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Influence of Magnetic Fields on the Suppression of Large-Scale Convection by Plume-Driven Convection

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In the solar convection zones, thermal convection is driven locally by a negative entropy gradient that exists throughout the layer. As a result, convection-zone-scale convection cells, known as giant cells, are expected to form. However, such large-scale convection has not yet been observed on the Sun. This discrepancy between theory and observation is known as the “convection conundrum” and suggests the need to revise current models of solar convection.

Plume-driven convection has been proposed to address this problem. According to this hypothesis, strong downflows (plumes) generated by radiative cooling at the photosphere act as the primary driving source of convection, resulting in a nearly adiabatic entropy gradient being maintained within the convection zone. This, in turn, suppresses the formation of large-scale convection.

Although several numerical studies of plume-driven convection have been conducted, none have taken the effects of magnetic fields into account. In contrast, the solar convection zone is filled with magnetic fields, which are known to strongly influence thermal convection. Therefore, to evaluate the plume-driven convection hypothesis, it is essential to perform numerical simulations that include magnetic fields.

In this study, we conducted magnetohydrodynamic simulations of plume-driven thermal convection in a Cartesian box to investigate the effects of magnetic fields. The results show that the presence of magnetic fields enhances the convective stability of the computational domain and suppresses the kinetic energy of flows with scales comparable to the domain depth by more than approximately 10% compared to the non-magnetic case. These findings support the plume-driven convection hypothesis.