# Gyre-driven decay of the Earth's magnetic dipole


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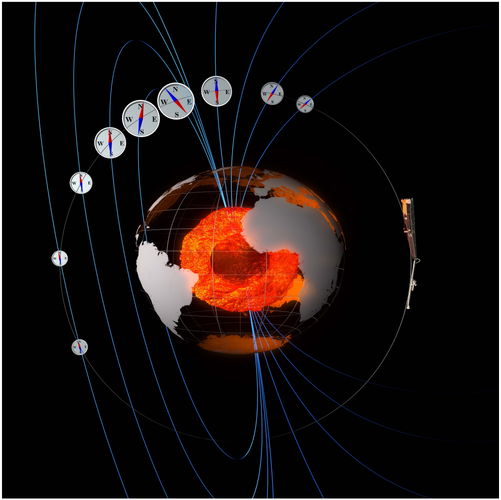
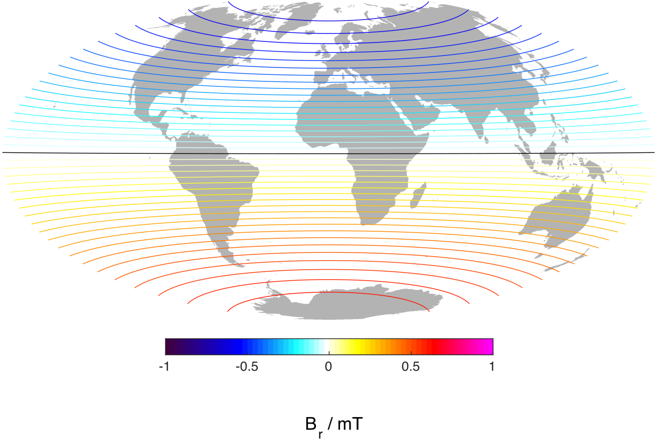
DTU Space
National Space Institute

# Earth's magnetic field: Predominantly an axial dipole



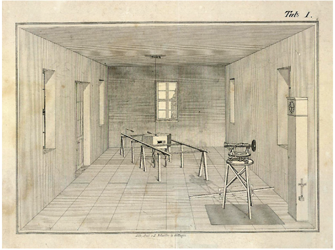
Credit:ESA

# Axial dipole field

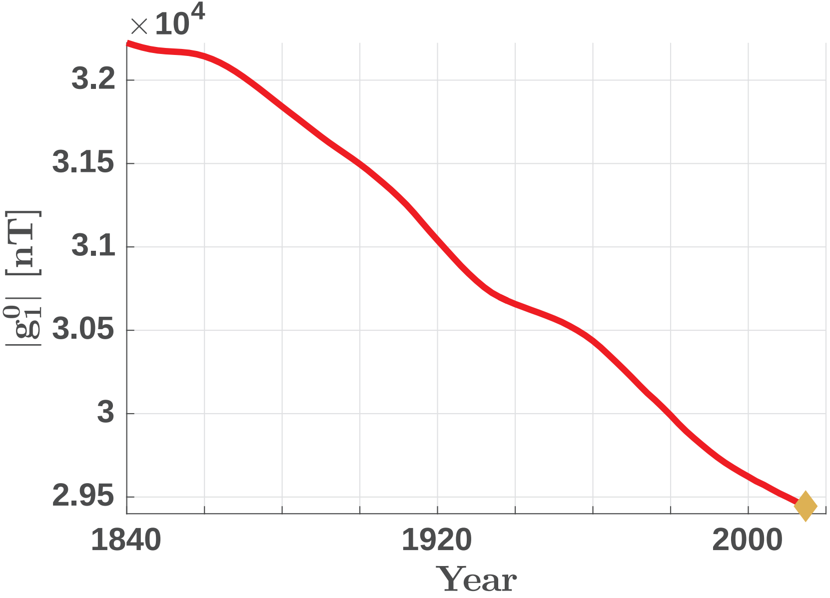



- Axial dipole $g_1^0$ is the first term in the spherical harmonic expansion of $\mathbf{B}$.
- Dipole represents 99.9% of field energy at 10 $R_e$.
- Dipole represents 93% of field energy at Earth's surface, 1 $R_e$.
- Dipole represents 37% of field energy at the core surface, 0.55 $R_e$

