# An accelerating high latitude jet in the Earth's core

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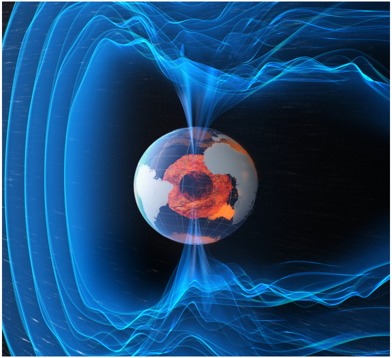
# Earth's magnetic field

- $> 98\%$ Earth's $\mathbf{B}$ field originates in the core
- Provides protection from the solar wind
- Generated by **dynamo action** in the core
- Not steady; continuously changing
  -> Secular Variation (SV)

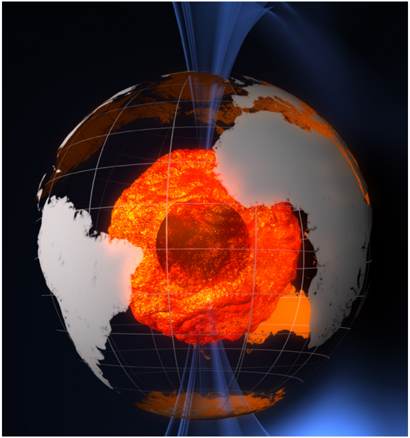


[Image credit: ESA]

## Outstanding scientific questions

- Structure of flows responsible for generating, and driving the evolution, of the field?
- Origin of core field changes on timescales of decades and less?

# The core

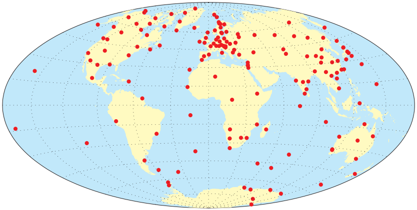


[Image credit: ESA]

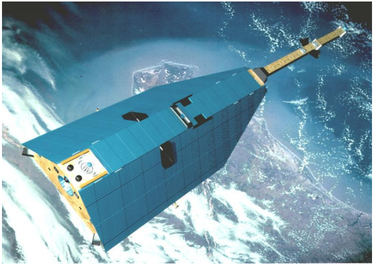
- The most inaccessible and least understood part of the Earth
- Extremely high temperatures (4000-6000K) and pressures (130-360 GPa)
- Iron alloy (mostly Fe plus Ni, and a little Si, O), density $10^4$ kg m$^{-3}$
- A turbulent place - vigorous motions are driven by cooling of the planet
- All obscured from view by 3000km of rocky mantle !

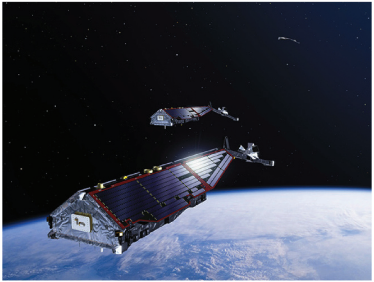
# Geomagnetic field observations

- **Ground observatories:**



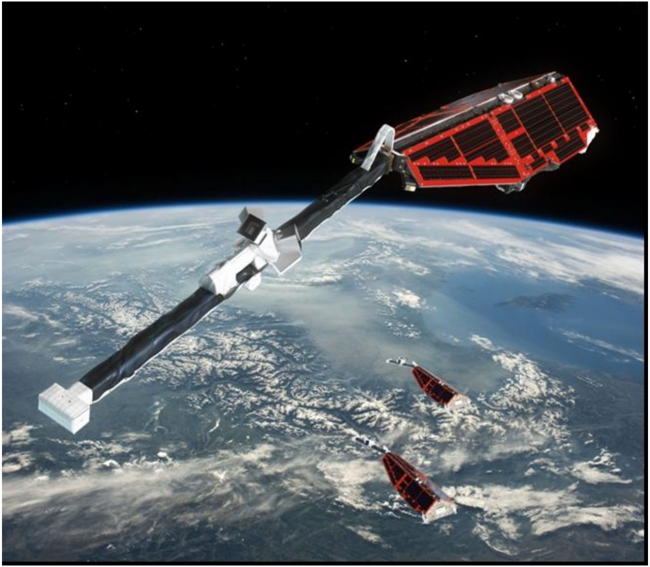
- **Low Earth Orbit Satellites: Ørsted, SAC-C, CHAMP and now *Swarm***



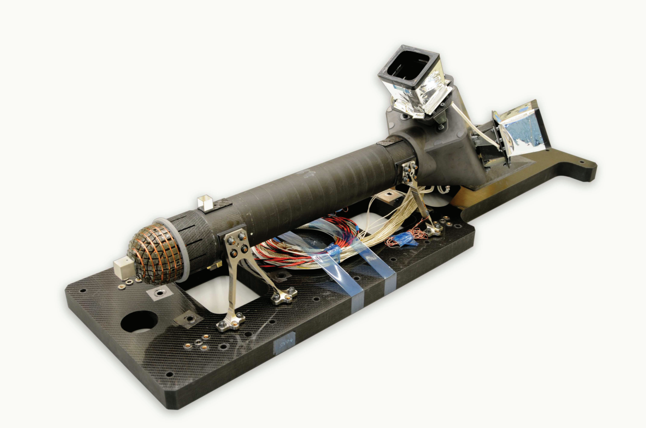


# The *Swarm* satellite constellation

- A pair of satellites (*Alpha*, *Charlie*), flying close together at lower altitude
- A third satellite (*Bravo*) slightly higher up

