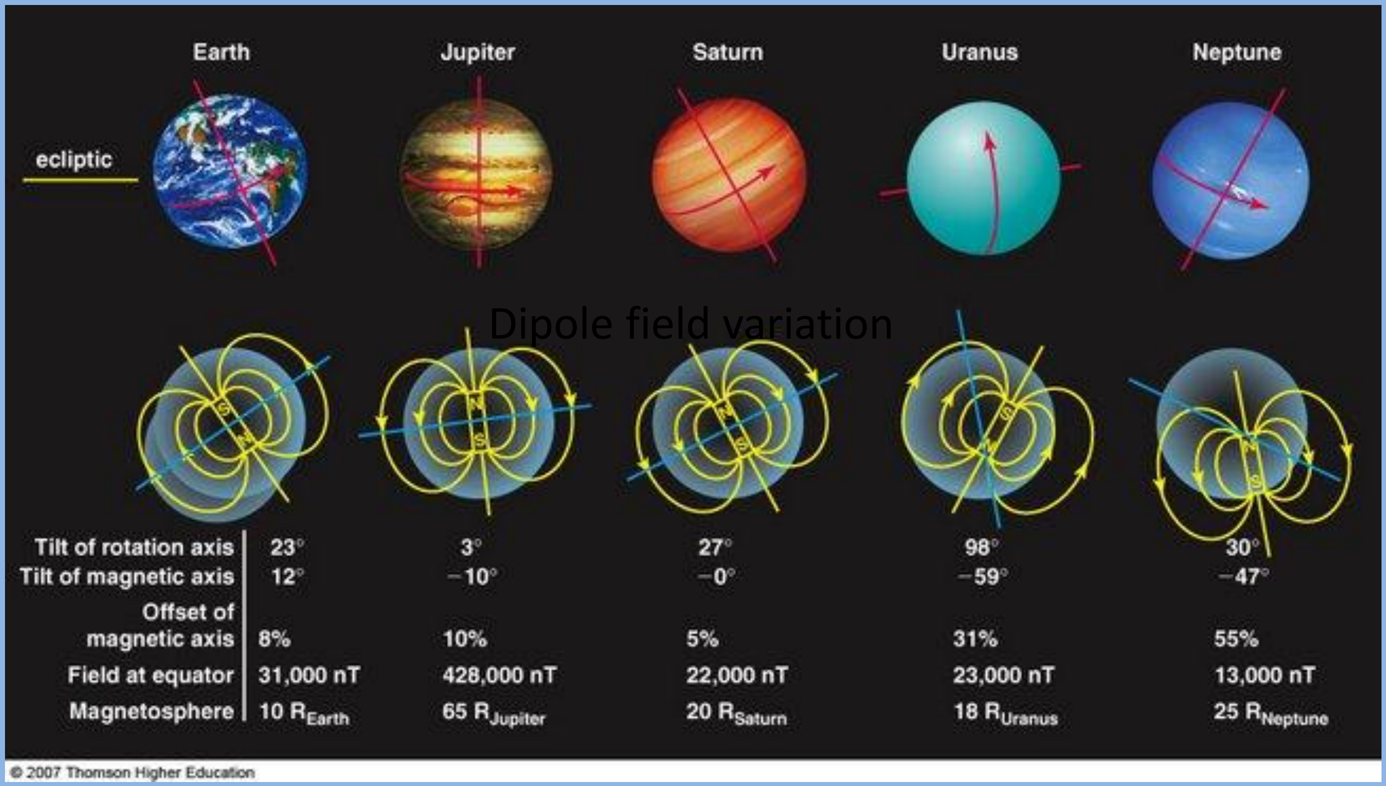
# Observational Constraints on Planetary Dynamos – What I think dynamo models should reflect!