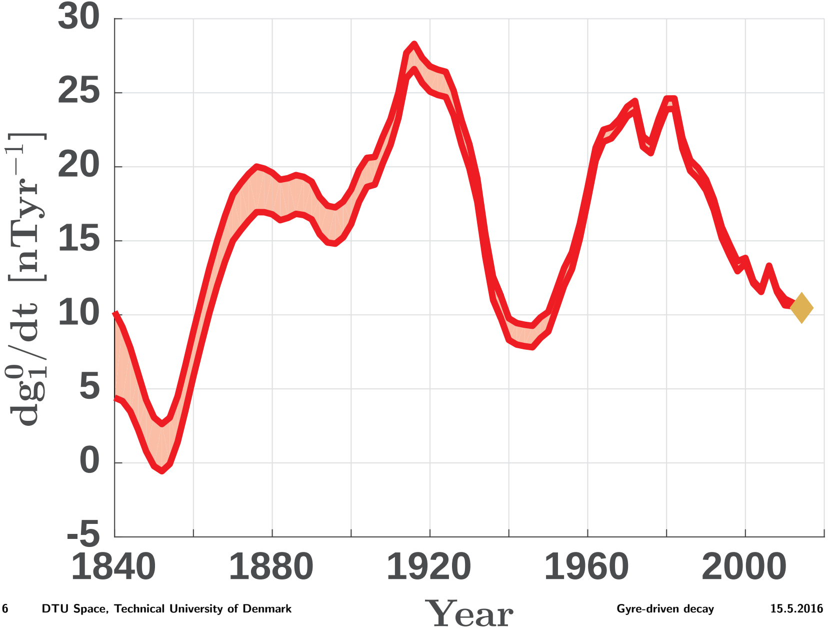
# 175 years of absolute observations




# Dipole magnitude has decayed ∼10% since 1840



# Dipole decay rate fluctuations on decadal time scales



# Origin of the decay: MHD processes in the core

The rate of change of the dipole moment is

$$\frac{d\mathbf{m}}{dt} = \frac{1}{2}\int \widehat{\mathbf{r}} \times \frac{\partial \mathbf{J}}{\partial t}\, dV = \frac{3}{2\mu_0}\int \frac{\partial \mathbf{B}}{\partial t}\, dV. \tag{1}$$

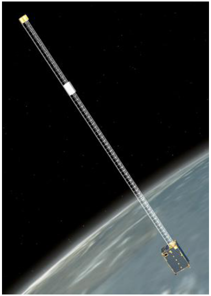
Substituting from the magnetic induction equation

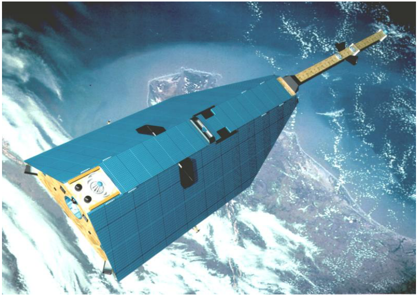
$$\frac{d\mathbf{m}}{dt} = \frac{3}{2\mu_0}\int [\nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}]\, dV. \tag{2}$$

Taking the axial component, expanding and integrating by parts, find that the axial dipole moment (ADM) change can be written as