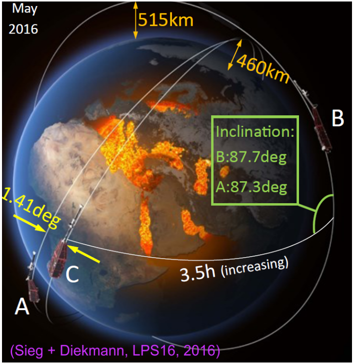


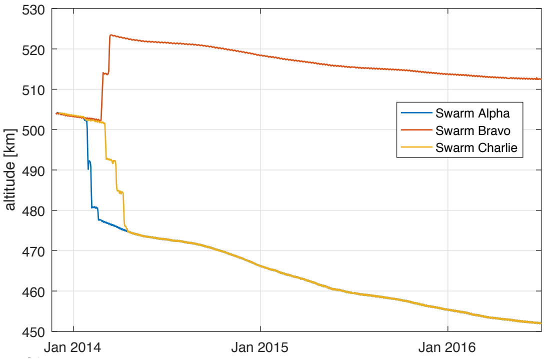
# Instruments from DTU Space



- Vector Field Magnetometers and star trackers from MI division are crucial to *Swarm*, as they were used on Ørsted and CHAMP.

# Current status of constellation



# Global geomagnetic field models

- CHAOS series of geomagnetic field models aims to describe the near-Earth magnetic field to high spatial and temporal resolution *(Olsen et al., 2006, 2009, 2010, 2014)*

- **Potential field approach:** $\mathbf{B} = -\nabla V$ where $V = V^{\text{int}} + V^{\text{ext}}$.

- The internal part of the potential takes the form

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

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

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

- Also co-estimate the large-scale magnetospheric field

- And work with satellite vector data in **magnetometer frame**, co-estimating Euler angles

# Model Estimation

- **DTU's latest geomagnetic model**, CHAOS-6 *(Finlay et al., 2016)*

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

- Derived from 7,873,156 data

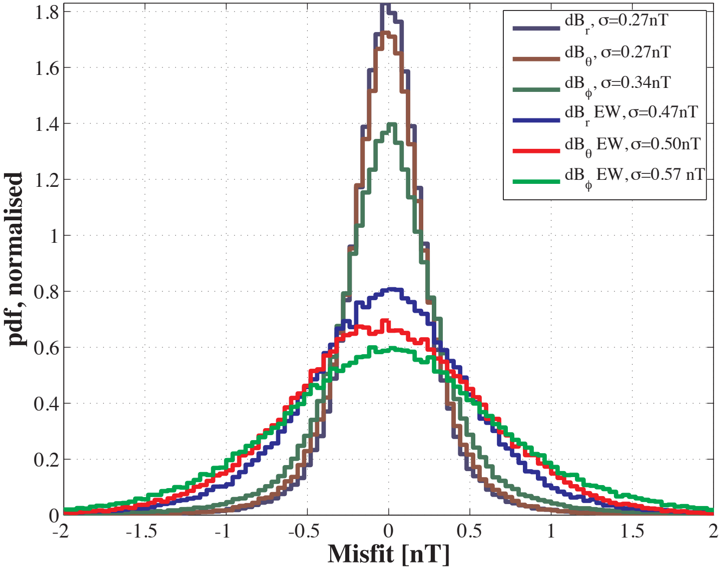
- **Robust non-linear least squares including regularization**, iteratively minimizing

$$[\mathbf{d} - F(\mathbf{m})]^T \underline{\underline{\mathbf{W}}}^{-1} [\mathbf{d} - F(\mathbf{m})] + \lambda_2 \mathbf{m}^T \underline{\underline{\mathbf{\Lambda}}}_2 \mathbf{m} + \lambda_3 \mathbf{m}^T \underline{\underline{\mathbf{\Lambda}}}_3 \mathbf{m}$$

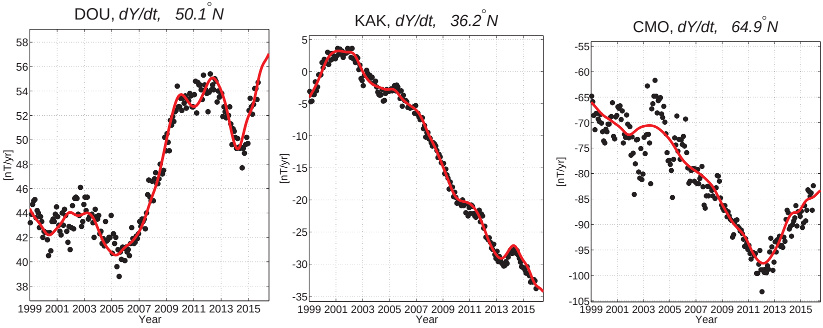
  $\underline{\underline{\mathbf{W}}}$ is a Huber weighting matrix, $\underline{\underline{\mathbf{\Lambda}}}_2$ and $\underline{\underline{\mathbf{\Lambda}}}_3$ are regularization matrices

- Weighted rms misfit to non-polar, dark *Swarm* scalar data is **2.14 nT**,
  For scalar field differences, **0.26 nT** along-track and **0.45 nT** across-track.