Richard Holme
University of Liverpool

- Non-symmetry of fields of Uranus and Neptune
- Magnetic field and secular variation of Jupiter
- Geomagnetic secular variation spectrum
- Stable stratification and waves at the top of the Core
- Palaeointensity and inner core nucleation

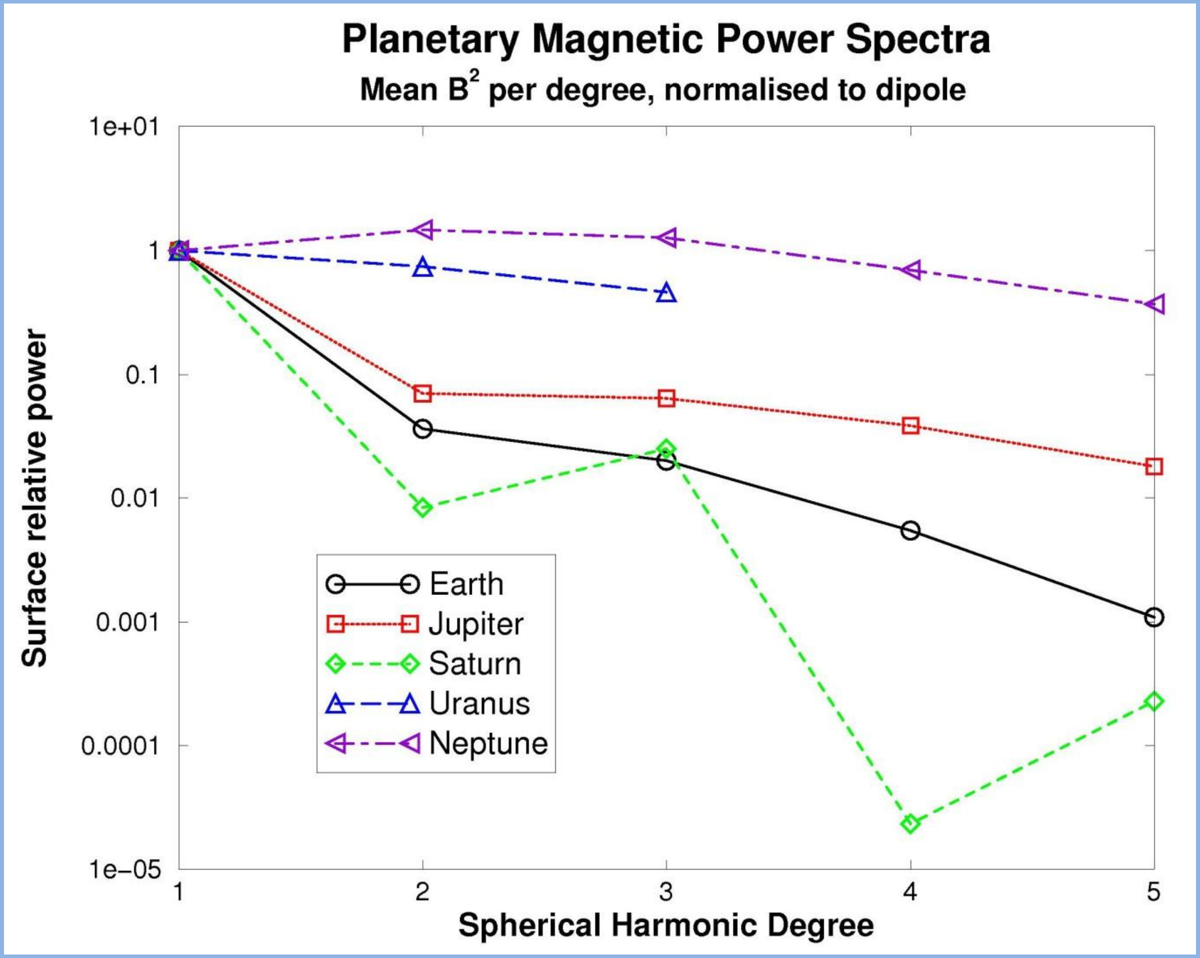