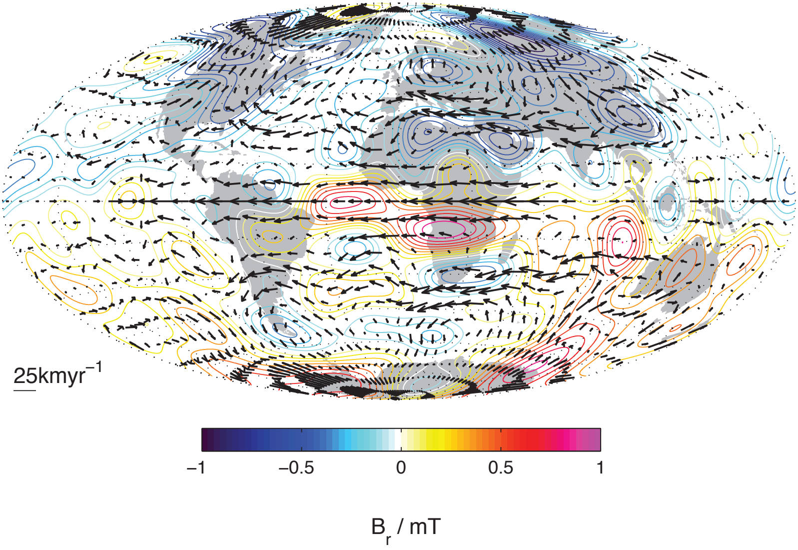
$$\frac{dm_z}{dt} = \underbrace{-\frac{3}{2\mu_0}\int u_\theta \sin\theta B_r\, dS}_{\text{ADM change due to meridional advection}} + \underbrace{\frac{3\eta}{2\mu_0}\int \widehat{\mathbf{z}} \cdot \nabla^2 \mathbf{B}}_{\text{ADM change due to Ohmic diffusion}}\, dV. \tag{3}$$

# Satellite vector field observations 1999-2010

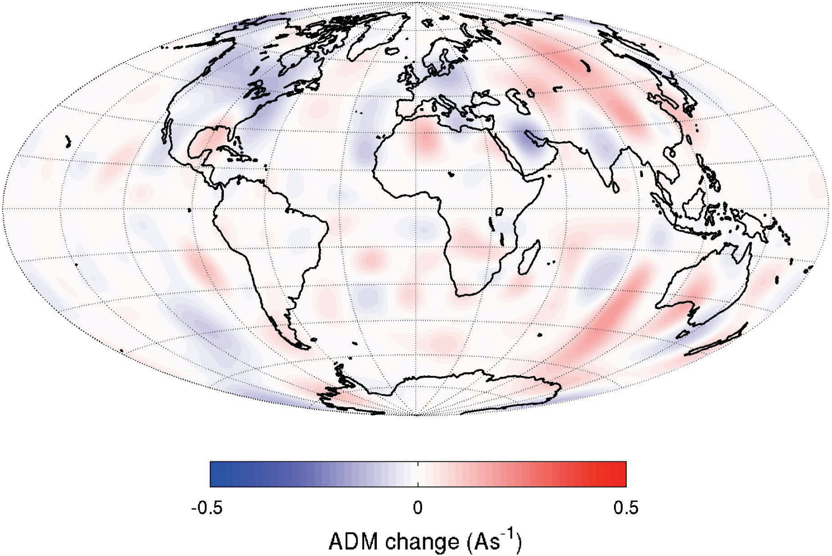




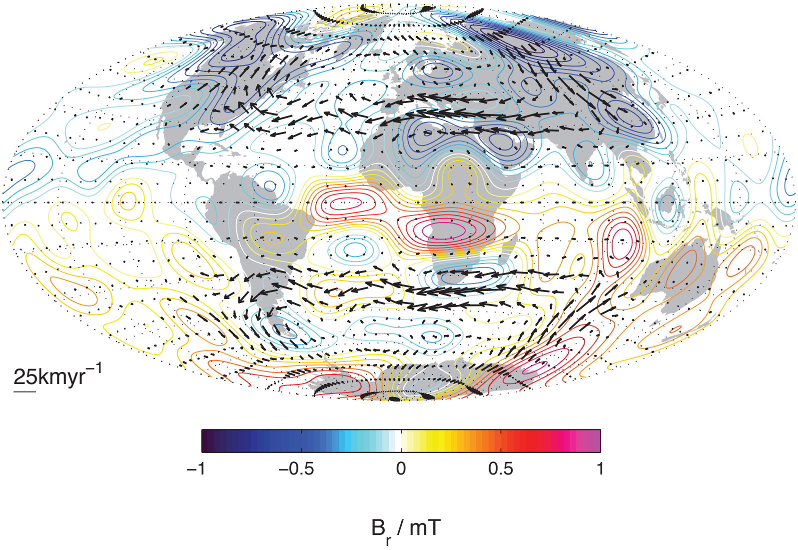
# Core surface field and flow: 2000-2010