# Fit to Swarm field difference data: histograms of residuals

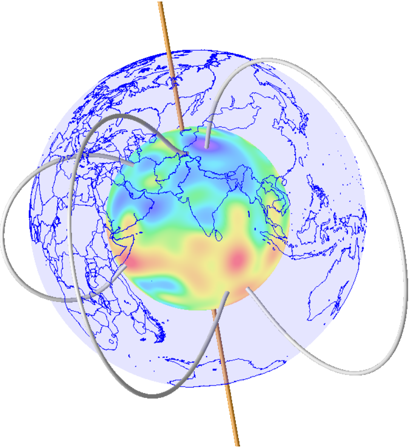


# Fit to ground observatory data, Eastward component $dY/dt$



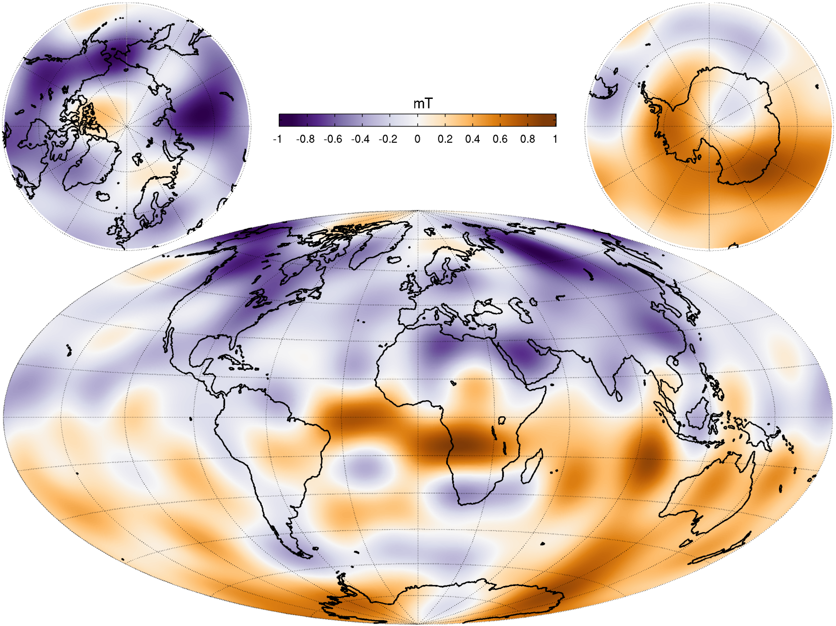
# Downward continuation to the core-mantle boundary

- Wish to understand origin of changes
  -> need to descend to core
- Possible to downward continue through mantle
  (Neglecting currents there on timescales $>$ 1 yr)
- Small scales amplified as approach source
- Field at core surface stable to degree 13
  (above this crust dominate)
- Field change (SV) stable to degree 18



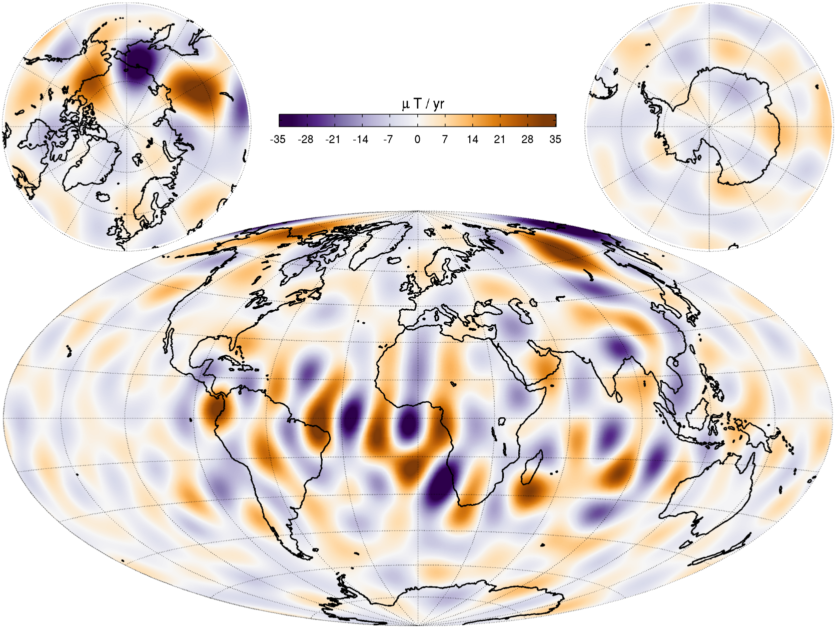
$$B_r = \sum_{n=1}^{N} \sum_{m=0}^{n} (n+1) \left( g_n^m \cos m\phi + h_n^m \sin m\phi \right) \left( \frac{a}{r} \right)^{n+2} P_n^m \left( \cos\theta \right)$$

