On the vigor of mantle convection and stagnant lid formation in super-Earths

MIYAGOSHI, Takehiro[1]* ; KAMEYAMA, Masanori[2] ; OGAWA, Masaki[3]

[1]JAMSTEC, [2]Ehime University, [3]University of Tokyo

Super-Earths are extra-solar terrestrial planets which have large sizes and masses (up to about ten times the Earth's mass). Understanding mantle convection in super-Earths is a key to clarifying their evolution, surface environment, and habitability. In large super-Earths, the mantle depth far exceeds the thermal scale height, and adiabatic compression strongly influences super-Earths' mantle convection in contrast to the Earth's one. In this paper, we present numerical models of mantle convection in super-Earths with high compressibility, high Rayleigh number, temperature-dependent viscosity and depth-dependent thermal expansivity.

Thermal convection of compressible infinite Prandtl number fluid is solved in a rectangular box under anelastic approximation by the ACuTEMAN (Kameyama et al. 2005). The model of the super-Earths includes depth-dependent thermal expansivity and density, as well as a strong temperature-dependence of viscosity. We assume the mass of the planet is ten times the Earth's. The Rayleigh number defined with the viscosity at the core-mantle boundary (CMB) Ra is 1E10. A viscosity contrast r up to 1E7 arises between the CMB and the surface owing to the temperature-dependence of viscosity. The employed grid number is 1024 (horizontal) and 256 (vertical).

We identified the stagnant lid regime in the model of super-Earths. When the viscosity contrast r is larger than about 1E6, a stagnant lid of highly viscous fluid is formed along the surface. The lid hardly moves and is not involved in the convection, as has been observed earlier for the Boussinesq model of the Earth's mantle convection (Kameyama and Ogawa, 2000). The lithosphere is as thick as about thirty percent of the depth of the whole mantle, and the Nusselt number is about three at r=1E7 and Ra = 1E10. This value is comparable to that of the Earth's model at the same r but at much lower Ra of 6E6 (Kameyama and Ogawa, 2000). The lithosphere is much thicker than has been expected earlier for super-Earths (e.g., Valencia et al. 2007), and the thick lithosphere is likely to affect the possibility of plate tectonics at the surface of super-Earths. The strong effect of adiabatic compression also affects the dynamics of hot plumes that ascend from the CMB when the temperature-dependence of the viscosity is strong: At r >~1E3, hot plumes from the CMB are strongly suppressed. They do not ascend to the surface of the planet. The overall pattern of convective circulation in the mantle is, therefore, dominated by the cold plumes that descend from the lithosphere to the CMB. The low efficiency of heat transport by the mild convection would strongly affect the evolution history of super-Earths, and is likely to weaken the core convection, and thus, the magnetic field of super-Earths.

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