# Contributions from meridional flux transport decay



# Simplified model: Observed field plus filtered gyre



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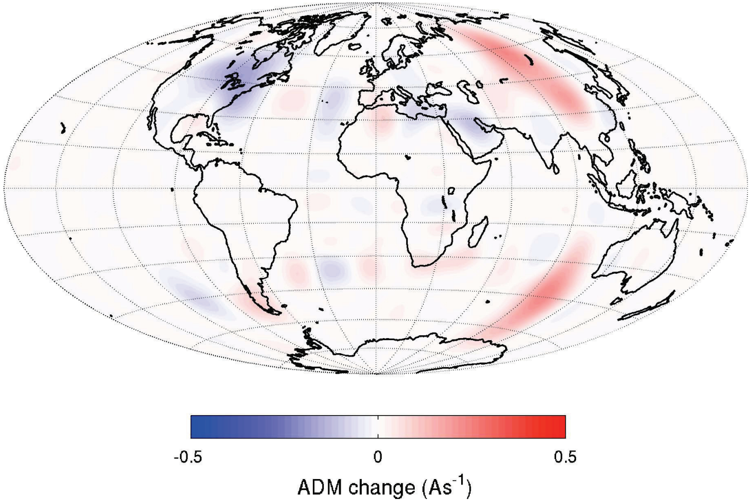
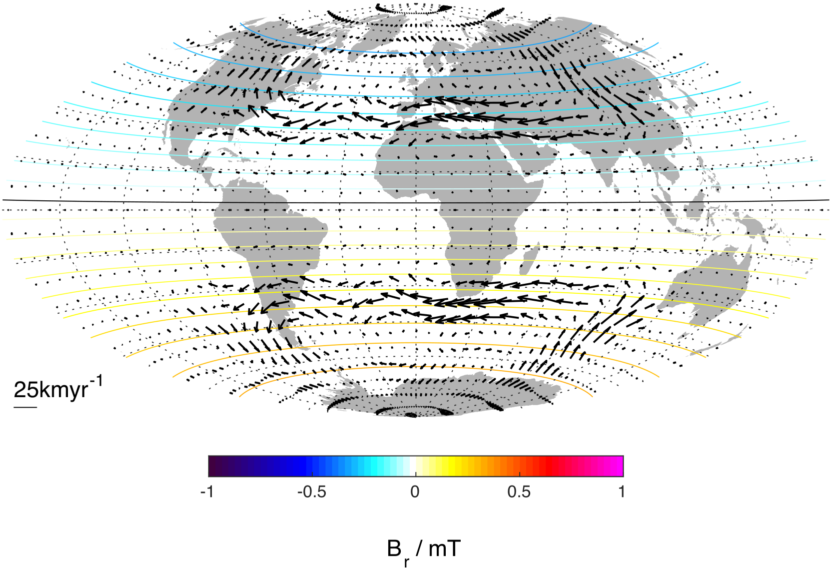