# Radial field $B_r$ at core surface in 2015



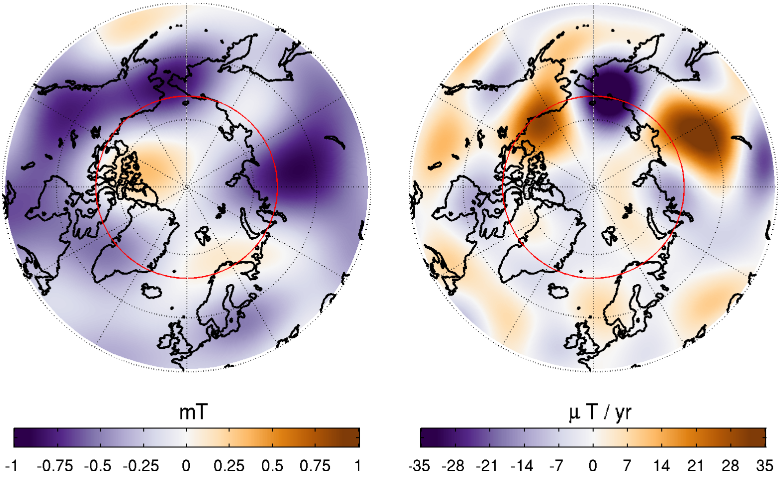

*[CHAOS-6]*

# Radial field SV $dB_r/dt$ at core surface in 2015

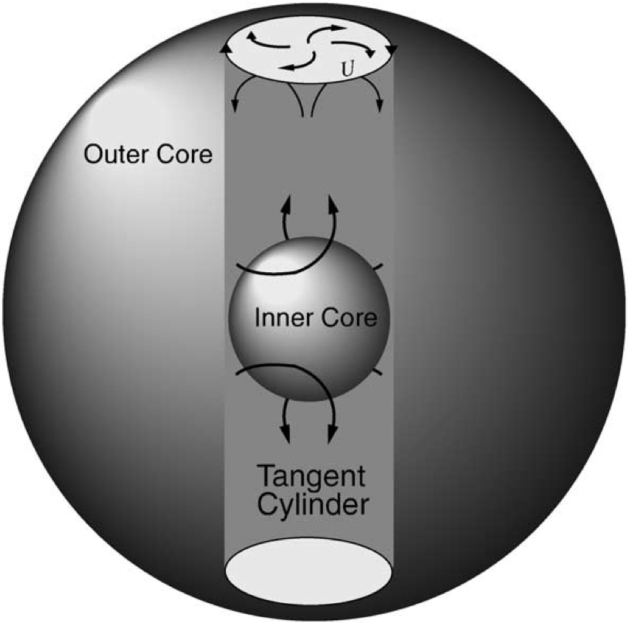



*[CHAOS-6]*

# Core surface $B_r$ and $dB_r/dt$ in Northern Polar Region, 2015



# The inner core tangent cylinder



# Inversion for responsible core motions

- For field changes on year to decade timescales, Maxwell's equations reduce to

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

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- We parameterize $\mathbf{u}$ in terms of a simple flow close to the tangent cylinder, defined by the stream-function $\Psi(s, \phi, z)$

$$u_s = \frac{1}{Hs}\frac{\partial \Psi}{\partial \phi}, \qquad u_\phi = -\frac{1}{H}\frac{\partial \Psi}{\partial s}, \qquad u_z = \frac{dH}{ds}\frac{z}{H^2 s}\frac{\partial \Psi}{\partial \phi} \quad H = \sqrt{1-s^2}$$

where

$$\Psi = \sum_{m=0}^{M} a_m\, e^{im\phi} \int_0^s \Phi_m(s')\sqrt{1-s'^2}\, ds', \qquad \Phi_m(s) = \left[\sqrt{1-s^2}\, e^{-\beta^2} - c_m\right] s^{m+1}$$

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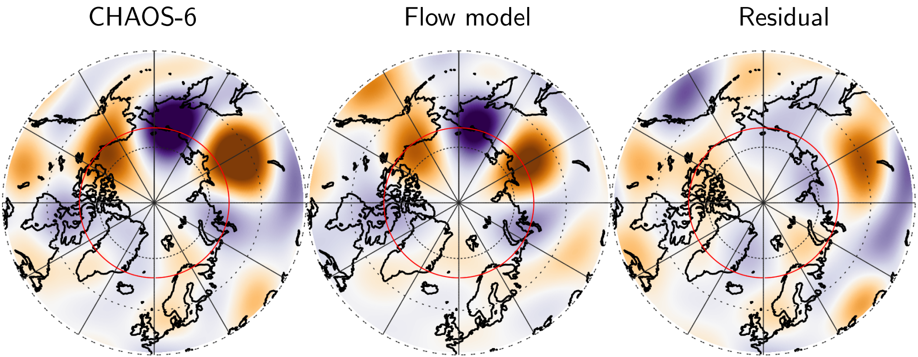
- And seek the flow parameters $a_m$, $c_m$, $\beta$ that minimize the residual measure

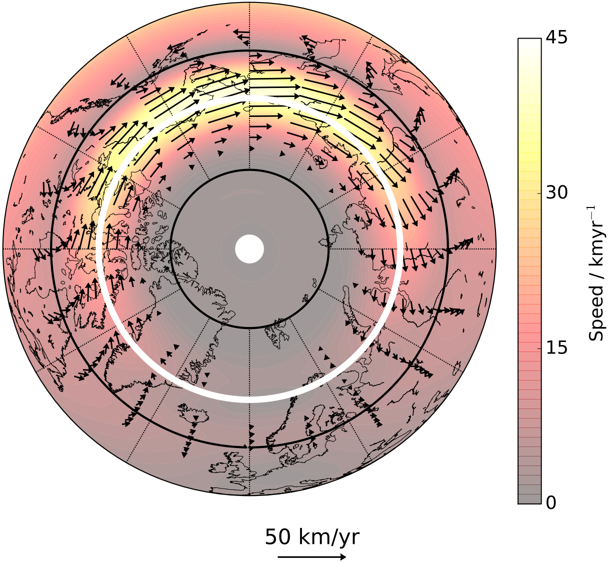
$$\mathcal{R}_{\mathcal{N}+\mathcal{S}} = \int_0^{360} \int_{10^\circ}^{30^\circ} (SV_{obs} - SV_{syn})^2 \sin\theta d\theta d\phi + \int_0^{360} \int_{150^\circ}^{170^\circ} (SV_{obs} - SV_{syn})^2 \sin\theta d\theta d\phi$$

# Fit to observed field change



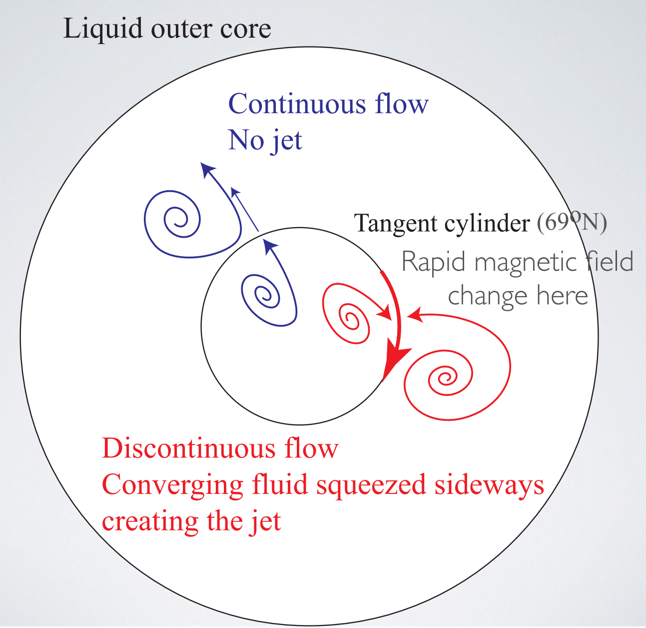

[Livermore et al. (2017)]

