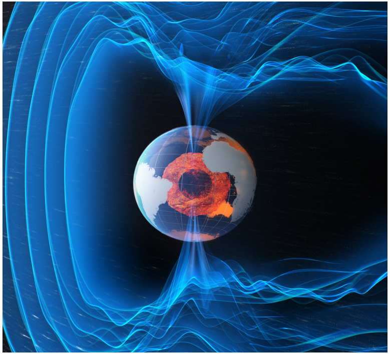
Earth's time-varying core magnetic field from five years of Swarm data

C.C. Finlay, N. Olsen, L. Tøffner-Clausen, M. Hammer and C. Kloss

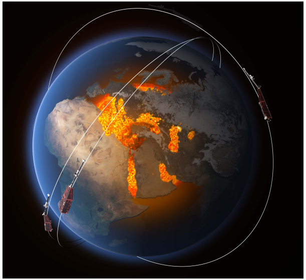
DTU Space, Technical University of Denmark

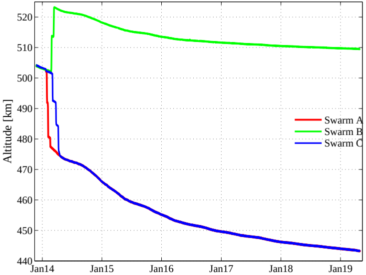


Swarm satellite trio: Five years measuring Earth's magnetic field

- Three identical satellites launched 22nd Nov 2013
- *Swarm* A, C now at altitude 440 km, longitudinal sep. ∼150 km
- *Swarm* B now at altitude 510 km, differential drift in local time

- Vector (FGM) and absolute scalar (ASM) magnetometers
- Remote scalar calib. of *Swarm C* from *Swarm A* since Nov 2014
- Small magnetic disturbance due to thermoelectric currents on satellites. Effect now understood and can be modelled
- Excellent availability of calibrated magnetic data: almost all days since launch suitable for scientific studies





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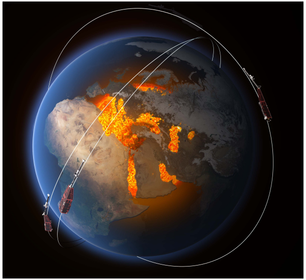
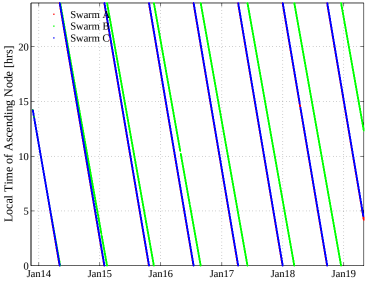




CHAOS-6x9 global field model, using Swarm data Nov 2013 - April 2019

- Latest update of CHAOS field model series *[Olsen et al., 2014; Finlay et al., 2016]*
- *Swarm* data: **MAG L1b 1Hz, version 0505** (vector & scalar field, along/across track diffs)

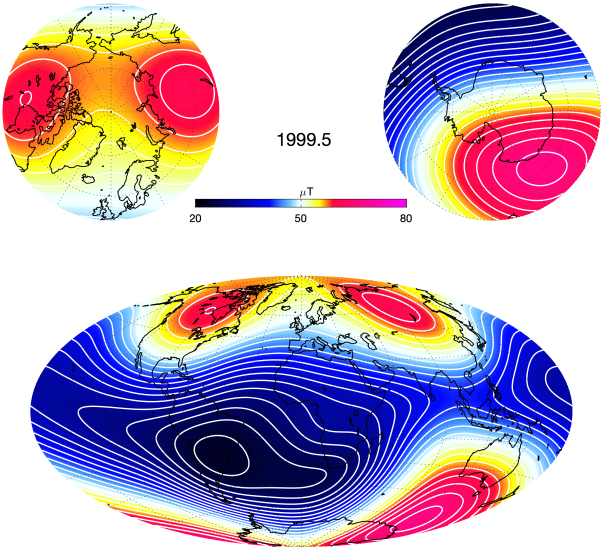
  \+ CHAMP, Ørsted and SAC-C satellite data, all from geomagnetically quiet times
  \+ Ground Observatory Revised Monthly Means (AUX_OBS 0119 from BGS), as available in April 2019
- 11,652,019 data in all
- **Time-dep. internal field to SH deg 20**, static internal field to degree 120.
- **Ext field in SM and GSM coords.** Time-dep via RC index (with induction), offset params in 5/30 day bins.
- **Euler angles** describing rotation between VFM and star tracker frame co-estimated
- Model estimation by **regularized, robust, non-linear least squares** iteratively minimizing

$$\Theta = [\mathbf{d} - F(\mathbf{m})]^T \underline{\underline{\mathbf{W}}} [\mathbf{d} - F(\mathbf{m})] + \lambda_2 \mathbf{m}^T \underline{\underline{\mathbf{\Lambda}}}_2 \mathbf{m} + \lambda_3 \mathbf{m}^T \underline{\underline{\mathbf{\Lambda}}}_3 \mathbf{m}$$

- Weighted rms misfit to *Swarm* non-polar, dark scalar data is **2.06 nT**.
  For scalar field differences, **0.25 nT** along-track and **0.41 nT** cross-track.
- Code to evaluate CHAOS-6-x9 model available in python(**ChaosMagPy** package), Matlab and Fortran from

`http://www.spacecenter.dk/files/magnetic-models/CHAOS-6/`

Evolution of field strength at Earth's surface



[Finlay et al., 2016 update, CHAOS-6-x9, to degree 20]

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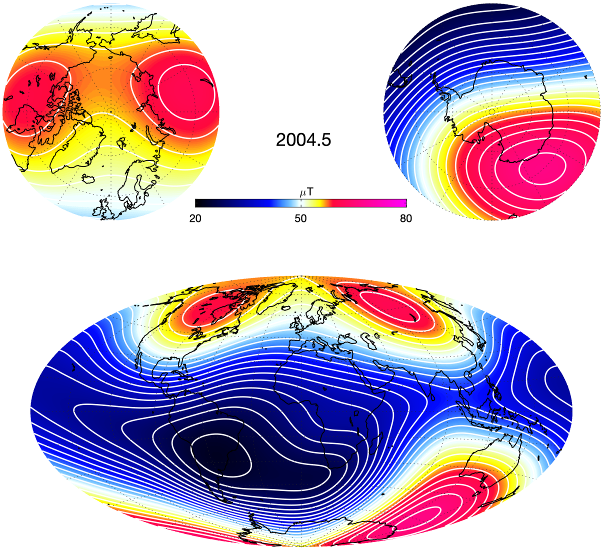