# A Simple Picture




Fine for outreach and many external field studies

Not fine for internal studies

# Power Spectra




Important constraint, but not everything

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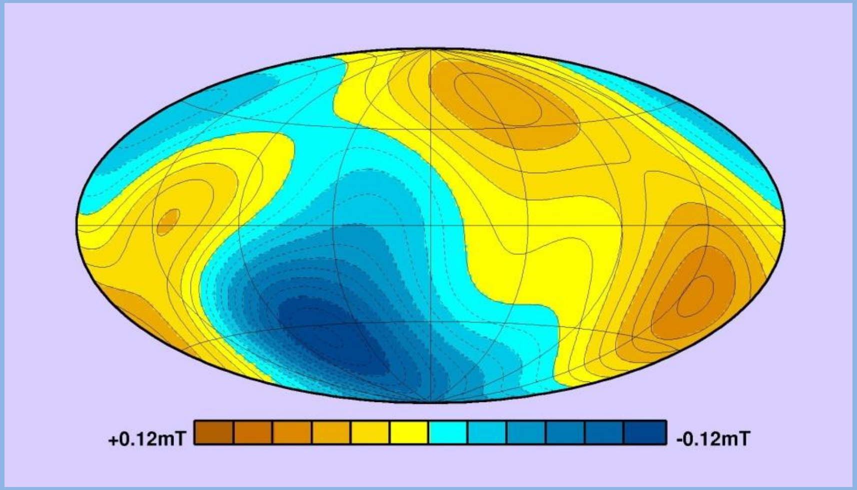
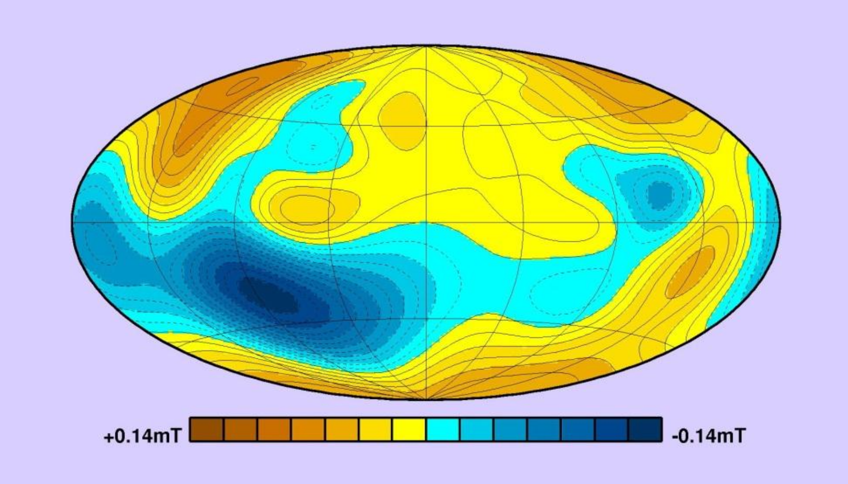
# Uranus and Neptune Surface Fields

