§10. MHD Dynamo Simulation

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Aiming at understanding of magnetic field generation process in rapidly rotating stars and planets represented by the Earth, computer simulations of magentohydrodynamics (MHD) dynamo were performed in a rotating spherical shell geometry. Thermal convection and dynamo process with Ekman number of the order of 10^{-7} were studied. New structures of convection motion, dynamo-generated electrical current, and magnetic field are found. The flow is organized as a set of thin, sheet-like plumes. The current is made of small-scale coil structure with magnetic flux tubes within each of the coil. These flux tubes are connected each other to form large scale helical magnetic field structure.

Numerical simulations with high performance computer (HPC) have been playing important roles in the study of the convection motion and its MHD dynamo process of the Earth and other planets. However, the direct numerical simulation (DNS) with real parameter values is beyond the power of today's high-end HPC since Reynolds number Re of these celestial bodies are extremely high. Take, for example, the Earth's liquid iron core whose radius $r_o = 3.5 \times 10^6$ [m] and the kinematic viscosity $\nu = 10^{-6}$ [m2/s] has Re = $O(10^9)$.

Dividing celestial dynamo systems into two categories by its rotation rate, the Earth and other planets belong to a group of rapidly rotating systems. In this study, we have focused on this rapid-rotator dynamo systems.

The rotation rate of the MHD dynamo system is depicted by another non-dimensional number called Ekman number Ek. Here we define Ek = $\nu/2\Omega r_o^2$. Ω is the angular rotation rate of the system. For the Earth's outer core, Ek $\approx O(10^{-15})$. Since the depth of the Ekman boundary layer is given as $\delta E \approx \sqrt{E}\, r_o \approx 10^{-1}$[m] for the Earth, covering the whole core size r_o = 3500[km] with numerical mesh that is of the same, or smaller, order of δE is obviously impractical.

The adopted Ek values in geodynamo simulations are therefore much higher than the real value of the Earth's core, with coarser grid mesh than the ideal one. For example, we performed one of the first self consistent geodynamo simulations in the spherical geometry in 1995 in which Ek was $O(10^{-4})$. The value of Ek used in geodynamo simulations have been decreasing steadily since then in accordance with the development of the HPC; Ek = $O(10^{-5})$ were reported from late 1990's and Ek = $O(10^{-6})$ were in this decade.

Convection structure in a rotating spherical shell depends on various parameters. Increasing the Rayleigh number Ra leads to vigorous convection and turbulent flow. Decreasing of Ek, which is proportional to ν, generally leads to smaller scale flows. Ek is also proportional to Ω^{-1} and Ω affects the flow v through the Coriolis force $2v \times \Omega$. The smaller Ek, the smaller the spatial scale of the flow perpendicular to Ω. At the same time, the flow tends to become uniform along Ω due to the Taylor-Proudman's theorem.

Convection under relatively small Ra is organized as a set of columnar cells which is elongated along Ω. This structure was predicted by the linear analysis by Busse. It was confirmed by Gilman & Miller by nonlinear numerical simulations for the solar convection. The flow structure of the Busse column is analyzed in detail by other nonlinear simulations. It is widely accepted that the Busse column is a fundamental structure of the convection when Ek is relatively large.

We have performed MHD dynamo simulations in a rapidly rotating spherical shell with Ekman number Ek = $O(10^{-7})$ and have found that the convection structure and dynamo process are qualitatively different from those found in higher Ekman number regime with Ek > $O(10^{-6})$. Obtained results are summarized as follows and these results are reported in our recent papers[1)-3)]:

- The convection structure is a set of thin plume sheets, not columnar cells. The sheet plume convection, which was first found in water experiments, is numerically con- firmed.
- The sheet plume convection is an effective dynamo, generating electric current in the spherical shell. The current field is organized as a set of small coils. A localized magnetic flux tube is formed in each current coil.
- The magnetic energy is generated by the field line stretching in the plume sheet in which fluid parcels are accelerating in the s-direction. Each magnetic flux tube, or current coil, resides in the convection sheet flows.
- The convection sheet plumes are composed of cyclonic and anti-cyclonic layers. Magnetic field lines in the southern hemisphere are drawn to the equator when it is involved in cyclonic layers, and they are drawn to the opposite direction (away from the equator) in anti-cyclonic layers. The existence of the z-component of the flow in the sheet plumes leads to the formation of helical magnetic fields that connect magnetic flux tubes of localized magnetic intensity in the sheet plumes.

1) Miyagoshi, T., Kageyama, A. and Sato T.: Phys. Plasmas, in press
2) Miyagoshi, T., Kageyama, A. and Sato T.: Nature **463** (2010) 793.
3) Ohno, N. and Kageyama, A.: Comput. Phys. Comm. **181** (2010) 720.