Magneto-Coriolis waves in Earth’s core

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ESA project « Swarm + 4D Deep Earth: Core »

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Swarm 10 Year Anniversary & Science Conference 2024

advection (or convection) time in Earth's core

from the intensities of the field

$$|B| \sim 40\mu\mathrm{T}$$

and of its rate of change

$$|\partial_t B| \sim 200 \text{ nT/yr}$$

→ advection time

$$\tau_U = |B|/|\partial_t B| \sim 200 \text{ yrs}$$

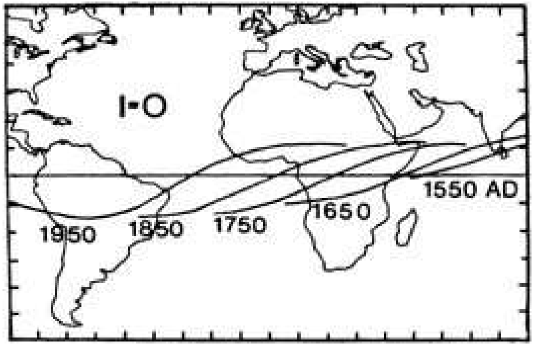
→ flow velocity

$$U \approx L/\tau_U \sim 10 \text{ km/yr}$$

magnitude similar to the westward drift

e.g. Bullard et al. 1950; Finlay & Jackson 2003

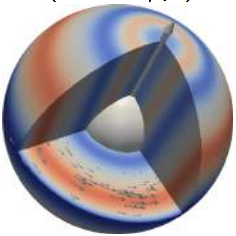
evolution of the magnetic equator



Thomson 1989

Alfvén (or magnetic) time in Earth's core

- torsional Alfvén waves of period 6-yr detected from observatory data
- tiny magnetic signal (~ 2 nT/yr)



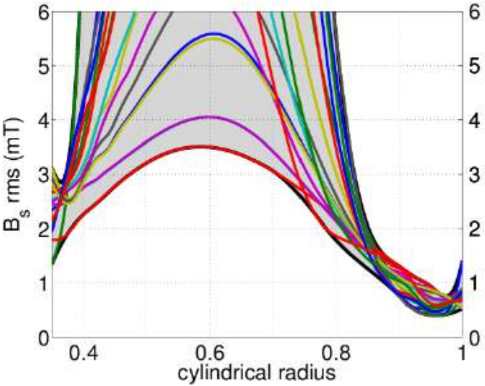
- Alfvén speed

$$V_A = |\mathrm{B}|/\sqrt{\rho\mu} \sim 1000 \text{ km/yr} \gg U$$

$\Rightarrow$ magnetic time

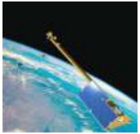
$$\tau_A = L/V_A \sim 2 \text{ yrs} \ll \tau_U$$

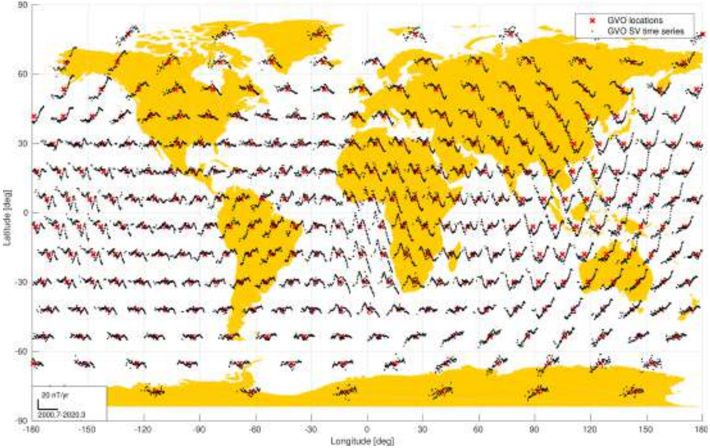
... field intensity deep in the core
$|\mathrm{B}| \approx 5$ mT $\sim 10|B_{CMB}|$