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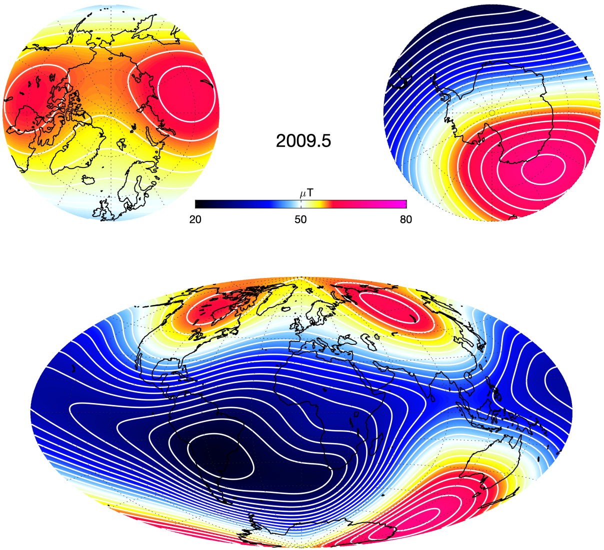

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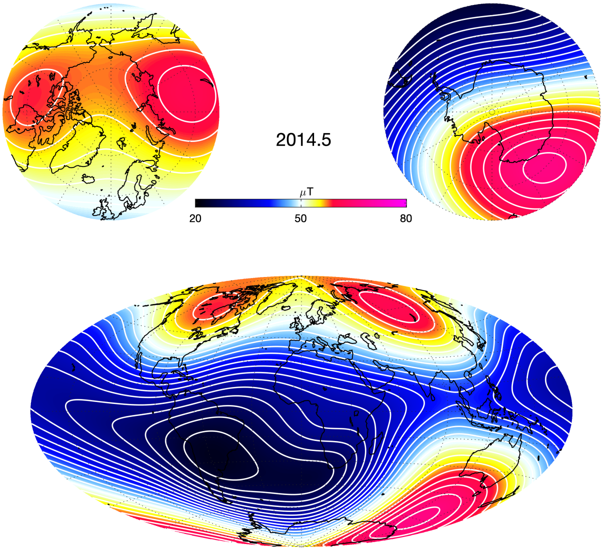

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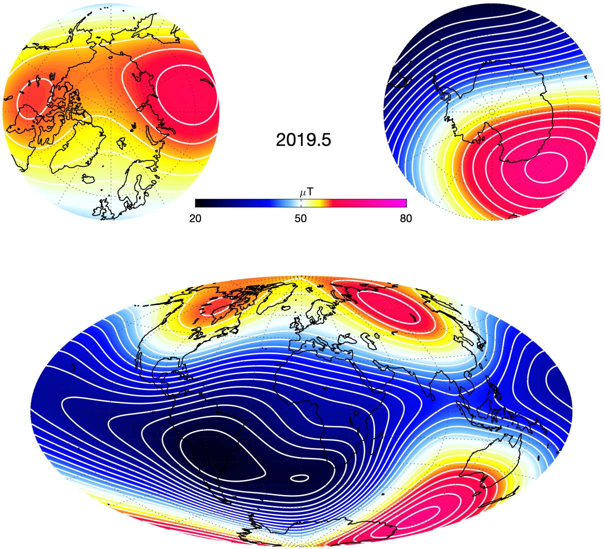

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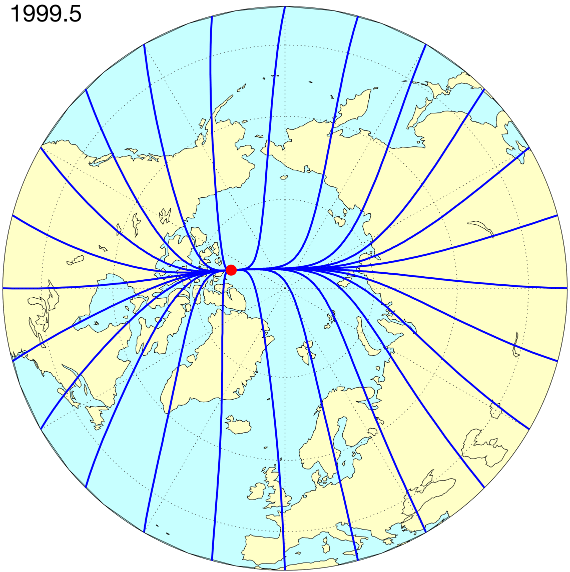
Surprisingly linear motion of the North Magnetic Pole



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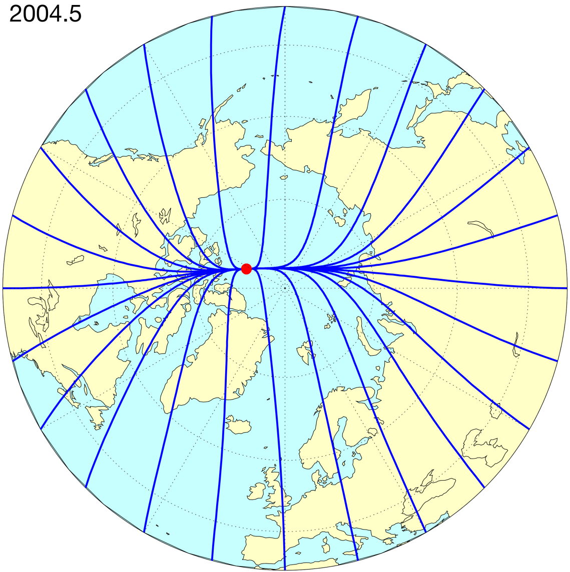

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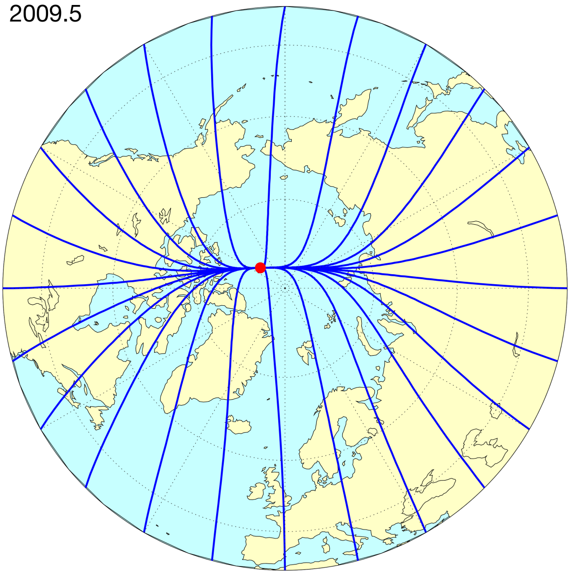

