Core Flows inferred from Geomagnetic Field Models and the Earth's Dynamo

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Summary

Are the presently inverted large scale core velocity fields enough to explain the geodynamo?

Our kinematic dynamo calculations use large-scale, quasi-geostrophic (QG) flows inverted from geomagnetic field models, which, as such, incorporate flow structures that are Earth-like, as the large eccentric gyre and the anticyclone under North Pacific. Furthermore, the QG hypothesis allows straightforward prolongation of the flow from the core surface to the bulk.

We obtain magnetic field growth only when the QG flow is perturbed by *magnetic pumping* [7] that parameterizes the effect of an internal toroidal magnetic field of Elsasser number Λ on the flow. The magnetic pumping distorts the columnar flow and introduces helicity. Dynamo action is observed for $\Lambda \geq 0.25$ and magnetic Reynolds numbers $Rm \geq 200$. This suggests that our **large scale flow captures the relevant features for the generation of the Earth's magnetic field and that the invisible small scale flow may not be directly involved in the process**.

Near the threshold, the resulting magnetic field is dominated by an axial dipole, with some reversed flux patches. Time-dependence is also considered, derived from principal component analysis applied to the inverted flows [2]. We find that time periods from 120 to 50 years do not affect the mean growth rate of the kinematic dynamos.

Method

- Surface core flow is inferred from the geomagnetic secular variation.
- Assuming a Quasi-Geostrophic (QG) flow, we can prolongate the symmetric part of the flow in the whole core [1, 6].
- Principal Component Analysis (PCA) is used to extract the main spatial patterns and associated time-series[2].
- The XSHELLS code [3] is used to solve the kinematic dynamo problem (by time-stepping the induction equation).
- The time-dependence of each main spatial structure is prescribed as periodic, with a period obtained by fitting a sinisoid to each retrieved time-series [5].
- A magnetic-pumping parameterization allows to introduce helicity and produce a dynamo.

Core Flows

The flow is split into symmetric $\mathbf{v}^+$ and anti-symmetric $\mathbf{v}^-$ parts.

- The $\mathbf{v}^+$ QG flow (columnar flow) satisfies the following relation at the core surface:

$$\nabla_H \cdot \mathbf{u}^+ = 2u_\theta^+ \tan\theta \qquad (1)$$

- No kinematical constraint applied on $\mathbf{u}^-$.
- We penalize azimuthal gradients as in [6].

$$R_A = \int_{\text{CMB}} \left[\frac{1}{\sin\theta}\frac{\partial \mathbf{u}}{\partial \phi}\right]^2 dS \quad \propto \ell m^2 \qquad (2)$$

- Weak small scale damping, as the small viscosity and magnetic diffusivity in the core should not damp the flow at the scales that can be probed by magnetic field models; we thus also weakly penalize radial vorticity and horizontal divergence.

Magnetic Pumping

On centenial time-scales the influence of the Lorentz force on the flow should be taken into account. We assume the Earth permeated by a simple toroidal field $\mathbf{B_0}$ of dipolar symmetry (Fig. 1, left). The resulting magnetic pumping [7] is proportional to the local vorticity and to the square of the magnetic field and **adds helicity to the flow**. The Elsasser number $\Lambda = B_0^2/\mu_0\rho\Omega\eta$ controls the strength of the magnetic pumping, where B_0 is the maximum of the amplitude of the large scale magnetic field, ρ is the fluid density and Ω the rotation rate of the Earth.

We prescribe, for all azimuthal wavenumber m:

$$v_z^{mp} = \Lambda\, V_0\, f(z/H(s))\, b(s)\, m^2 \xi_m(s) \qquad (3)$$

where $\xi_m(s)$ is the quasi-geostrophic streamfunction, $b(s) = 4s(r_c - s)/r_c^2$ captures magnetic field variations with s, while $f(x) = -\frac{7}{2}x(1-x)^2(1+x)^2$ captures vertical variations due to the magnetic field geometry.

We have approximated the local vorticity by $m^2\xi_m$. This allows us to conveniently satisfy the mass-conservation by adding a contribution v_ϕ^{mp} to the azimuthal flow:

$$v_\phi^{mp} = \Lambda V_0\, ism\, \xi_m(s)\, b(s)\, \frac{1}{H(s)} f'(z/H(s)) \qquad (4)$$

A meridional cross-section of the resulting flow is shown in Fig. 1 (right).