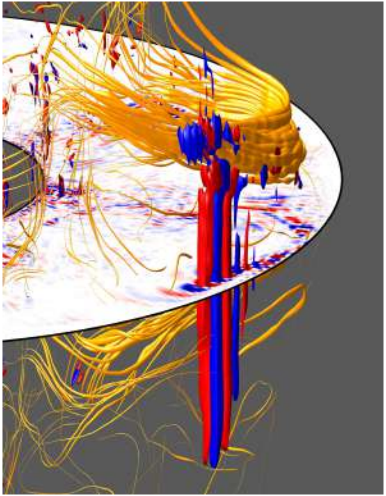
Gillet et al. 2010

1999–now: 25 yr of monitoring from space

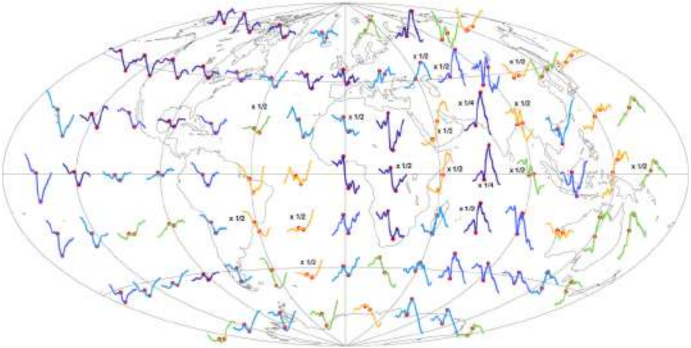




- Oersted, CHAMP, CryoSat-2 & Swarm
  (Hammer et al. 2021)
- interannual signal ∼ 10 nT/yr
- which source ?
- must be non-zonal (Gillet et al. 2015; Kloss & Finlay 2019)



see Talk by O. Barrois

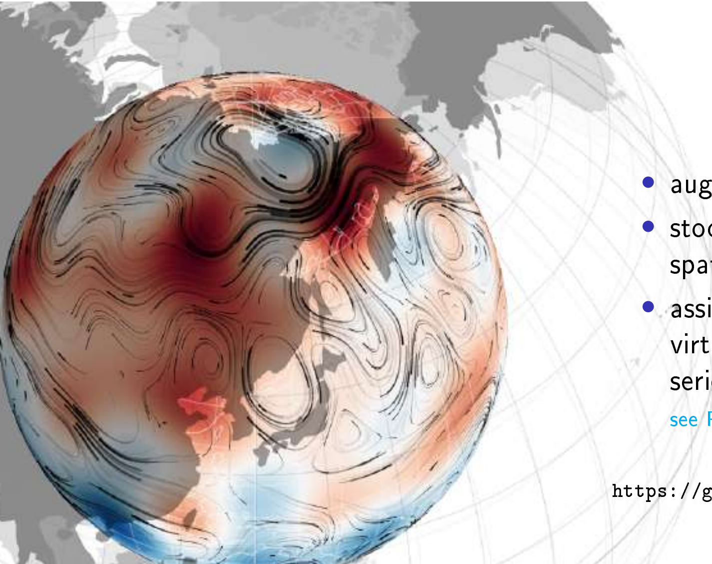


simulated jerks related to axially invariant (or quasi-geostrophic, QG) hydro-magnetic waves

Aubert & Finlay 2019; Aubert & Gillet 2021; Aubert et al. 2022

pygeodyn: a geomagnetic data assimilation tool

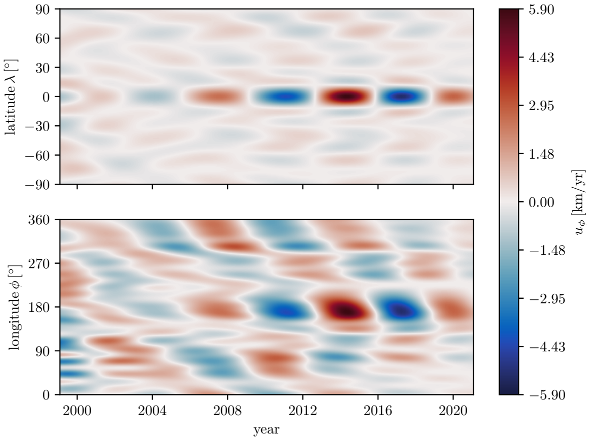
Huder et al. 2019; Gillet et al. 2019; Istas et al. 2023