# A localized jet at the tangent cylinder

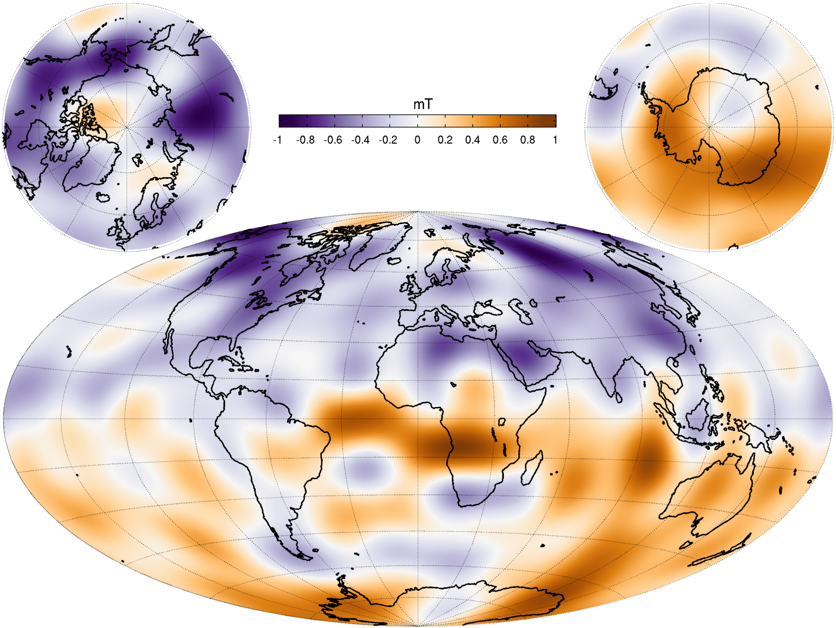



*[Livermore et al. (2017)]*

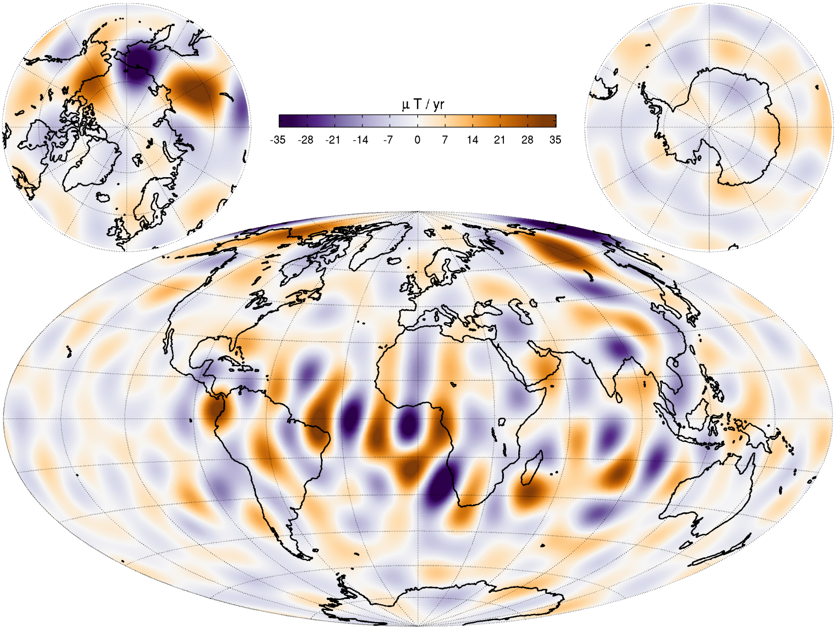
# Physical origin of the tangent cylinder jet



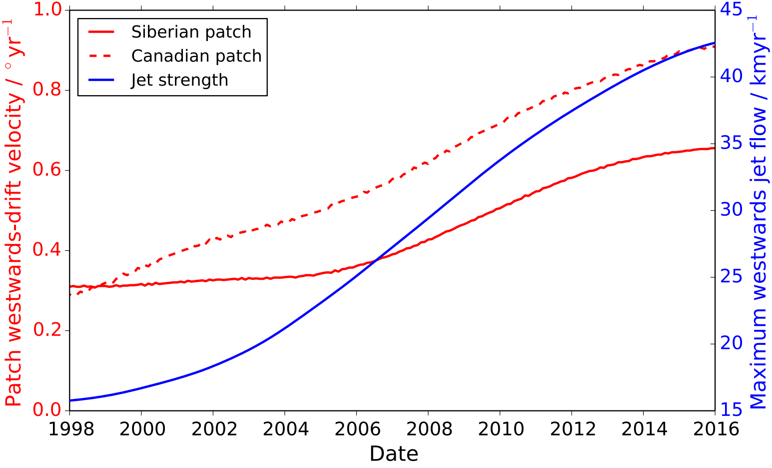
# Time-dependence of core surface field



# Time-dependence of core surface SV



# Acceleration of the tangent cylinder jet

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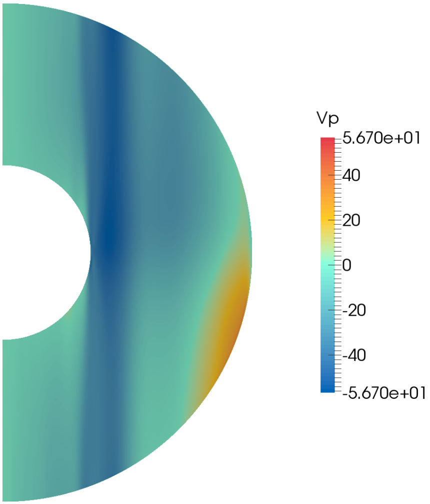
# Possible implications for the dynamo process