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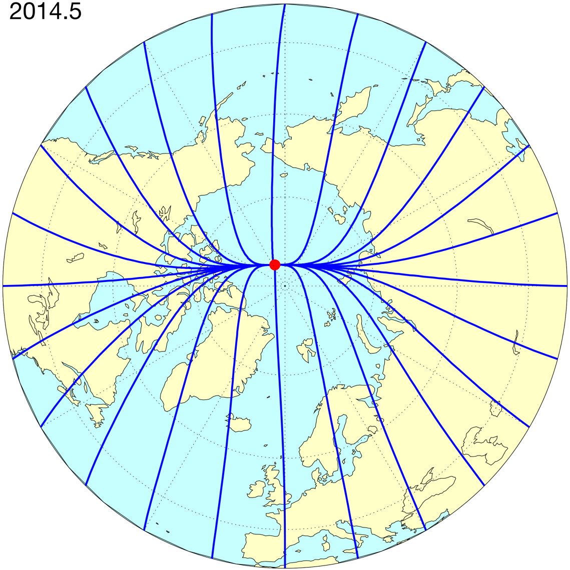

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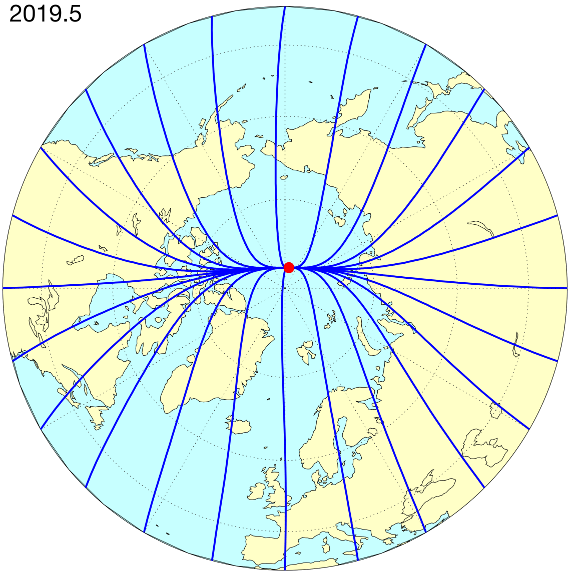

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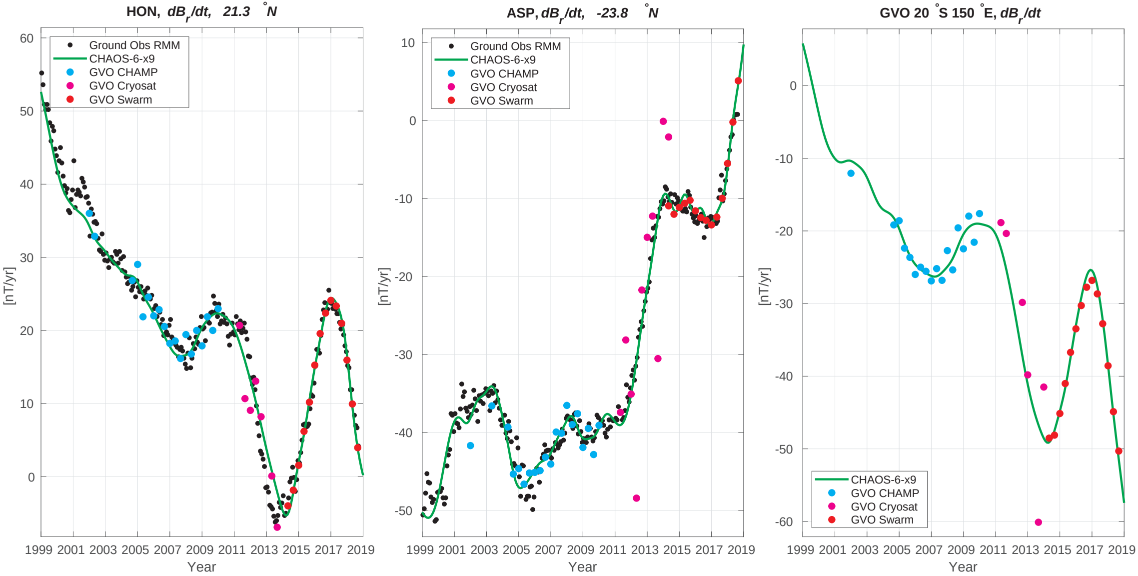
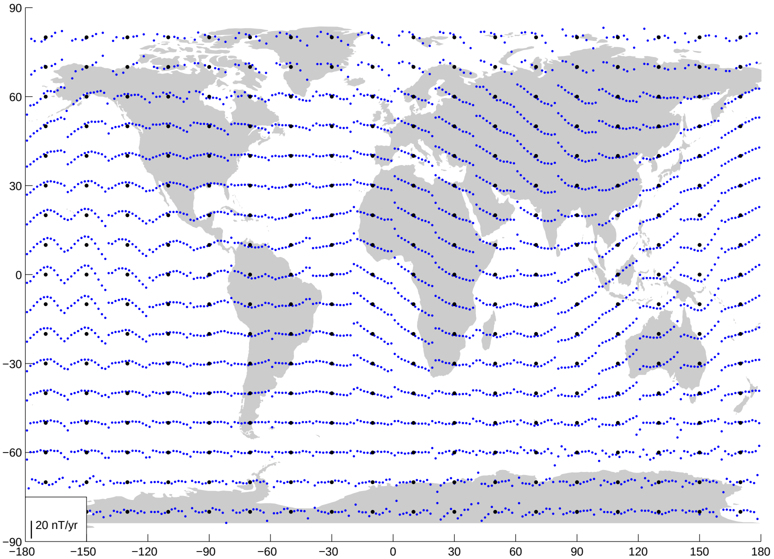
Time series of Secular Variation around the Pacific: ground and satellite data

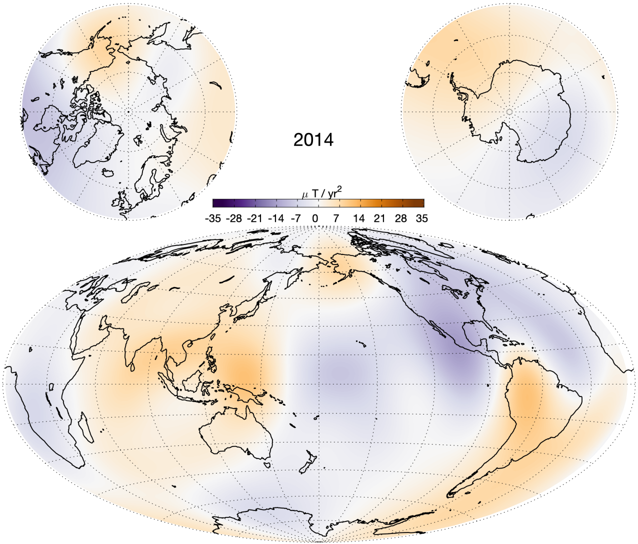


Secular Variation in a global grid of Geomagnetic Virtual Observatories



[GVOs: 4-monthly mean data derived from Swarm, DISC project starting June'19.]