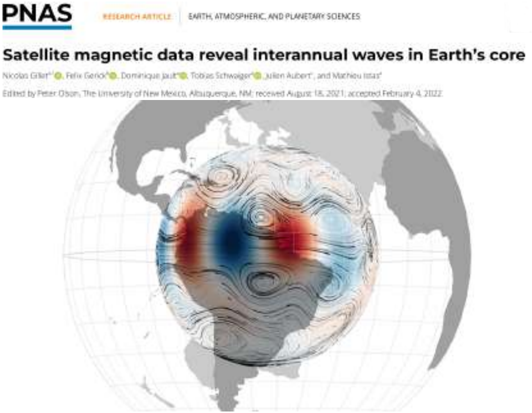


- augmented state ensemble Kalman filter
- stochastic model anchored to geodynamo spatio-temporal statistics
- assimilate either Gauss coefficient data, virtual and ground-based observatory series, or local core surface estimates
  see Poster by H. Rogers

https://geodyn.univ-grenoble-alpes.fr/

discovery of QG MC waves from satellite data





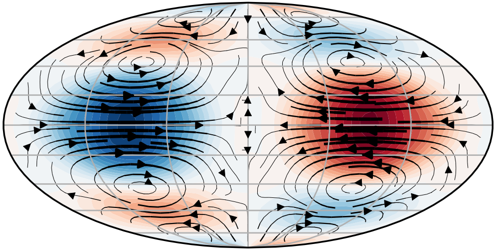
- propagation speed
  - westward: $C_\phi \sim V_A \gg U \sim 5$ km/yr
  - outward: $V_A > C_s \sim 200$ km/yr$\gg U$

gathers numerical, theoretical and observational advances

since confirmed by Ropp & Lesur (2023), Li et al (2024)

interannual Magneto-Coriolis (MC) modes

- MC waves very dispersive → believed undetectable at $T \sim \tau_A$ (Hide, 1966)
- refuted for eigenmodes with low k_ϕ, large k_s (Gerick et al. 2021)



see Talk by F. Gerick

→ equatorial window: $\ell_\theta \gtrsim 10\ell_s$

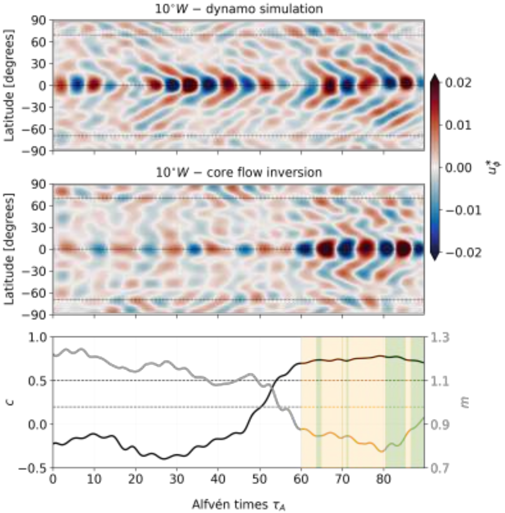
→ carried by the background B_s

- dispersion relation $\omega = \dfrac{V_A^2 k_s^4 h^2}{2k_\phi \Omega}$

$$V_A^2(s,\phi) = \frac{1}{2h\rho\mu}\int_{-h}^{h} B_s^2(s,\phi,z)dz$$

(Gillet et al. 2022)

synthetic validation using geodynamo simulation data



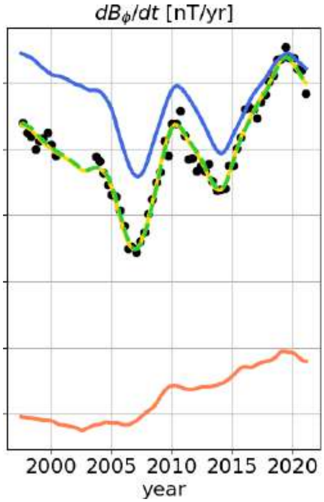
band-pass filter flow for $T \in [6 - 13.5]\tau_A$

partial recovery of the flow patterns, improved:

- for larger flow magnitude
- towards longer time-scale
- with better data coverage
- for simpler geometries

Schwaiger et al. (2024)

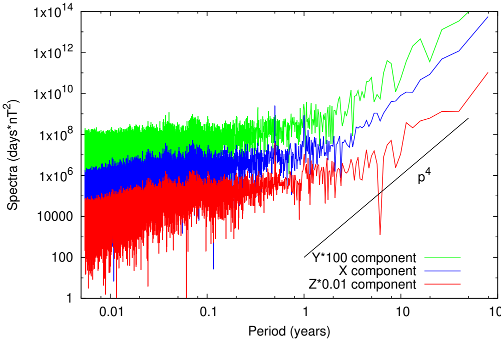
QG MC waves & observed field changes



Ascencion Island
equatorial Atlantic

from large scale flow
subgrid processes
+ diffusion
● SV data

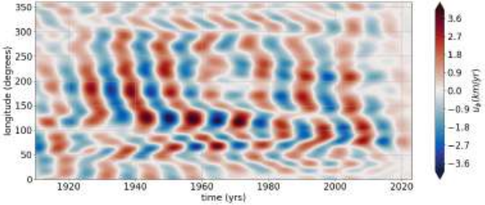
PSD @ Hermanus, South Africa



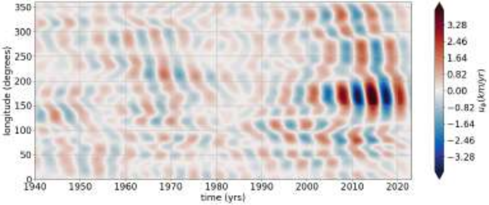
Lesur et al. 2022

→ MC waves at various periods in geophysical observations?