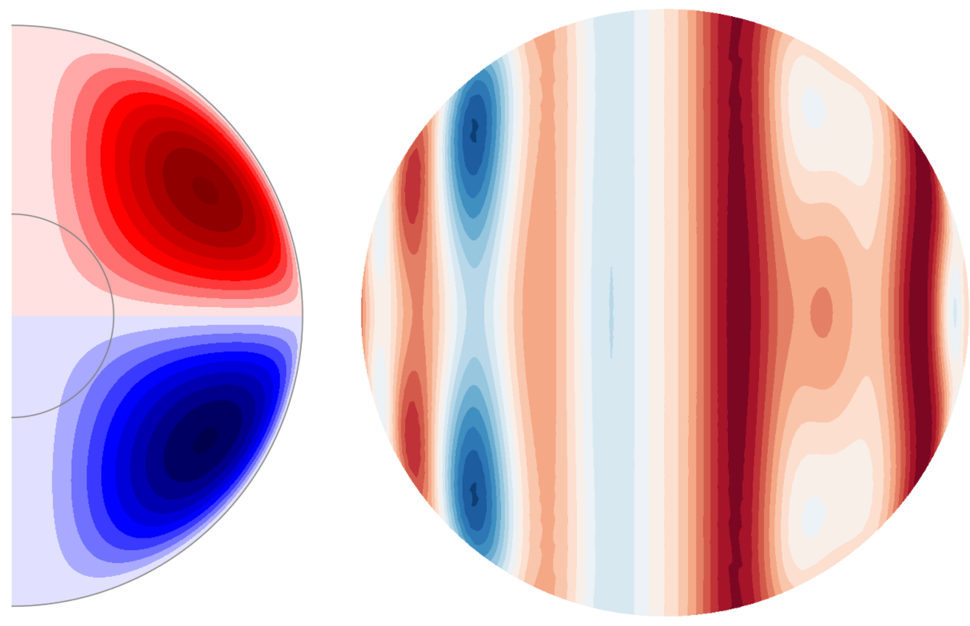

Figure 1: **Left:** the toroidal field $\mathbf{B_0}$ that enters the magnetic pumping. **Right:** the flow distorted by the magnetic pumping (flow component perpendicular to the plane containing the axis).

Kinematic dynamos with core-flows

Magnetic pumping leads to dynamo action for $\Lambda \geq 0.25$ and $Rm \geq 200$.