Uranus



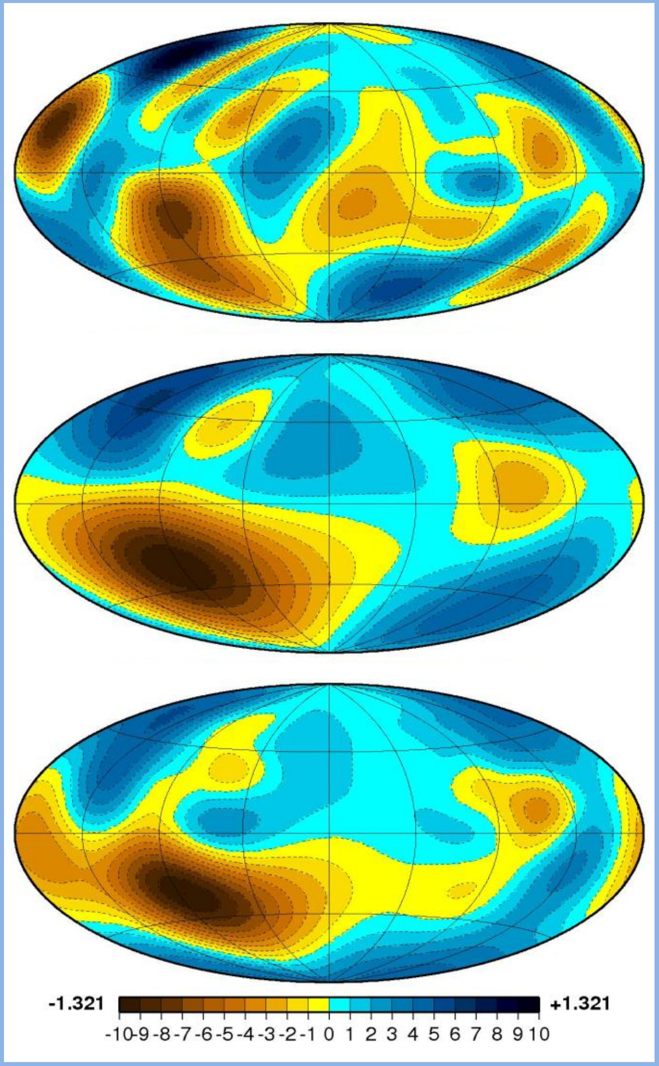

Neptune




- Very un-Earth-like – not dipolar even at surface
- Very different kind of field structure – differences in
  - Electrical conductivity?
  - Dynamical regime?
  - Energetics?

# Neptune field model range

- Three different models of surface field of Neptune
- All three models fit the data
- Decision for the modeller:
  - More complex model fits the data better, but is this detail required?
  - Simpler model fits well enough
  - Seek trade-off between explaining data and complexity