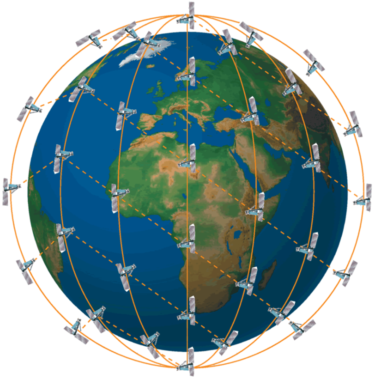



- Shear at tangent cylinder is important for dynamos in rapidly-rotating regime
- Fundamental for building toroidal field within core
- May play a role in dynamo oscillations and reversals

# Some open questions

- How deep does this jet extend into core?
- Why has it recently been accelerating?
- How will it develop in the upcoming years?

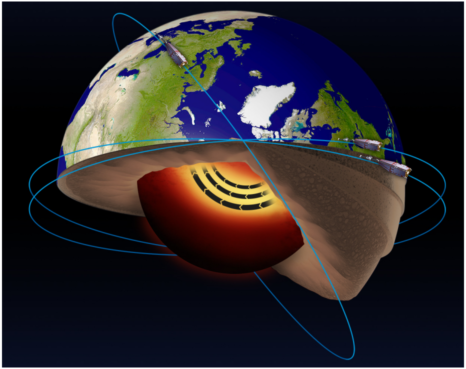
# A look to the future



- **Dream:** Accurate forecasting of geomagnetic field changes decades ahead
- Will require sufficient understanding of core dynamics and dynamo process
- **And** long-term monitoring from space at multiple local times (for assimilation)
- Perhaps with many small, mini/nanosatellites, simultaneously measuring field?

# Conclusions

(1) *Swarm* data show intense field change is occuring under Canada and Siberia



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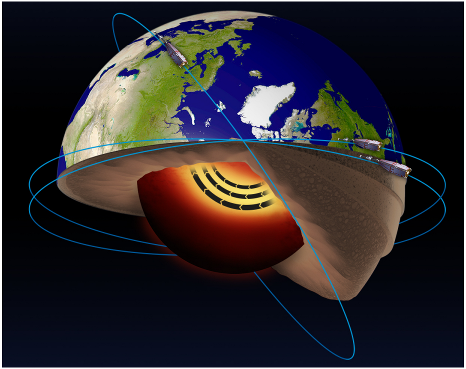

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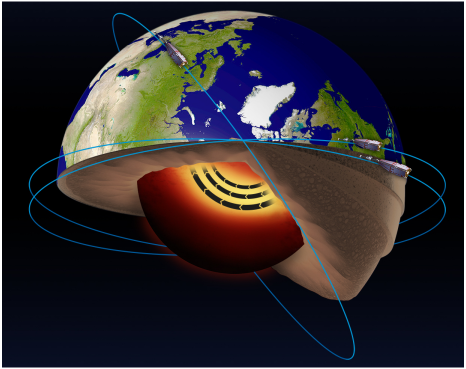
(3) Jet velocity is ∼40 km/yr, three times higher than average flow in the core



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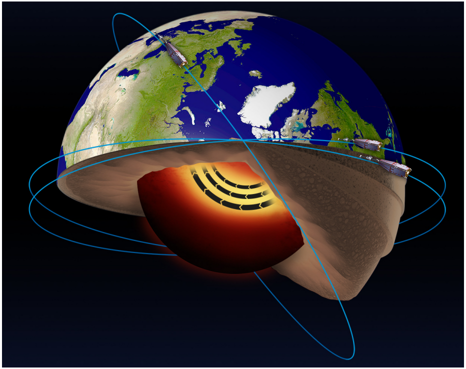
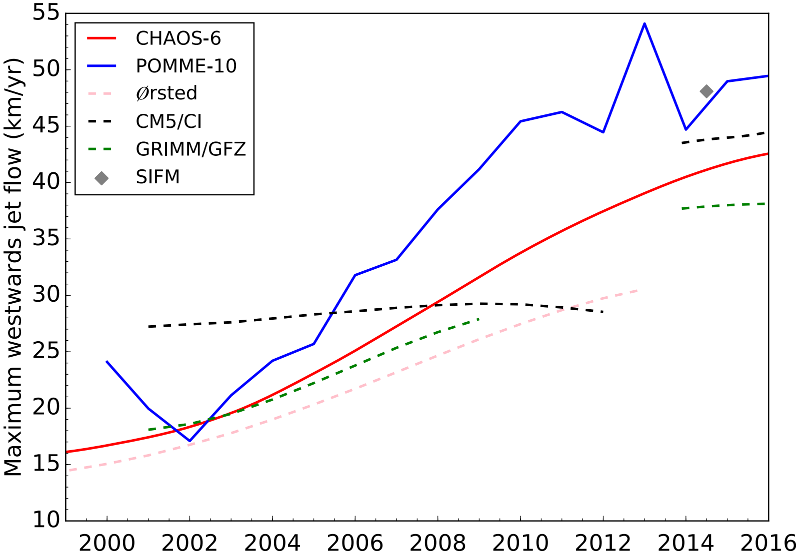
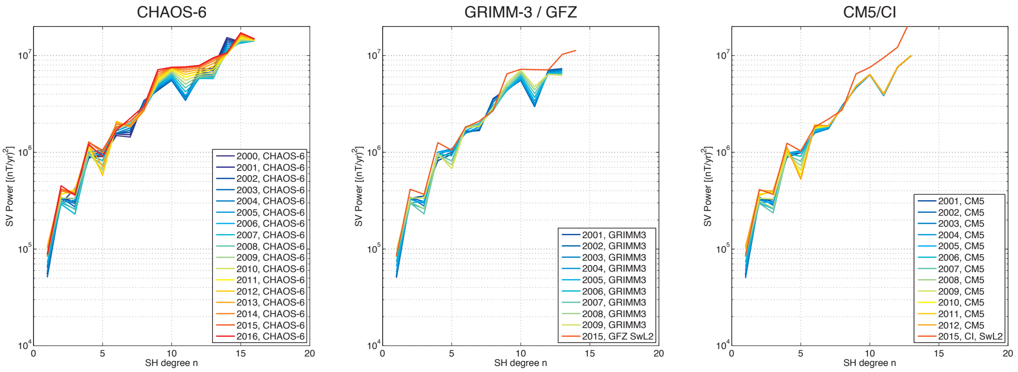
(4) May be an important ingredient in the geodynamo and its fluctuations



