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強い圧縮性を持つ流体中の熱対流に関する線形解析
Linear analysis on the onset of thermal convection of highly compressible fluids

亀山 真典 [1]*
KAMEYAMA, Masanori[1]*

[1] 愛媛大学・地球深部研
[1]GRC, Ehime University

A series of linear stability analysis was performed on the onset of thermal convection in a highly compressible fluid, in order to study the fundamental nature of mantle convection of massive super-Earths in the presence of strong adiabatic compression. We consider the temporal evolution (growth or decay) of an infinitesimal perturbation superimposed to a highly compressible fluid which is in a hydrostatic (motionless) and conductive state in a basally-heated horizontal layer. As a model of pressure-dependence in material properties, we employed an exponential decrease in thermal expansivity and exponential increase in (reference) density with depth. The linearized equations for conservation of mass, momentum and internal (thermal) energy are numerically solved for the critical Rayleigh number as well as the vertical profiles of eigenfunctions for infinitesimal perturbations. The above calculations are repeatedly carried out by systematically varying (i) the dissipation number which measures the effect of adiabatic compression, (ii) the temperature at the top surface and (iii) the magnitude of pressure-dependence in thermal expansivity and reference density.

Our analysis demonstrated that the onset of thermal convection is strongly affected by the adiabatic compression, through modulating the static stability of thermal stratification in the fluid layer. For sufficiently strong adiabatic compression where a sufficiently thick "stratosphere" of stable stratification develops in the layer, for example, the critical Rayleigh number explosively increases with the dissipation number. The explosive changes in the critical Rayleigh number are associated with drastic decreases in the length scales of perturbations both in vertical and horizontal directions. In particular, for very strong adiabatic compression, the vertical motion of fluid is significantly suppressed in a thick "stratosphere", which narrows the incipient convection in a thin sublayer of unstable thermal stratification. In addition, when the effect of adiabatic compression is extremely strong so that the thermal stratification becomes stable in the entire layer, no perturbation is allowed to grow with time regardless of the Rayleigh number and/or the horizontal wavelength. We also found that the effect of adiabatic compression becomes prominent for higher temperature at the top surface of the fluid layer. These findings may imply the crucial importance of adiabatic compression in understanding the dynamics and evolution of the mantles of massive super-Earths, particularly for those orbiting their parent stars very closely.

キーワード: スーパー地球, マントル対流, 断熱圧縮, 熱膨張率
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