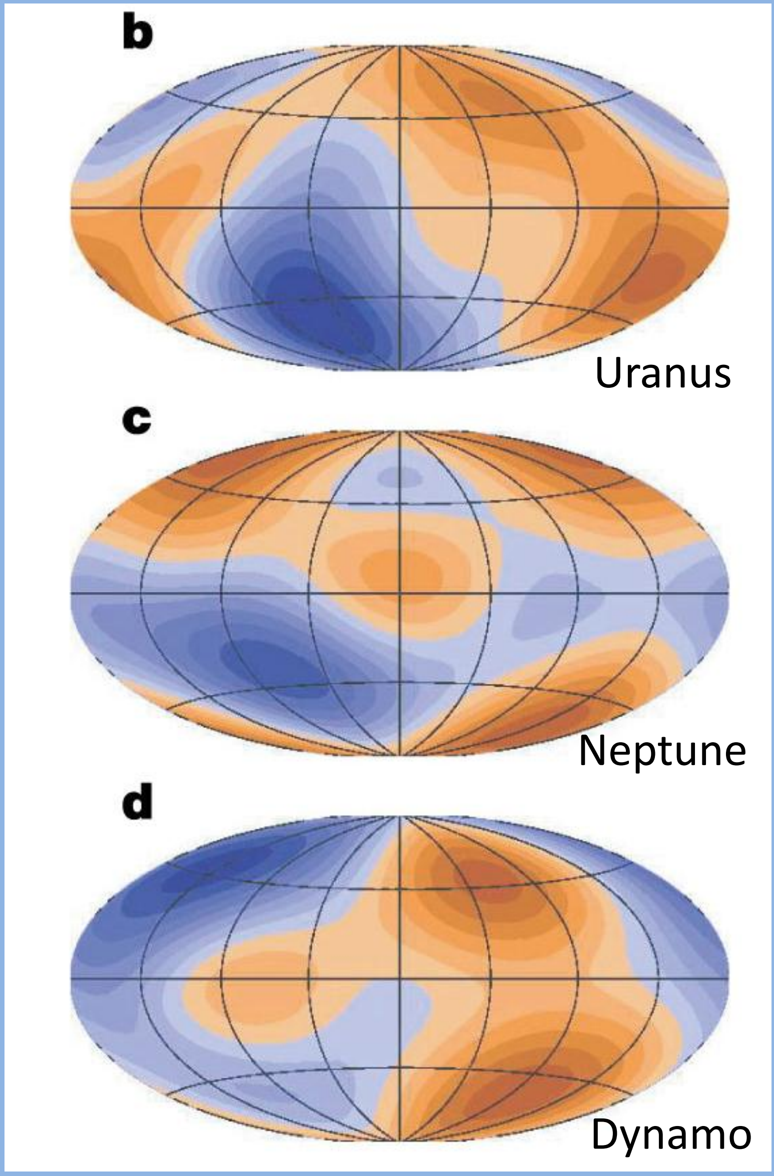


# Dynamo model interpretation

Comparison with observations not straightforward

- Example:
  - Truncate to common degree
  - Compare structure of field models from observations, dynamo
  - Similar complexity, power structure
- But – problem with too much symmetry
- Truncation losing information

**Solution – synthesise data from a dynamo model – invert and then compare**



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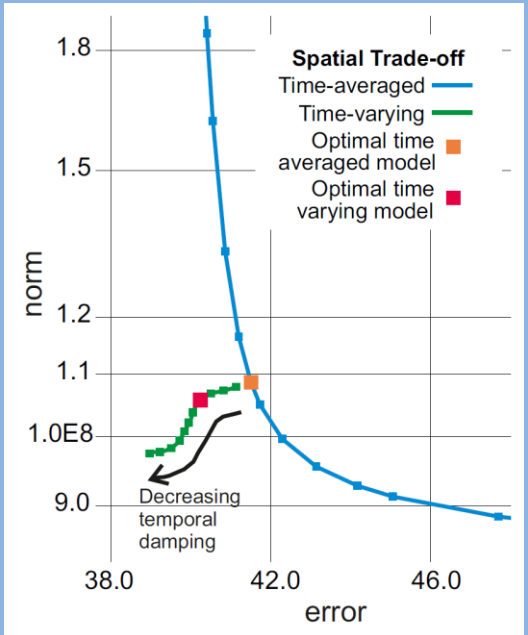
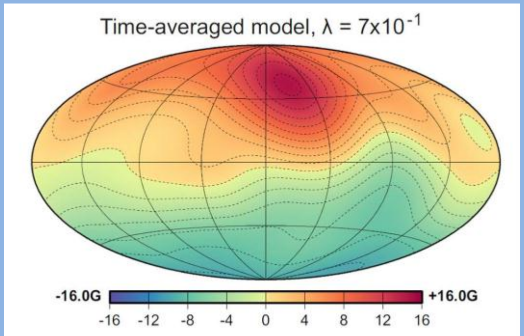
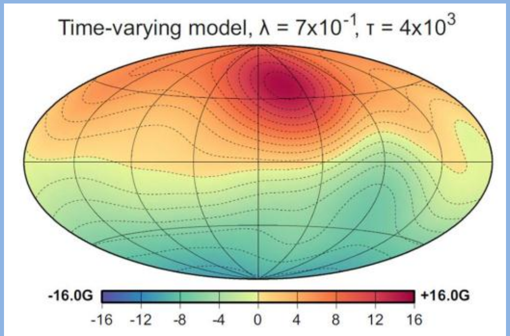
# Models of Jovian Field Change

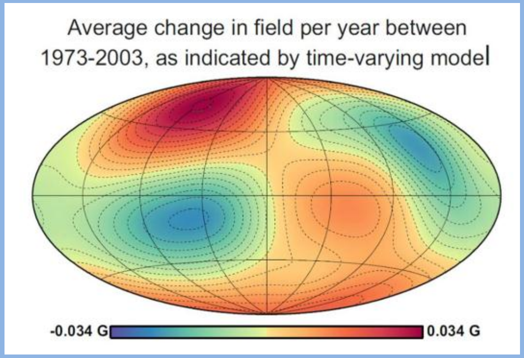
- Over 30 years of data from Pioneer to Galileo
- Dipole SV optimal model 0.042% $yr^{-1}$ (Earth ~ 0.06% $yr^{-1}$)
- Time variation not required – improvement in model better than increased spatial complexity