# Comparison with case of pure dipole field



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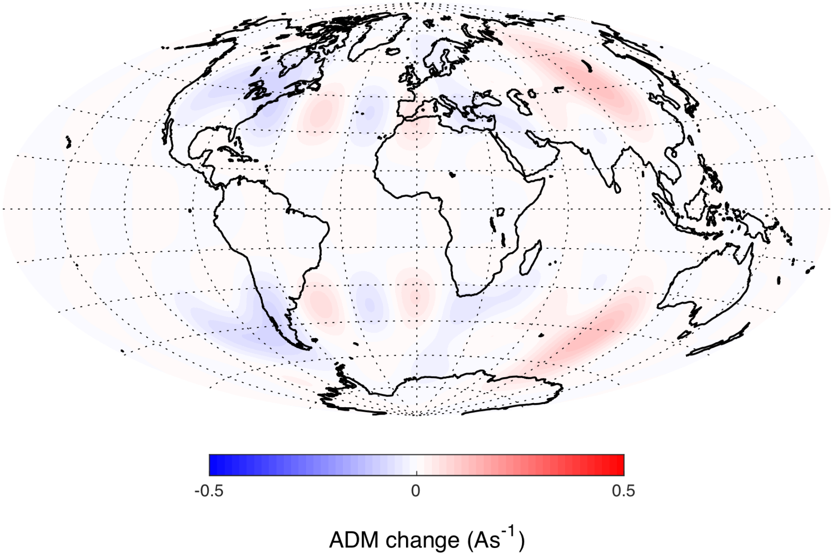
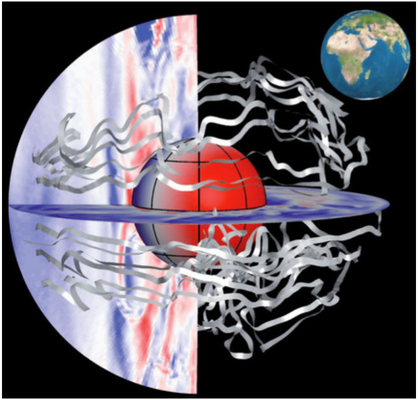
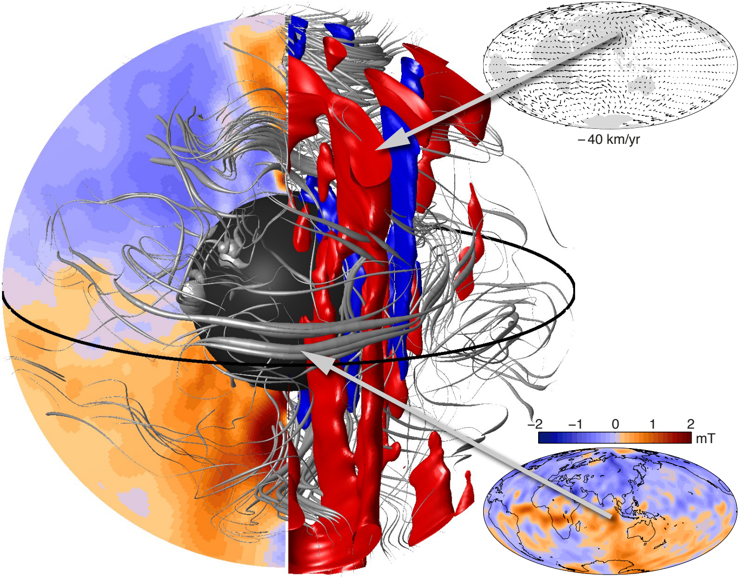


# A 3D dynamo model including magnetic diffusion

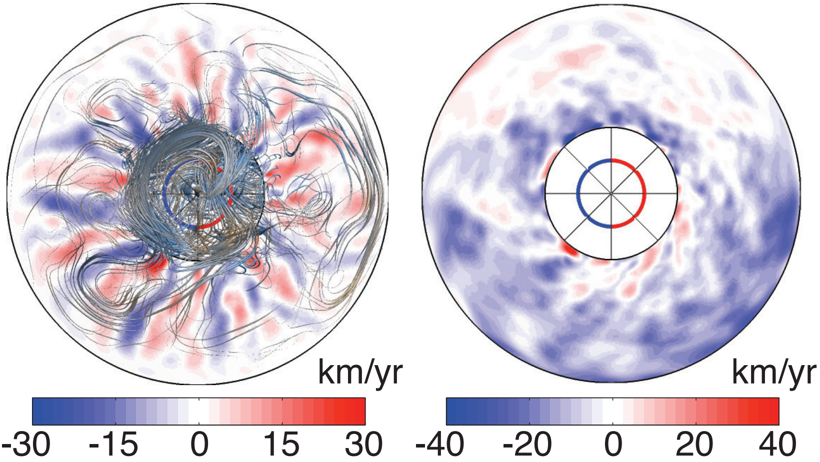


- Coupled Earth Dynamo Model (Aubert et al., 2013)
- EM coupling at ICB, gravitational coupling btw IC and mantle
- Relatively high magnetic Reynolds number, $Rm = 942$
- Produces a planetary-scale gyre as in core flow inversions

