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Slow magnetic Rossby waves, solitons, and the gyre in Earth's core

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Magnetohydrodynamic (MHD) waves excited in fluid cores of rapidly-rotating terrestrial planets can produce temporal variations of the intrinsic magnetic fields. Given a uniform magnetic field $\mathbf{B}_0$ in a frame rotating with rate $\mathbf{\Omega}$, one class of linear waves for which $(\mathbf{\Omega}.\mathbf{k})^2/|\mathbf{k}|^2 >> (\mathbf{B}_0.\mathbf{k})^2/\rho\mu_0$, $\mathbf{\Omega}.\mathbf{k} \sim 0$, and the frequency $\omega \sim -(\mathbf{B}_0.\mathbf{k})^2|\mathbf{k}|^2/\rho\mu_0\beta k$ are called slow magnetic (or magnetostrophic) Rossby waves. Here β denotes the beta parameter, $\mathbf{k}$ is the wavenumber vector, k is the azimuthal wavenumber, and the minus sign indicates waves travelling opposite to the hydrodynamic planetary wave, $\omega \sim \beta\, k/|\mathbf{k}|^2$. The magnetostrophic mode was hypothesised to account for the geomagnetic westward drift on timescales of hundreds of years [1]. The origin of the drift has been long a subject for debate: an alternative is advection due to a large-scale flow [2]. Signals from the waves have not evidently identified; recently-updated archaeological datasets are now possibly revealling some signatures [3]. Nonetheless, the wave hypothesis has the potential to infer the toroidal magnetic field, which is essentially 'hidden' within the planet's fluid core but is the key for understanding the dynamo mechanism.

By using DNS of convection-driven dynamos in rotating spherical shells, we demonstrated the slow waves could indeed be excited, riding on a mean zonal flow [4, 5]. The detection would enable us to estimate the toroidal field strength, such that O(1-10 mT) at a radius in Earth's core [4]. The value can be compared with the radial field strength that is inferred from axisymmetric, torsional Alfvén waves [6].

More theoretically, identifying waves may characterise the dynamical regime of the dynamo. The planetary dynamo is expected to be in a magnetostrophic balance which is among the Coriolis, pressure gradient, Lorentz, and/or buoyancy. Rotating magnetoconvection studies have suggested this would give rise to large-scale convective structures, subcriticality of dynamos, and excitation of slow waves. A couple of state-of-the-art geodynamo DNS [e.g. 7] are seemingly approaching such a regime, as extensively explored for the past decades.

Theoretical investigation is expanding to consider nonlinear properties of waves. Being motivated by observations in dynamo DNS [4, 5] as well as by the classic hydrodynamic theory [8], we sought coherent structures of the finite-amplitude waves. We asymptotically analysed the weakly-nonlinear, long wave in quasi-geostrophic (QG) MHD models and showed the evolution of the magnetostrophic Rossby waves in spherical shells should be governed by the Korteweg-de Vries equation [9, 10]. This implies multiple solitary eddies that interact in peculiar ways. The single soliton solution (figure 1 left) may be of particular geophysical interest. An isolated, anticyclonic gyre was found to persist, at least, for a hundred years in Earth's core [e.g. 11,12] (figure 1 right). Geodynamo DNS had demonstrated such a gyre could arise from the intrinsic convection [7] or from a flow induced by the couplings with the rocky mantle and/or the solid inner core [13].

This issue ends up in the debate: does the magnetic Rossby wave indeed exist in Earth. It necessitates a comprehensive, and efficient, survey for geomagnetic datasets, which now cover a wide range of timescales but are still limited and spatially inhomogeneous. We will pursue the data investigation by means of newly-available data-driven techniques.

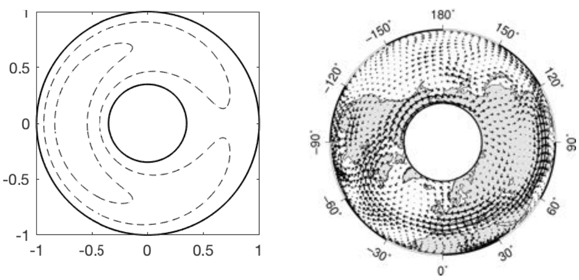

Figure 1. (Left) Streamlines of the 1-soliton solution of our QG-MHD spherical model [10]. (Right) The gyre revealed by core flow models inverted from the geomagnetic secular variation [12].

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