square.

We start from a simple and symmetric state, such as a ring-shaped magnetic flux with no flow and numerically integrate dynamical relaxations of the magnetic energy.

In some cases, the system settles down to a quasi-stationary state after a relatively short interval with fluid turbulence. The relaxed state has a highly symmetric structure of the flow with the magnetic field in which four swirls are located on vertices of a regular square [6, 7]. We have found that the flow belongs to a family of so-called twist flows. The magnetic field lines are aligned to the flow lines. This result goes beyond the scope of Woltjer-Taylor theory since the structure is a co-existent state of both the magnetic and flow fields with almost the same total energies.

In those simulations, the total angular momentum of the MHD fluid, or the rotation of the system, is absent. We have also performed similar simulations with the rotation of the system, and found higher magnetic energies. This is explained by an MHD dynamo effect with flow helicity.

The simulations are performed with a finite-difference method code on a spherical Chimera grid named Yin-Yang-Zhong grid [8], by which one can solve equations in a sphere without taking care of coordinate singularities on the poles and the origin.

In addition to the base grid system, a new technique for the data visualization is also used in this simulation. It is a kind of “interactive in-situ visualization” method proposed by the author [9,10]. The basic idea and the latest implementation of the method will be discussed in the talk.

References

[1] A. Kageyama, et al., Computer Simulation of a Magnetohydrodynamic Dynamo. II, Physics of Plasmas, Vol.2, No.5 (1995) pp.1421-1431
[2] A. Kageyama and T. Sato, Generation mechanism of a dipole field by a magnetohydrodynamic dynamo, Physical Review E, Vol.55, No.4 (1997) pp.4617-4626
[3] A. Kageyama, M. M. Ochi, and T. Sato, Flip-Flop Transitions of the Magnetic Intensity and Polarity Reversals in the Magnetohydrodynamic Dynamo, Physical Review Letters, Vol.82 (1999) pp.5409-5412
[4] A. Kageyama, T. Miyagoshi, and T. Sato, Formation of current coils in geodynamo simulations, Nature, vol.454, pp.1106-1109 (2008)
[5] T. Miyagoshi, A. Kageyama, and T. Sato, Zonal flow formation in the Earth's outer core, Nature, vol.463, pp.793-796 (2010)
[6] K. Yamamoto and A. Kageyama, MHD Relaxation with Flow in a Sphere, Procedia Computer Science, vol.80 (Proceedings of ICCS2016), pp.1374-1381 (2016)
[7] A. Kageyama, Magnetohydrodynamics Simulation in a Sphere by Yin–Yang–Zhong Grid, Proceedings of the 6th International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH2016), Lisbon, Portugal, Jul 29-31, 2016, ISBN:978-989-758-199-1, pp.239-243 (2016)
[8] H. Hayashi and A. Kageyama, Yin-Yang-Zhong grid: An overset grid system for a sphere, J. Comput. Phys., vol.305, pp.895-905 (2016)
[9] A. Kageyama and T. Yamada, An Approach to Exascale Visualization: Interactive Viewing of In-Situ Visualization, Comput. Phys. Comm., vol.185, pp.79-85, (2014)
[10] A. Kageyama, N. Sakamoto, and K. Yamamoto, Membrane Layer Method to Separate Simulation and Visualization forLarge-Scale In-Situ Visualizations, Proc. SIMULTECH 2018, in press