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Decoding the Geodynamo: Quantitative Dependence of Magnetic Field Diagnostics on Dimensionless Control Parameters

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Understanding the generation and evolution of planetary magnetic fields requires a quantitative grasp of how key dynamo diagnostics respond to variations in fundamental hydrodynamic control parameters. In this study, we perform a systematic numerical investigation of convection-driven dynamo models in rotating spherical shells, using a suite of simulations spanning several orders of magnitude in Ekman number (E), Rayleigh number (Ra), and magnetic Prandtl number (Pm). Our primary aim is to unravel the dependencies of magnetic energy, dipolarity, field symmetry, and temporal variability on these dimensionless parameters, which collectively govern the balance of forces and transport mechanisms in the system. We quantify the scaling laws of magnetic energy and dipole tilt angle as functions of Ra and Pm, revealing sharp transitions from stable, Earth-like dipoles to multipolar and fluctuating regimes. Spectral diagnostics further demonstrate how kinetic and magnetic energy cascade characteristics evolve with decreasing E, indicating the emergence of rotationally constrained turbulence and quasi-geostrophic behavior. By bridging local and global diagnostic perspectives, this work offers a refined parameter map for dynamo behavior and delineates the physical mechanisms that control magnetic field morphology. Our findings contribute to constraining geophysical models of the Earth's core and guiding future studies toward more Earth-relevant regimes.

Primary authors: PEQINI, Klaudio (Physics Department, Faculty of Natural Sciences, University of Tirana); Dr MARGJEKA, Ilirjan (INFN Bari)

Co-authors: OSMANAJ (ZEQIRLLARI), Rudina (Faculty of Natural Sciences, University of Tirana); ÇAÇA, Enkelejd (Polytechnic University of Tirana); ÇAKAJ, Olta (Department of Physics, Faculty of Natural Sciences, University of Tirana)

Presenter: PEQINI, Klaudio (Physics Department, Faculty of Natural Sciences, University of Tirana)

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