(Models of Victoria Ridley)



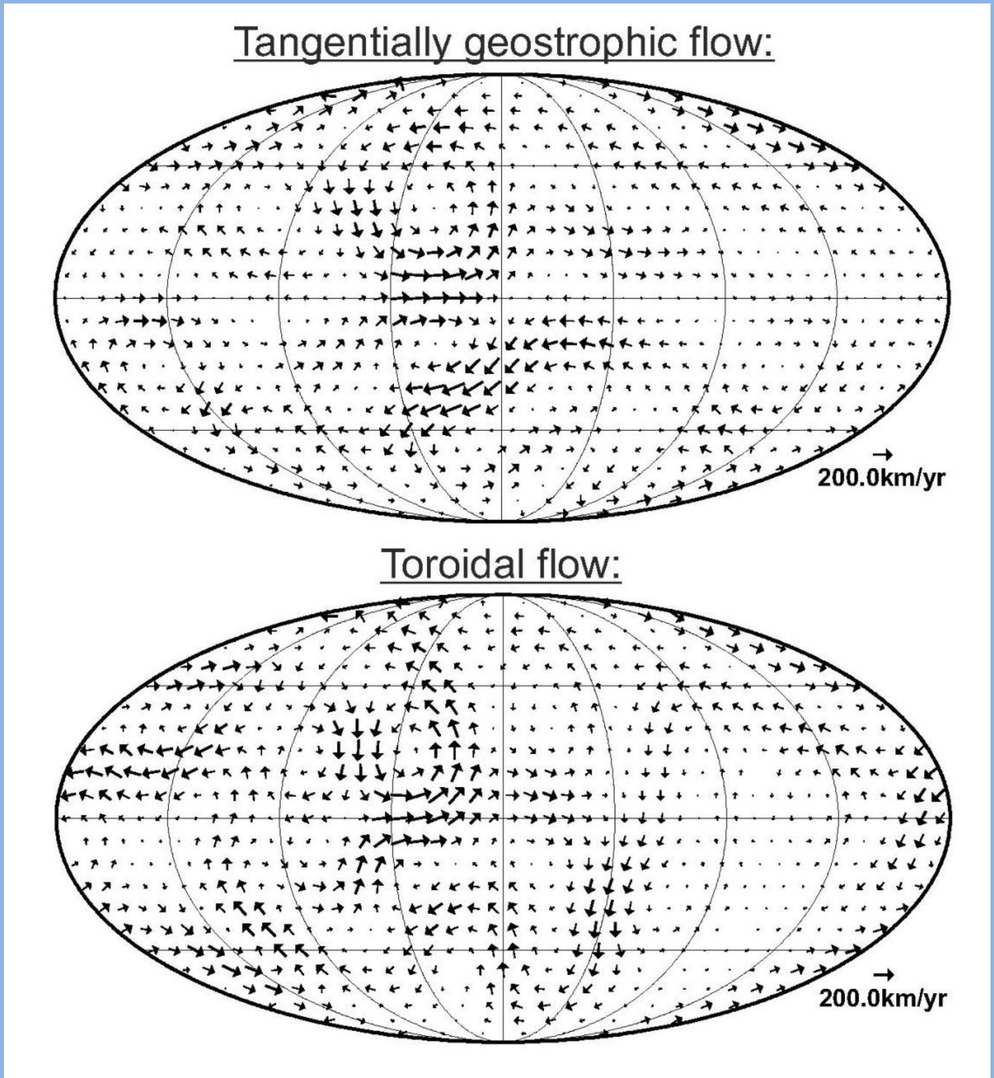



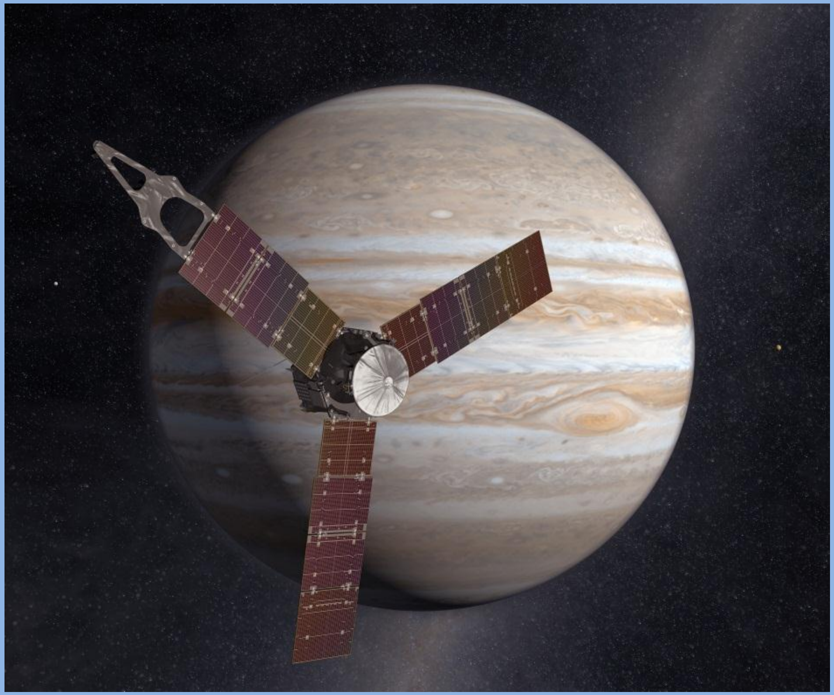



# Jovian Flow Modelling

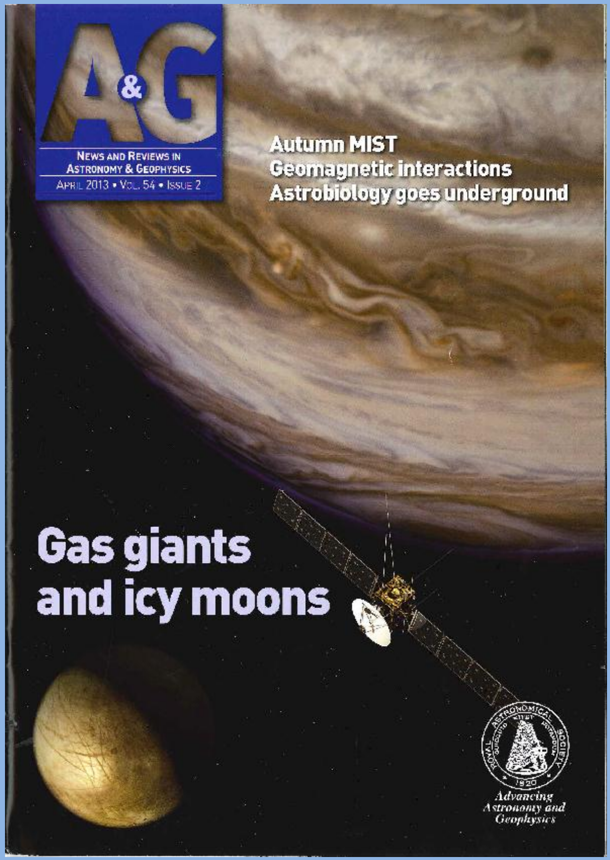
- From SV models, can infer flow at top of core – $0.85R_J$
- Require detailed flow structure to explain SV
- Cannot result from rotation alone