Acceleration of radial field at Earth's surface



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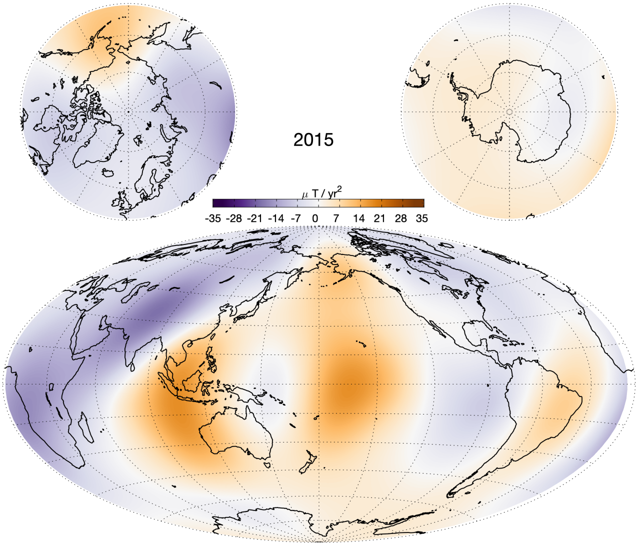

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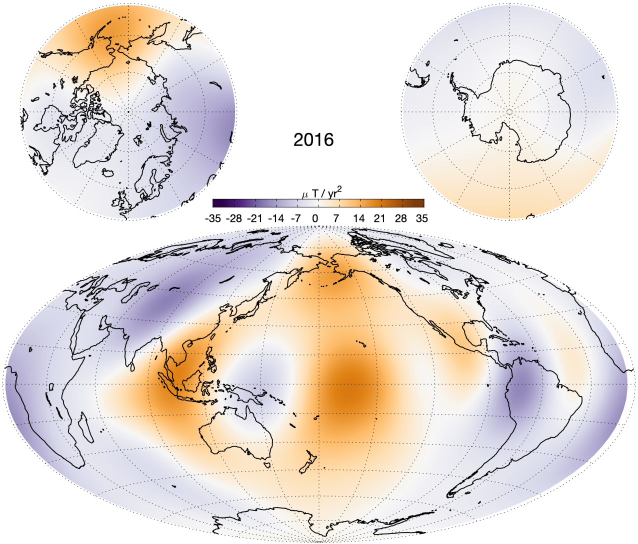

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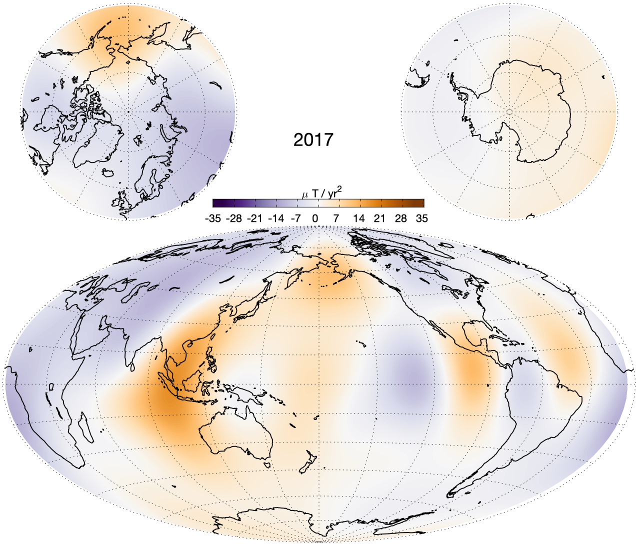

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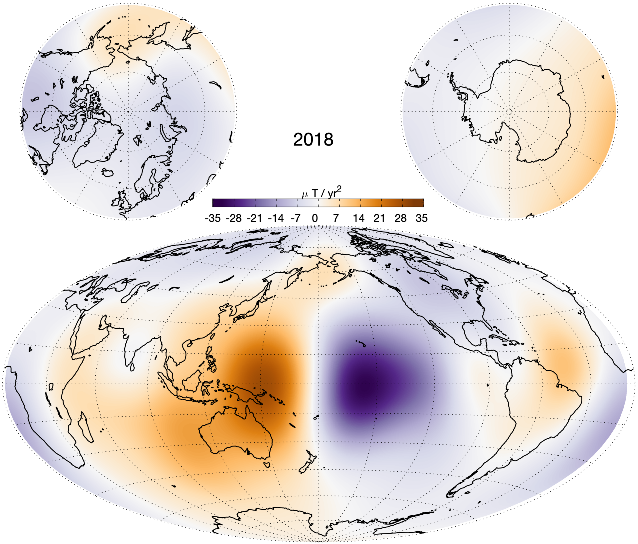

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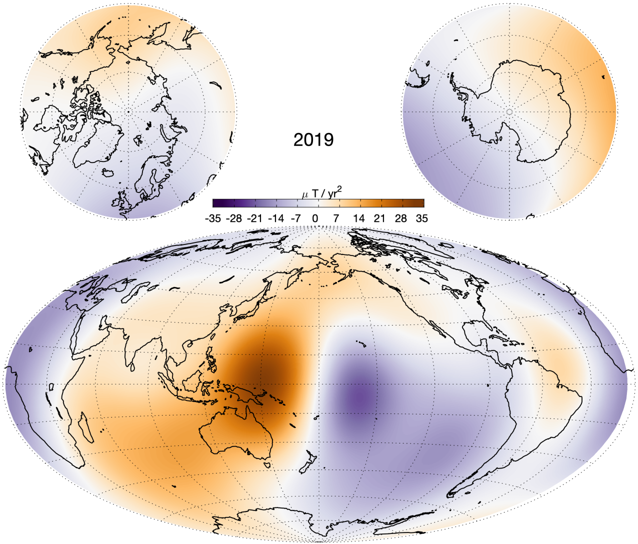

