Quantitative evaluation of the convection structure in the core with reference to a compositionally-driven lunar dynamo

*Fumi Hyodo[1], Futoshi Takahashi[2], Satoshi Kaneshima[2], Hisayoshi Shimizu[3], Hideo Tsunakawa[4]

1. Department of Earth and Planetary Sciences, Graduate School of Science, Kyushu University, 2. Department of Earth and Planetary Sciences, Faculty of Science, Kyushu University, 3. Earthquake Research Institute, University of Tokyo, 4. Japan Aerospace Exploration Agency

Now there is no global intrinsic magnetic field generated by a dynamo action on the Moon unlike the Earth, while lunar paleomagnetic records suggest that the Moon once had a magnetic field of several tens of μT in the period of 4.2 to 3.56 Ga [e.g., Garrick-Bethell et al., 2009]. Since this strength is the same as that of a surface field on the Earth in the order of magnitude, it is estimated that the magnetic field of the ancient Moon was maintained by a dynamo action. Various mechanisms of the lunar dynamo have been proposed so far. Some thermal history calculations of the lunar core show that the compositionally convection-driven dynamo due to inner core crystallization could continue from the early stage of the evolution to the present [e.g., Laneuville et al., 2014]. In order to investigate long-term variations of the lunar dynamo in detail, we perform numerical dynamo simulations using a MHD code [Takahashi, 2012] with a compositional buoyancy as a driving force of convection and a dynamo action. The duration of the lunar dynamo could be substantially longer than the magnetic diffusion time of the lunar core, which is a typical time-scale of the dynamo simulations. Therefore, we run the simulations for discrete time periods corresponding to different ages with three controlling parameters chosen to match thermal history of the lunar core computed by a thermochemical evolution model based on Sheinberg et al. (2015): (1) The ratio of the inner to the outer core radii χ similar to Heimpel et al. (2005), (2) the Ekman number E, and (3) the Rayleigh number Ra. Note that the Prandtl number Pr and the Magnetic Prandtl number Pm are fixed at 1 and 5, respectively, for all of our runs. We only consider compositional convection and define Ra as a function of a total mass flow of the light element from the inner core boundary. We change E and Ra at a given χ ranging from 0.1 to 0.7 based on a seismological observation of the Moon [Weber et al., 2011]. Parameter survey is carried out keeping E to be of O (10^{-4}).

We find that a larger Ra is needed to maintain convection and the dynamo as χ increases. The magnetic Reynolds number Rm, which is evaluated using the dynamic flow length scale L_u instead of the shell thickness, also increases with increasing χ. We find that the dynamo is maintained even if the Rm is less than 10 when χ<=0.5, unlike the cases of thick shell. Since Rm indicates the ratio of magnetic field generation to magnetic field diffusion, the results suggest that dynamo action is more efficient in a thin shell than in a thick shell. Furthermore, we find that the generated magnetic field is dipole-dominant in most cases, and the dipolarity f_{dip}, indicating the ratio of the dipole magnetic field at the core-mantle boundary, exceeds 0.7. An exception is obtained when χ is 0.5 and Ra is about six times the critical value. In this situation, the magnetic field is nondipolar and f_{dip} is less than 0.1. Also, in this anomalous case, the Elsasser number Λ is much smaller than unity. We find that both L_u and the ratio of the toroidal component to the poloidal component in the kinetic energy, KEP/KET, are relatively small in the case of the weak and nondipolar dynamo, compared with the other runs. Therefore, it is inferred that the morphology and strength of the magnetic field could change depending on the flow structure, which could be evaluated by the parameters such as L_u and KEP/KET.

Keywords: lunar dynamo, compositional convection, core crystallization, lunar thermochemical history, inner core growth, evolution of the magnetic field of the Moon