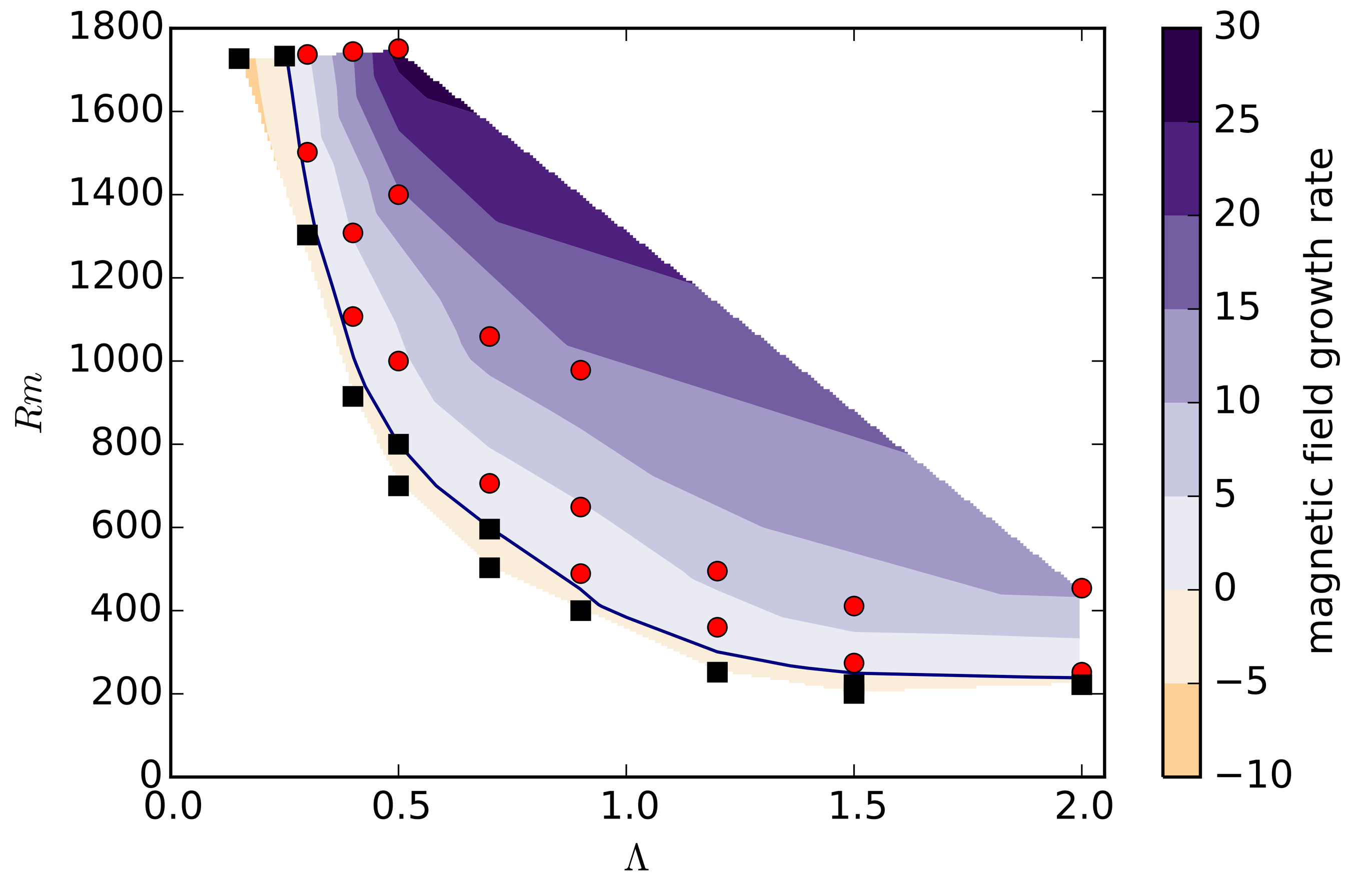

Figure 2: Growth rate (normalized by the magnetic diffusion time) as a function of the magnetic Reynolds number Rm and the Elsasser number Λ controlling the magnetic pumping. Black squares are failed dynamos (for which the magnetic field decays) while red circles are dynamos (exhibiting growing magnetic field).

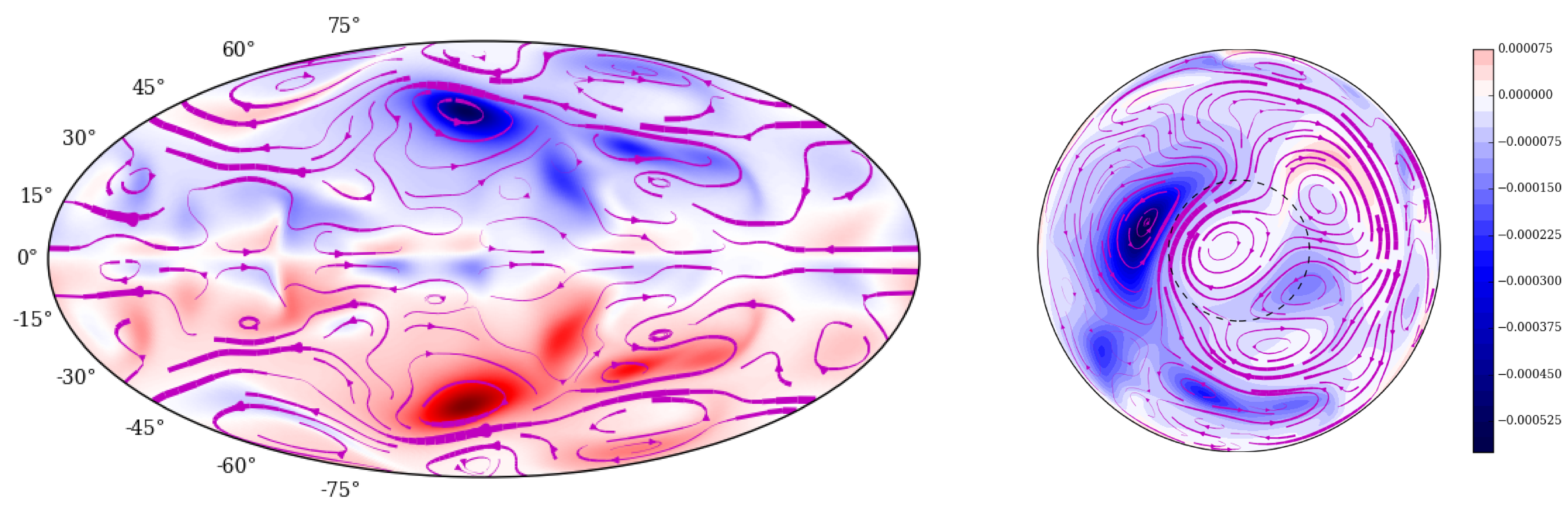

Figure 3: Growing radial magnetic field (colormap) and streamlines of the surface mean flow for $Rm = 978$ and $\Lambda = 0.9$. **Left:** Aitoff projection at the core surface centered on the pacific; **Right:** north-pole view projected onto the equatorial plane. The thickness of the streamlines is proportional to the velocity. The dashed circle marks the boundary of the Earth's inner-core.

Outlook

- The growing surface field is connected to the bulk field by **magnetic diffusion** only. Can we use this property to estimate magnetic diffusion at the Earth's core surface? Would the flow inverted from the growing field resemble the actual flow?
- Is this parameterized magnetic pumping realistic? What is the **effect of the magnetic field on convective columns** for $Rm \gg 1$ and long time-scales?
- Can we construct a **self-consistent quasi-geostrophic dynamo model [4] with a dynamic magnetic-pumping** (that depends on the actual magnetic field)?

References

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