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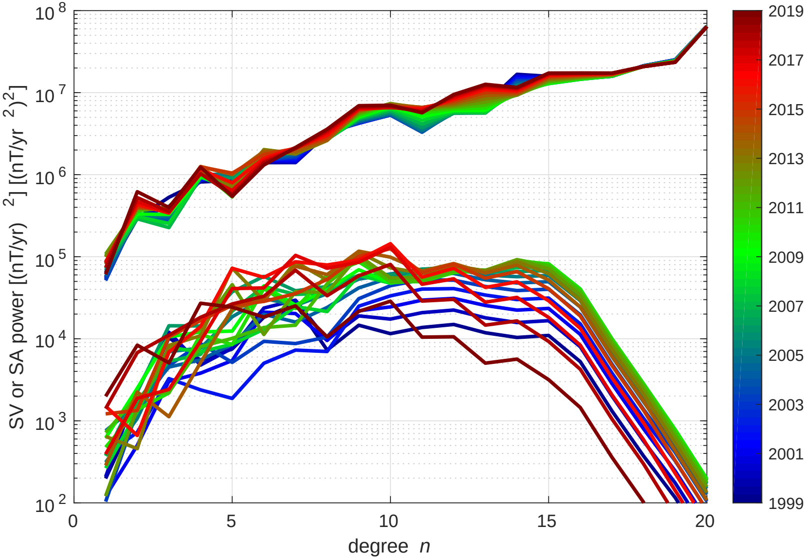
Spectra of SV and SA power at core surface



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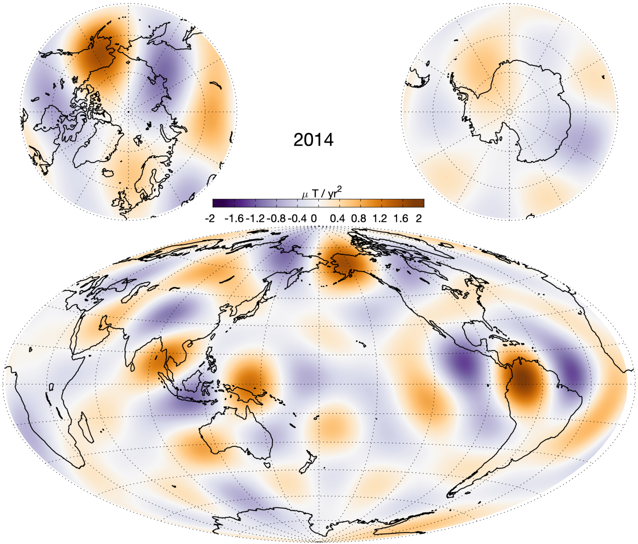

[Finlay et al., 2016 update, CHAOS-6-x9, to degree 9]

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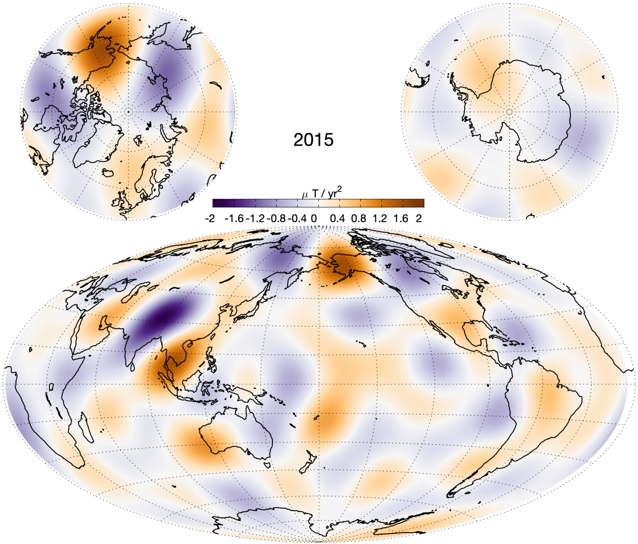

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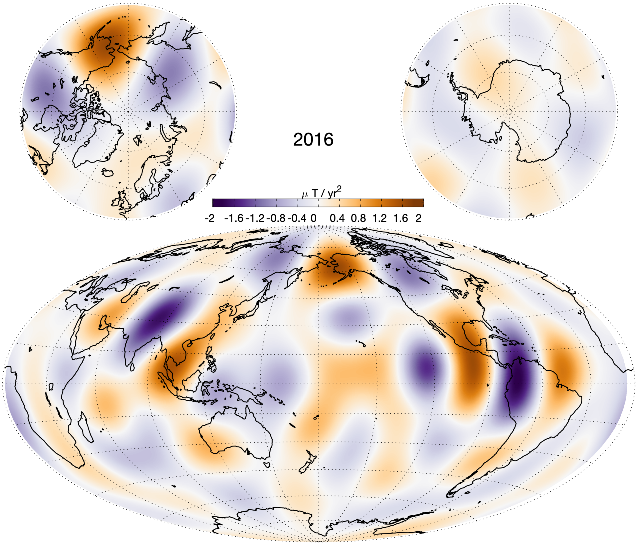

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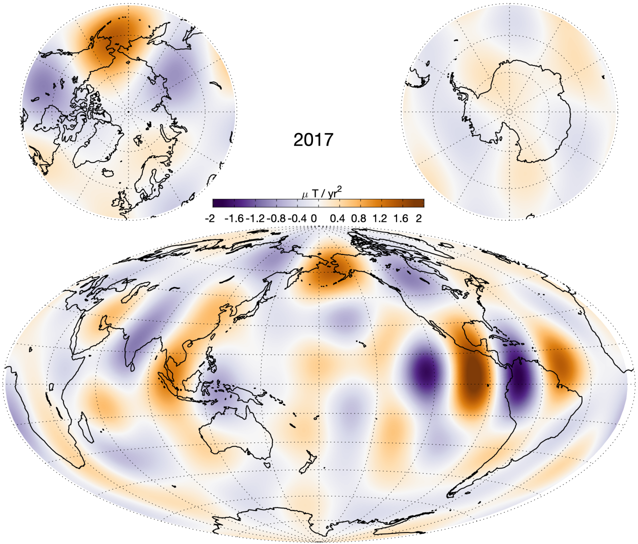