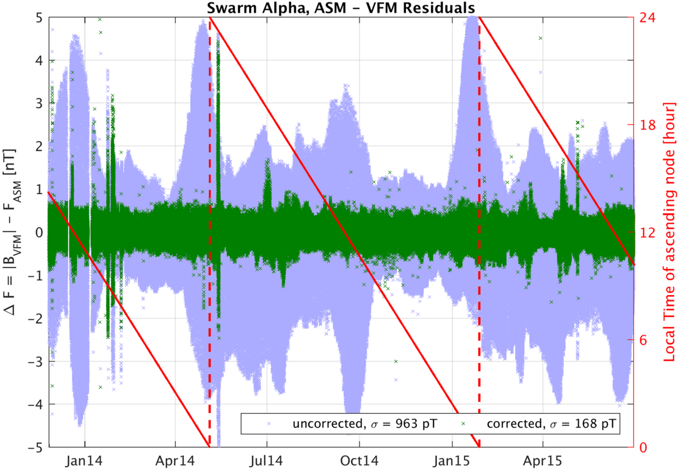
# Jet acceleration as seen by other field models



# SV Spectra from CHAOS-6, GRIMM, CM5/CI



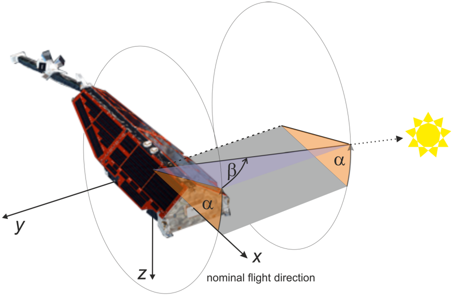
# In-flight calibration and characterization

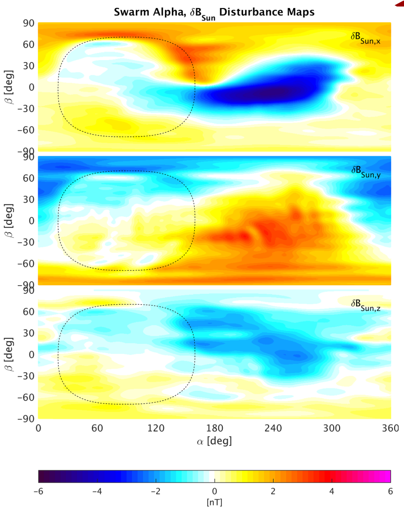



*[Tøffner-Clausen et al., (2016)]*

- Small, but unexpected, differences between ASM and VFM scalar intensities
- Due to a sun-driven disturbance, that varies with the solar incident angles
- Can be modelled and RMS residuals reduced e.g. to 0.168 nT for *Swarm Alpha*
- Important to find the root cause, investigations into this are ongoing

# In-flight calibration and characterization




*[Tøffner-Clausen et al., (2016)]*

- Are now able to model the Sun-driven disturbance
- For example, RMS residuals reduced from 0.96nT to 0.168 nT for *Swarm Alpha*
- Important to find the root cause, investigations are ongoing

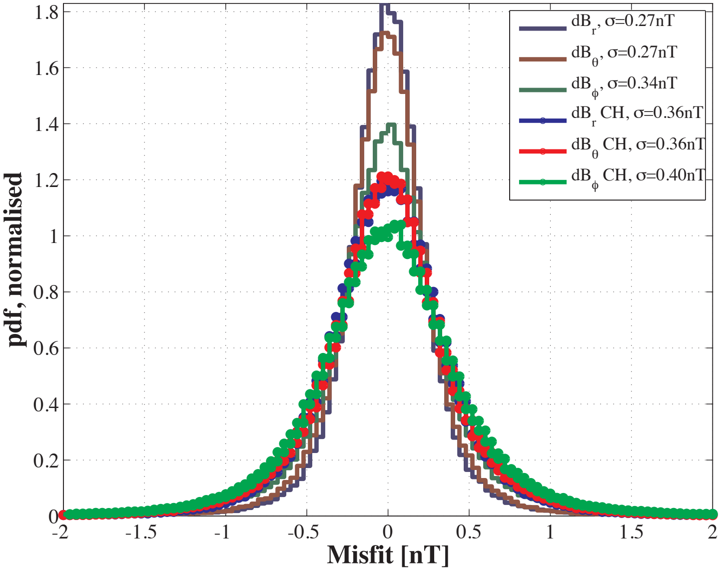
# CHAOS-6 model: Parameterization of the external Field

- For the external potential, expand in SM and GSM co-ordinate systems, with $\theta_d$ and $T_d$ being dipole co-lat. and dipole local time