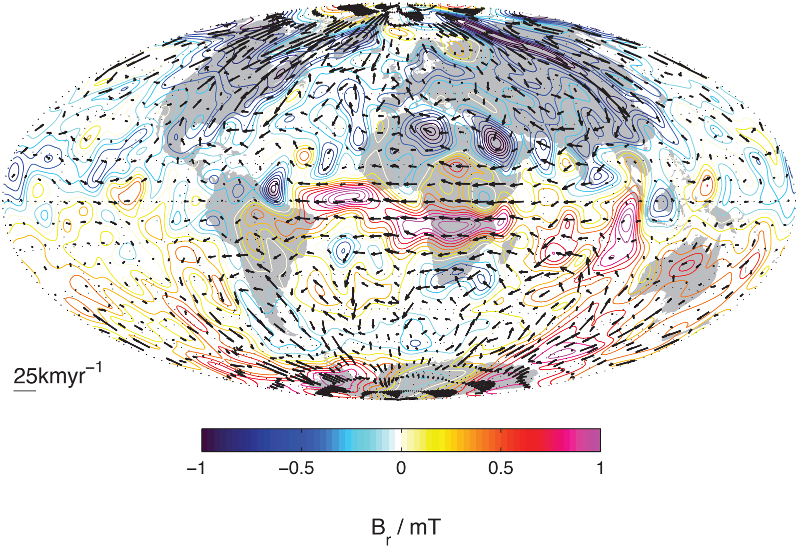
# Estimated geodynamo state in 2015



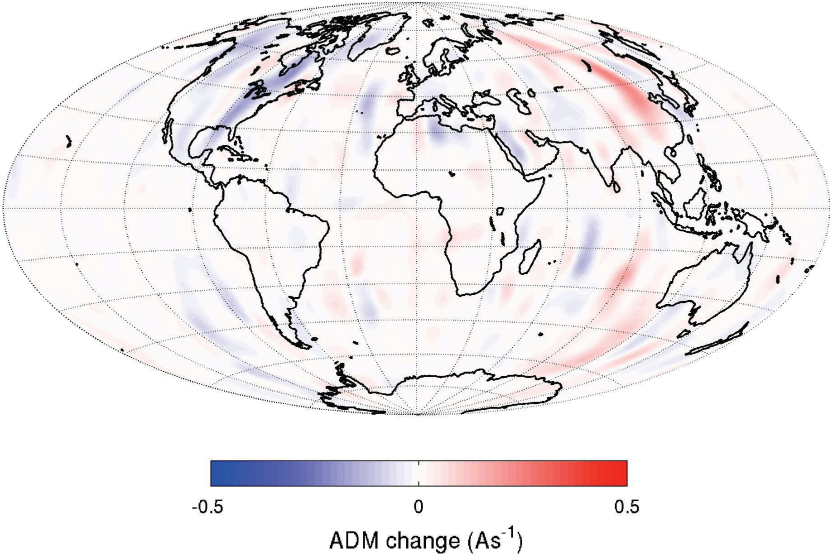
# Estimated field and flow within core in 2015