$T \in [10, 16]$ yr

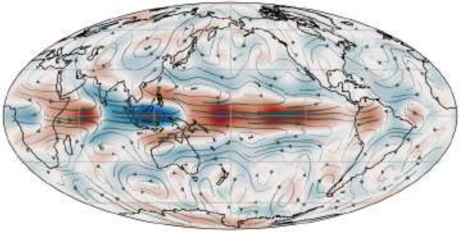


$T \in [5, 8]$ yr



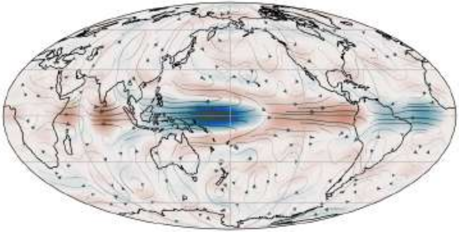
PC no. 1

36% variance over 1920–2023



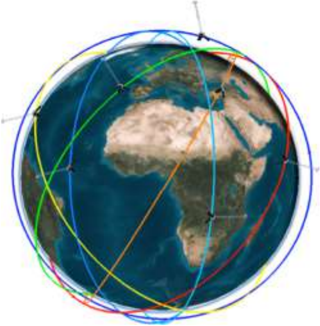
PC no. 1

55% variance over 1990–2023



improved understanding of the magnetic signal

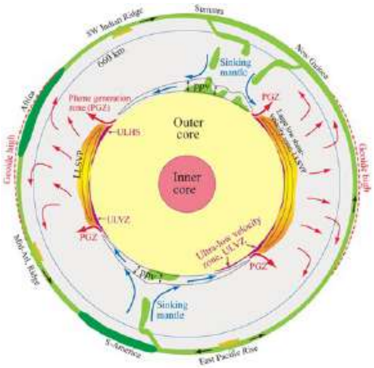
- QG MC waves: a natural explanation to transient field changes
- confidence gained from the confrontation of observations and numerical simulations



NanoMagSat

- longer times-cales:
- ... interprete historical and archeomagnetic records
- ... motivates long-lived coverage from space
- shorter interannual periods:
- ... distinguish QG MC from QG Alfvén waves
- ... improved separation of external sources with inclined orbit missions (MSS, NanoMagSat...)

see talk by Y. Jiang, poster by G. Hulot



Tronnes, 2010

- core dynamics more sensitive to the mantle conductance towards high frequencies

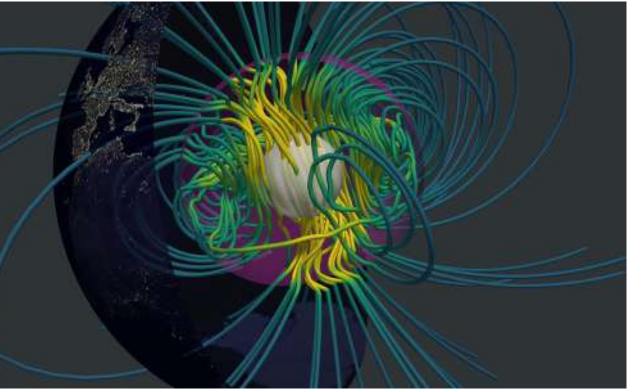
  Firsov et al. 2023

… constrain iron content composition of

- (thick) large low seismic velocity provinces
- (thin) ultra-low seismic velocity zones?

- angular momentum changes:
  sensitivity of the core flow predictions for various conductance models

using QG MC waves to constrain geodynamical issues



courtesy of N. Schaeffer

- image the dynamo field deep in the core through $V_A(s, \phi)$
- improved base-state within the core
  + deterministic description:
  ... magnetic field predictions?
  Aubert 2023
- geodynamical inferrences:
  - mantle heterogeneities, inner core viscosity (through torques & length-of-day)
  - heat flux & stratification level at the top of the core