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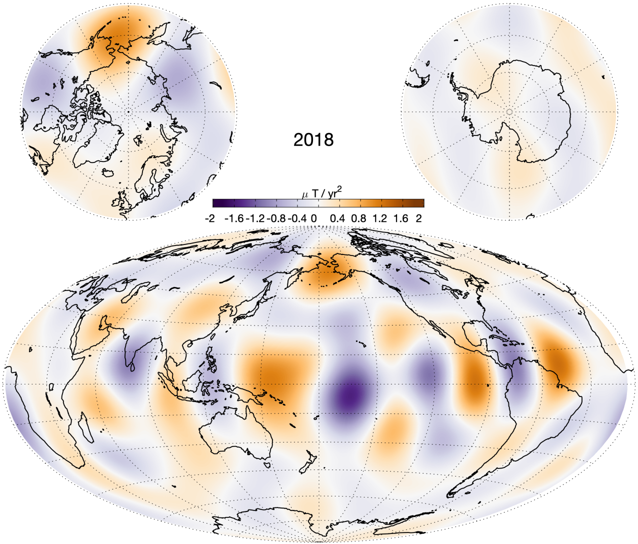

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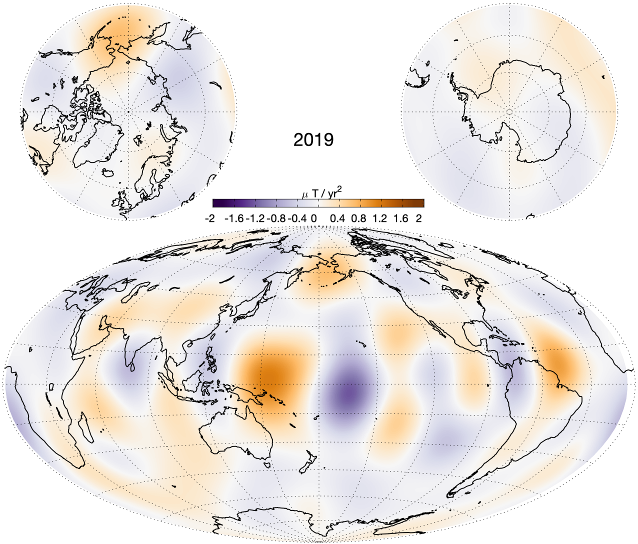

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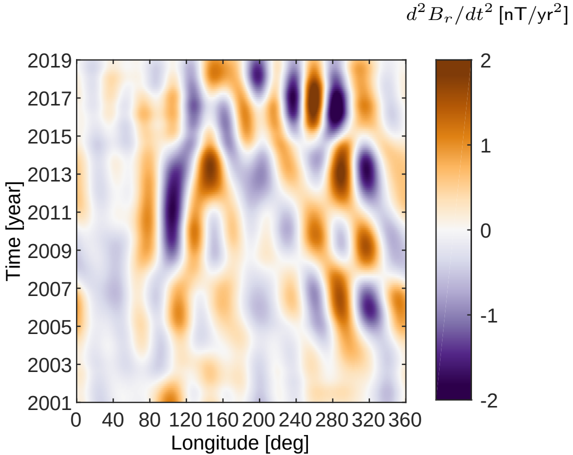
Evolution of SA at low latitudes, core surface



[CHAOS-6-x9, to degree 10]

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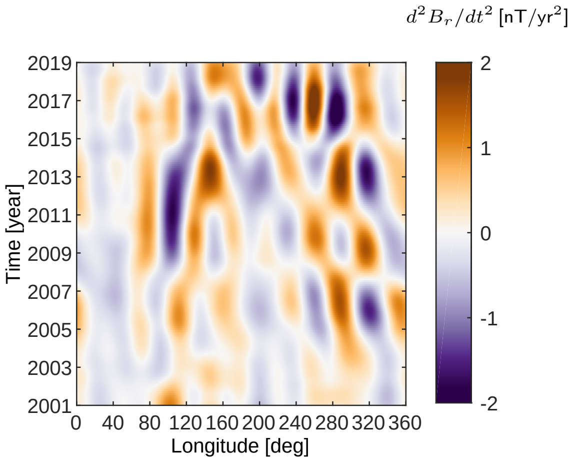

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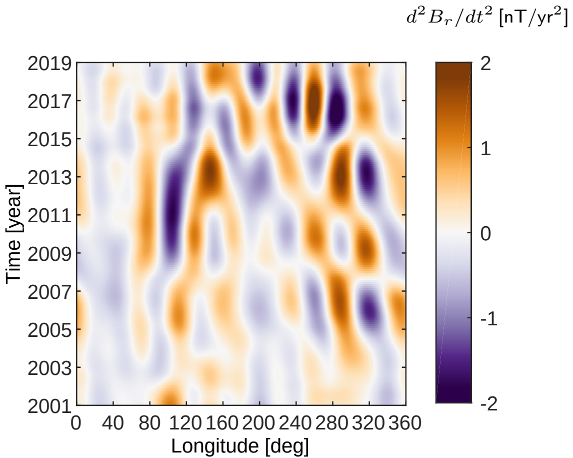

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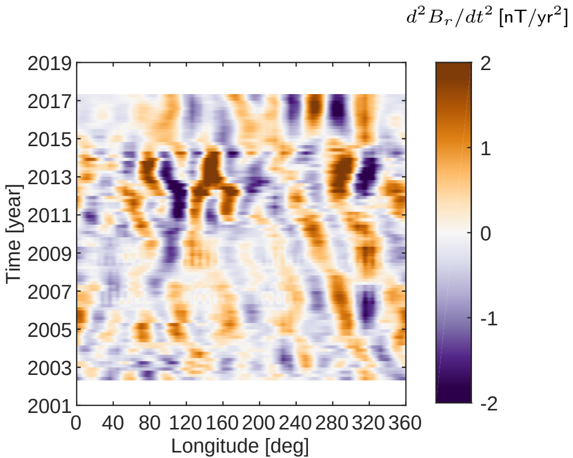

[SOLA, av. kernel width 42°, 2yr window]

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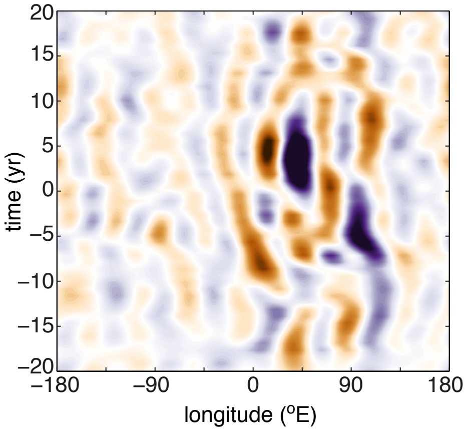

[Midpath dynamo model, to degree 9]

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- In numerical dynamo models, arrival of QG Álfven waves at the core surface produces intriguingly similar features *[Aubert and Finlay, 2019]*

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- Work ongoing to better isolate core signal and to uncover the responsible core dynamics
- Expanding opportunities to study geodynamo from satellite observations
  - Lengthening time series of global absolute observations provided by *Swarm*
  - Unexpected data from platform magnetometers e.g. Cryosat, DMSP, ...