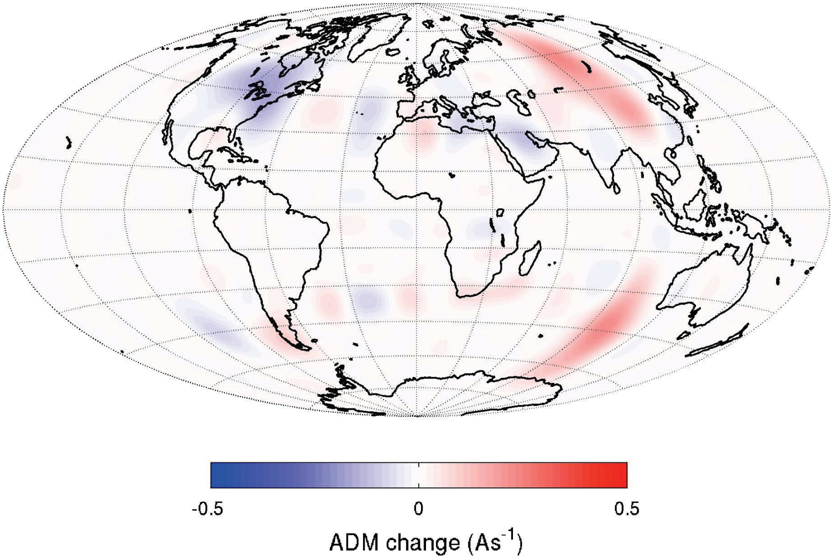
# Estimated core surface field and flow in 2015



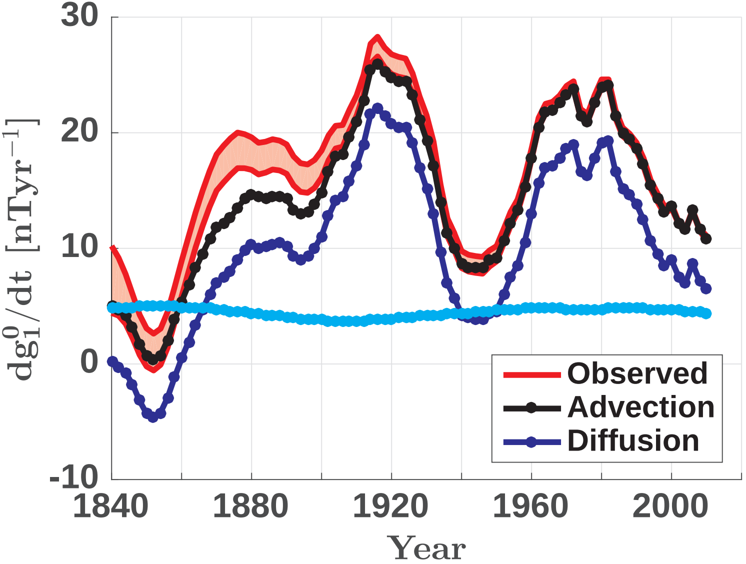
# Dipole decay due to meridional flux transport in 2015



