Convective Heat Transfer in Magnetic Field Reversals: Insights from a Low-Dimensional Dynamo Model

Giuseppina Nigro
University of Rome Tor Vergata
e-mail(speaker): giuseppina.nigro@roma2.infn.it

Stellar and planetary magnetic fields are generated by a dynamo mechanism produced through magneto-convection, energized by rotation. Magnetoconvection is a means of heat transport generally occurring in nature at dynamic regimes that are not yet accessible to current direct numerical simulations. Notably, despite its recognized importance in stellar emission and dynamo processes, the magneto-convective heat flux still needs to be studied in the extreme regimes that characterize natural dynamos.

With the aim of describing the dynamical regimes that characterise dynamos in nature, we develop a simplified model for thermally driven magnetoconvection using a modified MHD shell model [1]. Thanks to its low computational cost, the model allows the exploration of the asymptotic behaviour of convective heat transfer under extreme parameter conditions and generates extensive samples of magnetic polarity reversals (as depicted in Figure 1). These reversals have been statistically analyzed, showing agreement with paleomagnetic records and a positive correlation between global convective heat flux and reversal frequency [2]. In particular, Figure 1 shows an increasing number of magnetic polarity reversals with higher Nusselt number *Nu*, which is a dimensionless measure of the convective heat transport.

Notably, convergent cross mapping (CCM)—a statistical method for detecting causality in nonlinear systems—demonstrates a causal relationship, highlighting the critical role of convective heat transfer in triggering magnetic reversals [1]. This finding provides a possible explanation for the magnetic dichotomy observed in late M dwarf stars [2].

Moreover, by modulating a model parameter related to the system's kinetic helicity, we show that kinetic helicity also affects the magnetic reversal frequency. In particular, a periodic modulation of kinetic helicity reproduces key features of stochastic resonance, a mechanism proposed to explain the statistics of geomagnetic field reversals [3, 4].

Therefore, these results provide new insights into the roles of thermal and helical drivers in magnetic field dynamics, shedding light on the physical mechanisms behind magnetic variability in planetary and stellar systems.

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References

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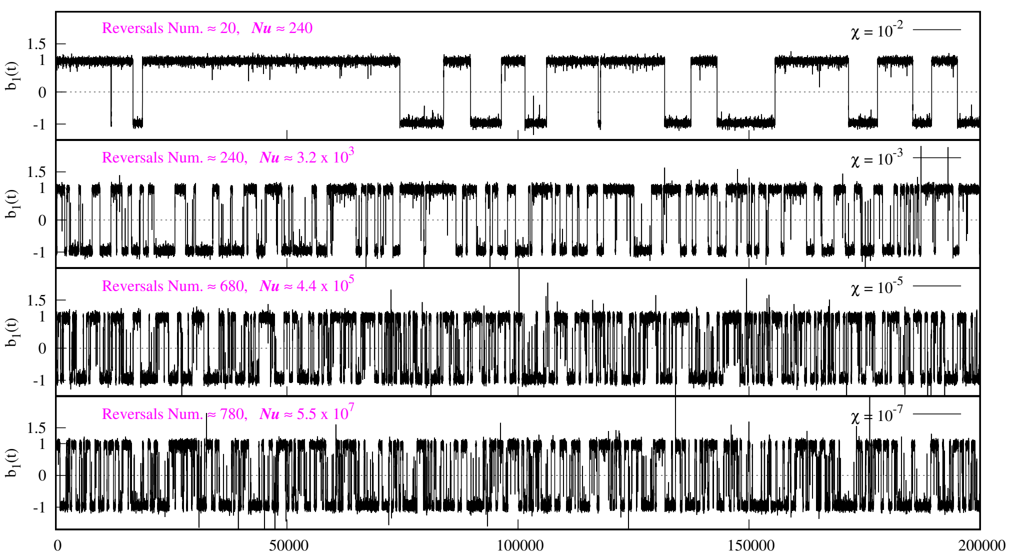

Figure 1: Simulations with a higher Nusselt number (*Nu*), a dimensionless measure of the convective heat flux, tend to develop many more reversals than those with a lower *Nu*. In each panel, the behaviour of the large-scale magnetic field $b_1(t)$ exhibits alternating polarity over time t. The different panels correspond to simulations with decreasing thermal diffusivity values χ, from the top to the bottom panel.