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The influence of magnetic fields in planetary dynamo models

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Magnetic fields are common throughout the solar system with properties as diverse as the planets themselves. Since these fields likely result from convectively driven dynamo action, the coupling between magnetic fields, fluid flow, and heat transfer must be understood in order to determine what controls the strength, morphology, and evolution of planetary magnetic fields. Towards this end, we have carried out a suite of dynamo and non-magnetic convection simulations to investigate the effect of the presence of magnetic fields on convection, the effect of varying convective vigor, and the effect of varying the rotation rate. This survey considers models with Prandtl number $Pr = 1$; magnetic Prandtl numbers up to $Pm = 5$; Ekman numbers in the range $10^{-3} \geq E \geq 10^{-5}$; and Rayleigh numbers from near onset to more than 1000 times critical. We measure the strengths and structures of magnetic fields and fluid motions, as well as heat transfer efficiency and in situ force balances. These analyses illustrate that dynamo action does not necessitate a fundamental change to the overall flow field, although the impact of magnetic fields is found to increase for lower Ekman numbers. By directly calculating the forces in each of our simulations, we show that the traditionally defined Elsasser number, Λ_i, overestimates the role of the Lorentz force in dynamos. The Coriolis force remains greater than the Lorentz force even in cases with $\Lambda_i \simeq 100$, explaining the persistence of columnar flows in $\Lambda_i > 1$ dynamo simulations, a quasigeostrophic phenomena. We argue that a dynamic Elsasser number, Λ_d, better represents the Lorentz to Coriolis force ratio. By applying the Λ_d parametrization to planetary settings, we predict that the convective dynamics (excluding zonal flows) in planetary interiors are only weakly influenced by their *large-scale* magnetic fields. Our survey also provides new insight into the breakdown of dipolar magnetic field generation since we observe a sharp transition from dipolar to multipolar dynamos in models with moderate to high Ekman numbers. Force calculations show that this transition occurs when the inertial and viscous forces become comparable. These results suggest that viscous effects are important for dipolar field generation in many present day dynamo simulations and imply that dynamo simulations with moderate Ekman numbers may not correctly capture the physics of planetary dynamos where viscosity is expected to be negligible.