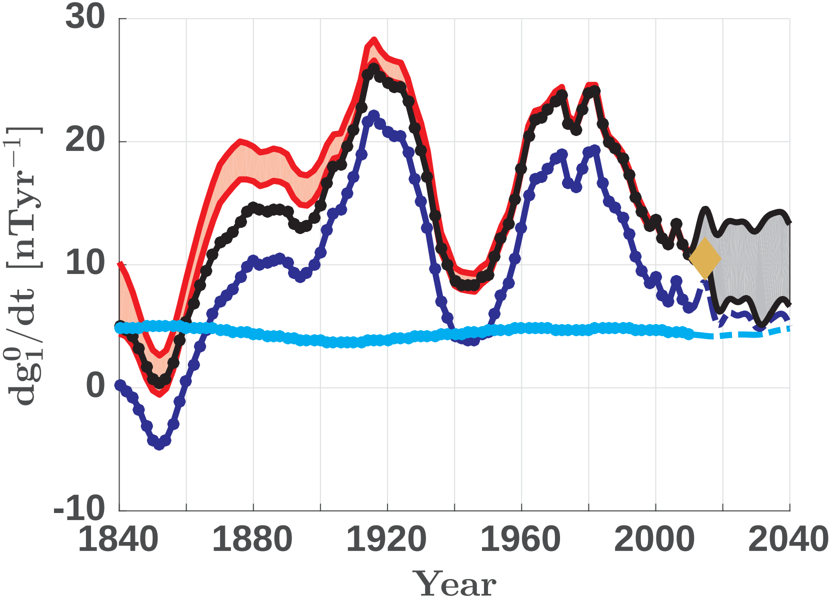
# Comparison with simple gyre model



# Retrospective analysis: Contributions to historical dipole decay



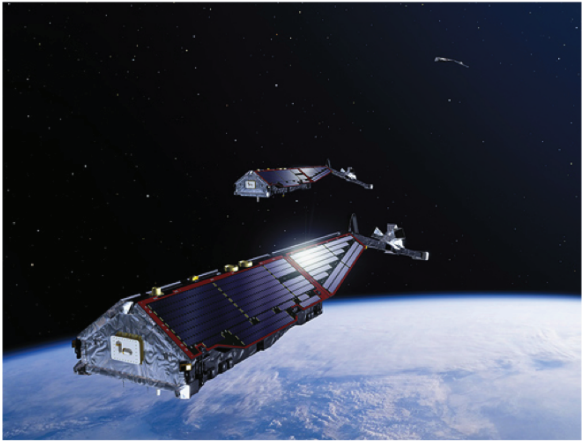
# Forecast of dipole decay rate for upcoming decades



# Summary

- The Earth's magnetic dipole has been decaying for the past 175 yrs.
- Planetary gyre transporting normal flux equatorward and reversed flux poleward accounts for much of the decrease.
- Mechanism requires field asymmetric (e.g. South Atlantic Anomaly).
- Dipole decay fluctuations due to fluctuations in meridional flux transport by the gyre.
- Magnetic diffusion makes a secondary, almost steady contribution.
- Mechanism suggests dipole will continue to decay, at least for next few decades.

# Outlook: Using *Swarm* data for more detailed tests



- Do fluctuations in equatorward flow correlate with fluctuations in the decay rate?

[PhD thesis of M. Hammer]

# Inverse geodynamo modelling: A Kalman filter approach

*[See Aubert (2013, 2014) for full details]*

- (i) Estimate $\mathbf{B}$ throughout core $\mathbf{x}_B$ to degree 30, from the poloidal field at the surface to degree 13, using the a-priori covariance matrix $\mathbf{P}_B$ derived from a large number of states $\mathbf{x}_B$:

$$\mathbf{x}_B = \mathbf{P}_B \mathbf{H}_B^T (\mathbf{H}_B \mathbf{P}_B \mathbf{H}_B^T + \mathbf{R}_B)^{-1} \mathbf{b} \qquad \text{where} \quad \mathbf{H}_B \mathbf{x}_B = \mathbf{b} \qquad (4)$$

- (ii) Estimate the core surface flow $\mathbf{x}_{fs}$ using the poloidal SV from a field model corrected by diffusion estimates from (i), $\dot{\mathbf{b}}$ :

$$\mathbf{x}_{fs} = \mathbf{P}_{fs} \mathbf{M}^T (\mathbf{M} \mathbf{P}_{fs} \mathbf{M}^T + \mathbf{R}_{\dot{B}})^{-1} (\dot{\mathbf{b}} + \mathbf{c}) \qquad \text{where} \quad \mathbf{M} \mathbf{x}_{fs} = \dot{\mathbf{b}} + \mathbf{c} \qquad (5)$$

- (iii) Estimate velocity throughout core $\mathbf{x}_u$ from $\mathbf{x}_{fs}$ using the a-priori covariance matrix $\mathbf{P}_u$

$$\mathbf{x}_u = \mathbf{P}_u \mathbf{H}_u^T (\mathbf{H}_u \mathbf{P}_u \mathbf{H}_u^T)^{-1} \mathbf{x}_{fs} \qquad \text{where} \quad \mathbf{H}_u \mathbf{x}_u = \mathbf{x}_{fs} \qquad (6)$$

- Provides an estimate of $(\mathbf{u}, \mathbf{B})$ throughout the core, at a given epoch, from a field model plus prior statistics from a self-consistent 3-D numerical dynamo simulation.