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Determining the simplest and most efficient axisymmetric kinematic dynamos in a sphere

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Planetary magnetic fields, created by the motion of conductive fluid in the interior of these bodies, can be studied by either considering the full magnetohydrodynamic problem or investigating a simplified system. While direct numerical simulations have successfully reproduced a number of planetary magnetic fields' features, these simulations often produce flows which are too complicated to be physically interpreted. In an attempt to better characterise what kind of flow structures produce particular magnetic field features, we consider a simplified approach to the problem, the *kinematic dynamo approximation*. Here, a time-invariant fluid flow is prescribed and the resulting magnetic field is investigated, neglecting the back-reaction of the magnetic field on the fluid flow. Dynamo action is achieved if the fluid flow is capable of sustaining a growing magnetic field against dissipation. The parameter which controls the strength of inductive to diffusive effects is the magnetic Reynolds number, Rm. The onset of dynamo action occurs at the critical magnetic Reynolds number, Rm_c. The aim of our study is to find the simplest and most efficient axisymmetric flows which act as kinematic dynamos in a sphere. Examining these optimal flows might help us identify some of the essential physical processes which are necessary to generate dynamo action. We present optimised versions of three axisymmetric kinematic dynamos first proposed by Dudley and James (Proc. R. Soc. Lond. A, 425:407-429, 1989): $t_1^0 s_1^0$, $t_1^0 s_2^0$ and $t_2^0 s_2^0$. These flows, which contain only one toroidal and one poloidal mode, are some of the simplest known functioning dynamos. Using a Lagrangian optimisation technique for steady flows in a sphere developed by Chen et al. (J. Fluid Mech, 839: 1-32, 2018), we found the smallest enstrophy-based critical magnetic Reynolds number for each flow type. A Galerkin method was used, in which the spectral coefficients of the fluid flow and magnetic field expansions were updated in order to maximise the final magnetic energy after two diffusion times. The optimised flows display Rm_c that are up to four times smaller than the original Dudley-James flows. All Rm_c are quite similar, suggesting that there is only a weak preference for a flow dominated by particular modes. Two of the three flows display good alignment of the velocity and vorticity in the inner region of the sphere, resulting in significant helicity, known to enhance dynamo action. Furthermore, since we are seeking kinematic dynamos with the simplest possible flow structure, we consider the optimisation of single mode flows. Purely toroidal flows are known not to be able to sustain dynamo action, and no example of a purely poloidal single mode dynamo has been found to date. Using the Lagrangian optimisation algorithm, we present a strategy to search for the purely poloidal s_1^0 and s_2^0 kinematic dynamos. These would be the simplest kinematic dynamos found to date.