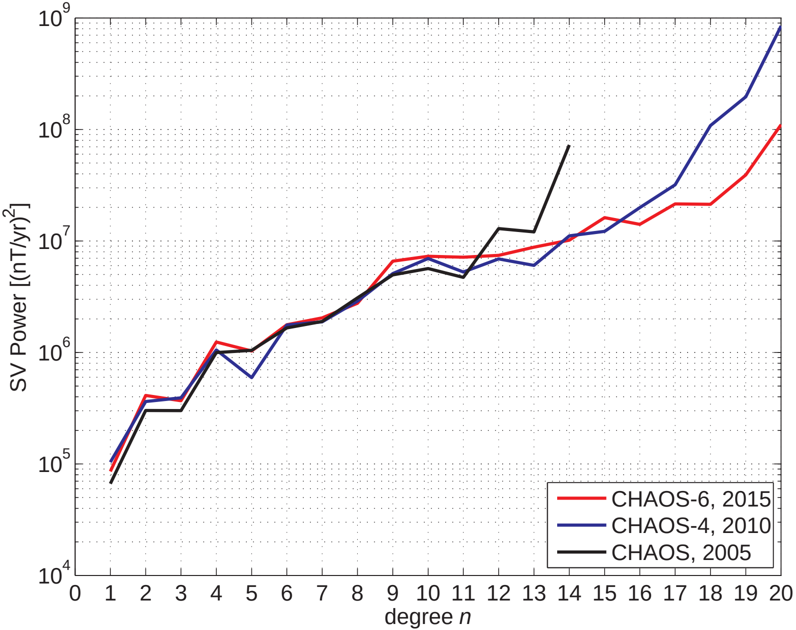
$$\begin{aligned} V^{\text{ext}} &= a \sum_{n=1}^{2} \sum_{m=0}^{n} \left( q_n^m \cos mT_d + s_n^m \sin mT_d \right) \left( \frac{r}{a} \right)^n P_n^m(\cos\theta_d) \\ &+ a \sum_{n=1}^{2} q_n^{0,\text{GSM}} R_n^0(r,\theta,\phi). \end{aligned}$$

- Degree-1 coefficients in *SM* coords dependent on the RC disturbance index

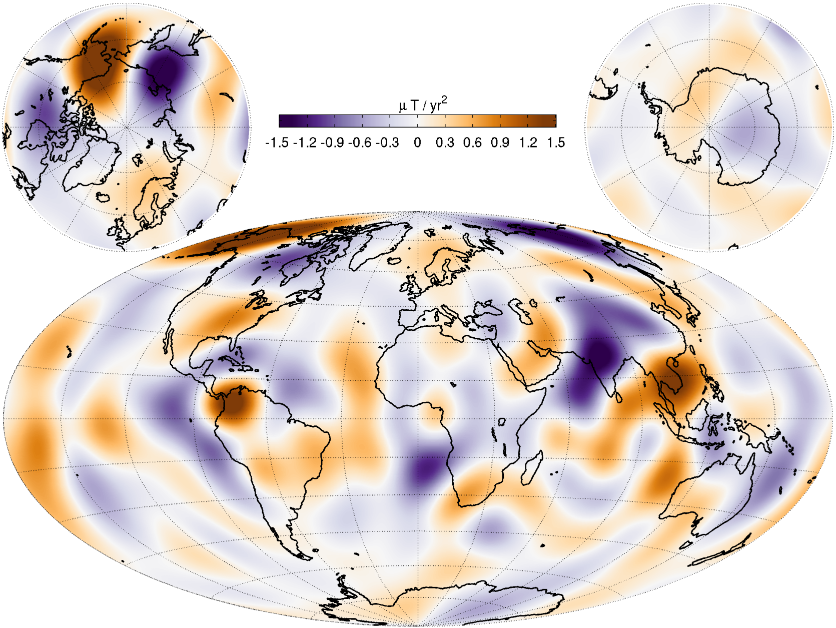
# Vector difference residuals, Swarm vs CHAMP



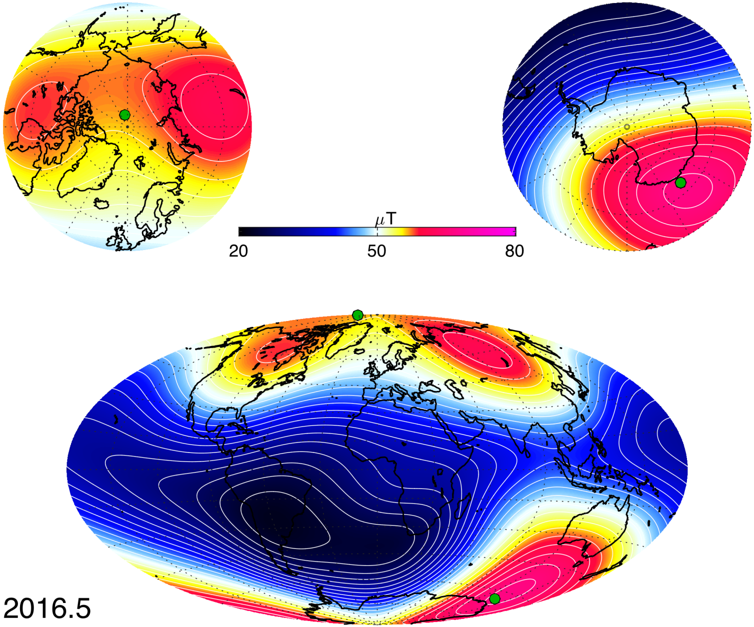
# Power spectrum of SV at core surface



# Time-dependence of core surface SA



# Field strength and magnetic pole position in 2016.5



# Field strength and magnetic pole position in 1999