CHAOS Field model: Parameterization

- **Potential field approach:** $\mathbf{B} = -\nabla V$ where $V = V^{\text{int}} + V^{\text{ext}}$.
- The internal part of the potential takes the form

$$V^{\text{int}} = a \sum_{n=1}^{N_{\text{int}}} \sum_{m=0}^{n} \left(g_n^m \cos m\phi + h_n^m \sin m\phi \right) \left(\frac{a}{r} \right)^{n+1} P_n^m (\cos\theta)$$

- For $n \leq 20$, expand in 6th order B-splines

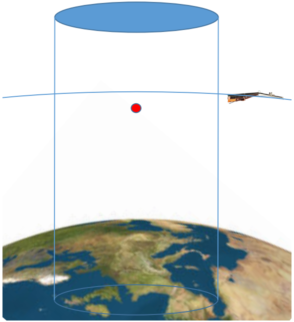
$$g_n^m(t) = \sum_{k=1}^{K} {}^k g_n^m B_k(t).$$

- Expand external potential in SM and GSM coordinates, with θ_d and T_d being dipole co-lat. and local time

$$\begin{aligned} V^{\text{ext}} &= a \sum_{n=1}^{2} \sum_{m=0}^{n} \left(q_n^m \cos mT_d + s_n^m \sin mT_d \right) \left(\frac{r}{a} \right)^{n} P_n^m (\cos\theta_d) \\ &+ a \sum_{n=1}^{2} q_n^{0,\text{GSM}} R_n^0(r,\theta,\phi). \end{aligned}$$

Virtual Observatories: point estimates at satellite altitude

- **Time series of monthly point estimates at satellite altitude**
  [Mandea and Olsen, 2006; Olsen and Mandea, 2007; Whaler and Beggan, 2015; Barrois et al., 2018]
- Take data within 700km of cylinder center, every 4 months
- Selection criteria: dark, quiet time data
  ($K_p < 3$, $|dRC/dt| < 3$nT/hr, IMF $B_z > 0$, $E_m < 0.8$ mV/m)
- Remove estimates of core, crustal, magnetospheric and S_q fields
- Work with sums and differences of data, along and across track

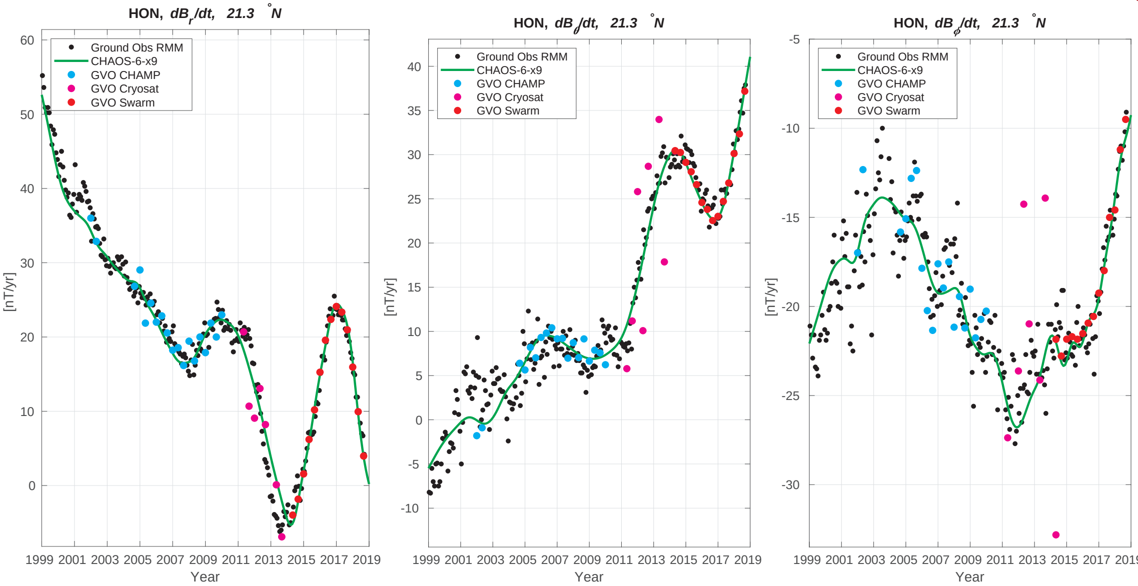


- Robust (Huber weighted) fit of **local cubic potential**

$$
\begin{aligned}
V(x,y,z) = {} & v_x x + v_y y + v_z z + v_{xx}x^2 + v_{yy}y^2 - (v_{xx}+v_{yy})z^2 \\
& +2v_{xy}xy + 2v_{xz}xz + 2v_{yz}yz - (v_{xyy}+v_{xzz})x^3 \\
& +3v_{xxy}x^2y + 3v_{xxz}x^2z + 3v_{xyy}xy^2 + 3v_{xzz}xz^2 + 6v_{xyz}xyz \\
& -(v_{xxy}-v_{yzz})y^3 + 3v_{yzz}y^2z + 3v_{yzz}yz^2 - (v_{xxz}+v_{yyz})z^3
\end{aligned}
$$

- Calculate prediction at chosen reference point using $\mathbf{B} = -\nabla V$

Secular variation as seen in ground and satellite data



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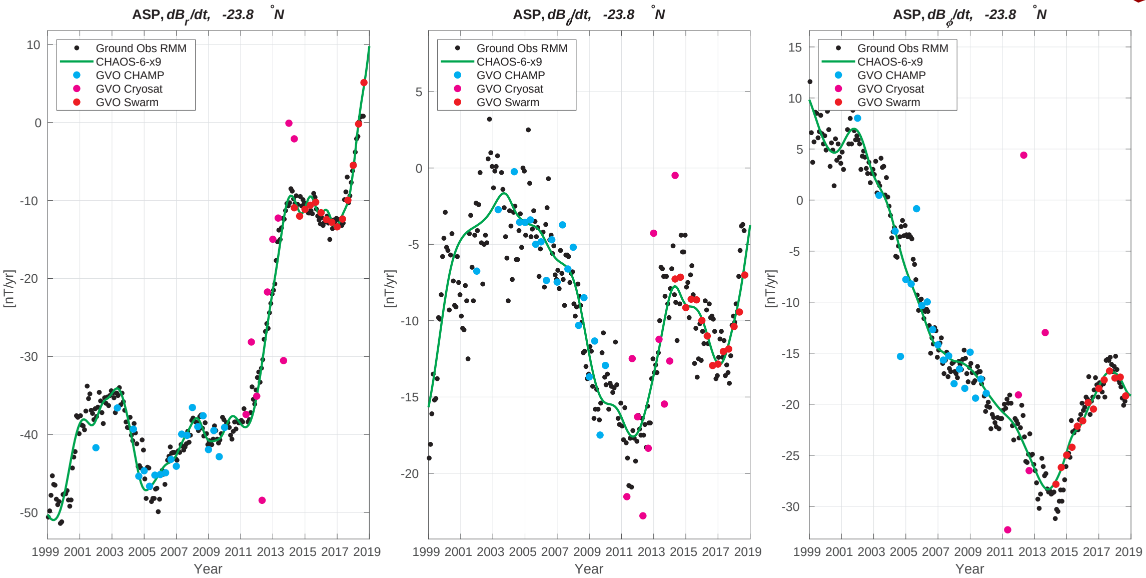

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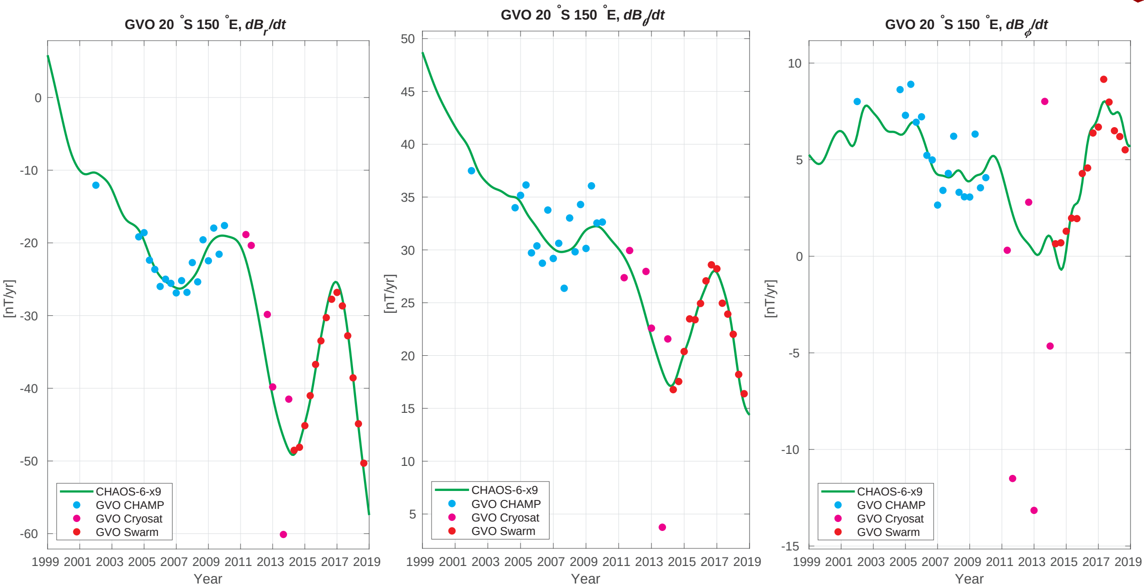
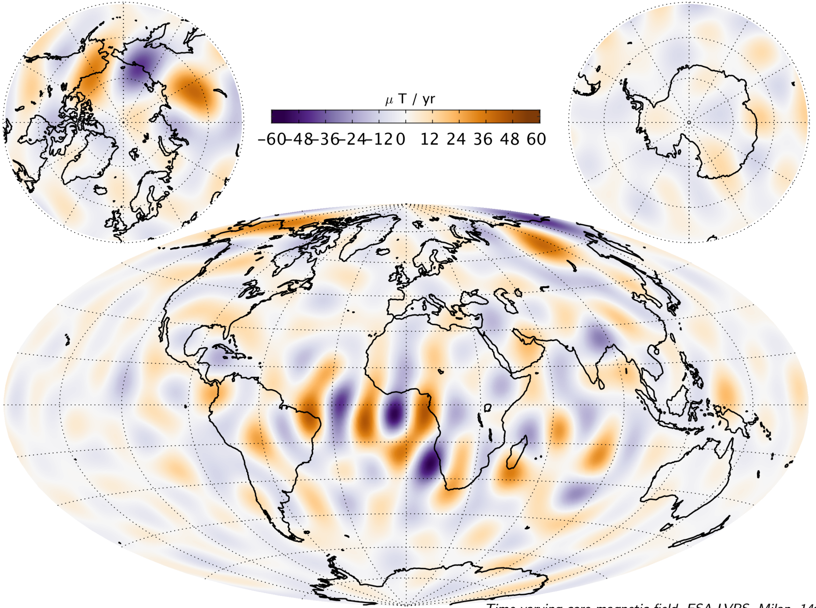
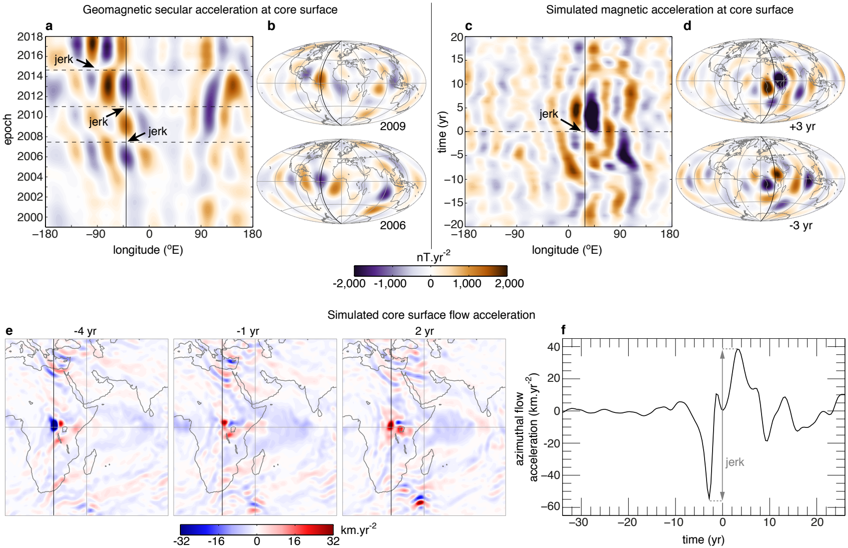


SV at the core surface, to degree 19





[Aubert and Finlay, 2019]