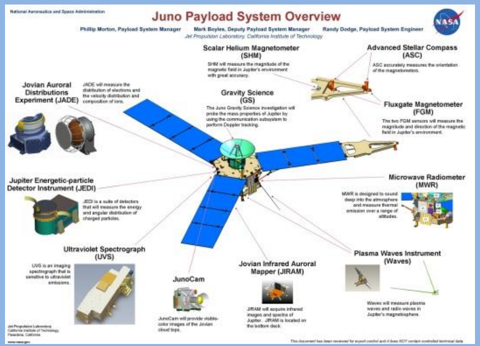


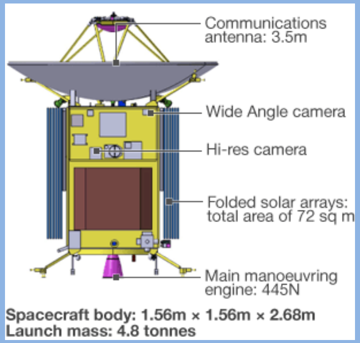
# New Jupiter Missions



Juno and JUICE

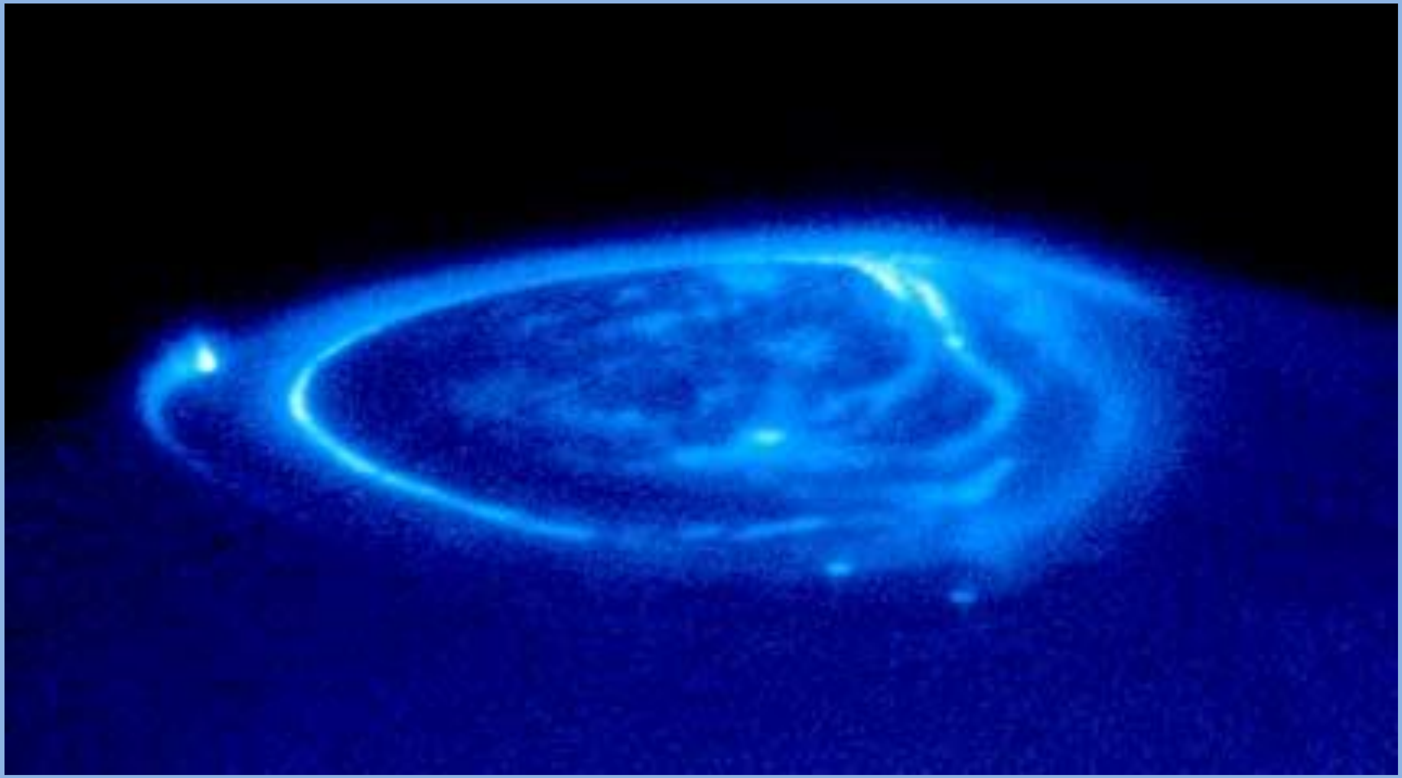


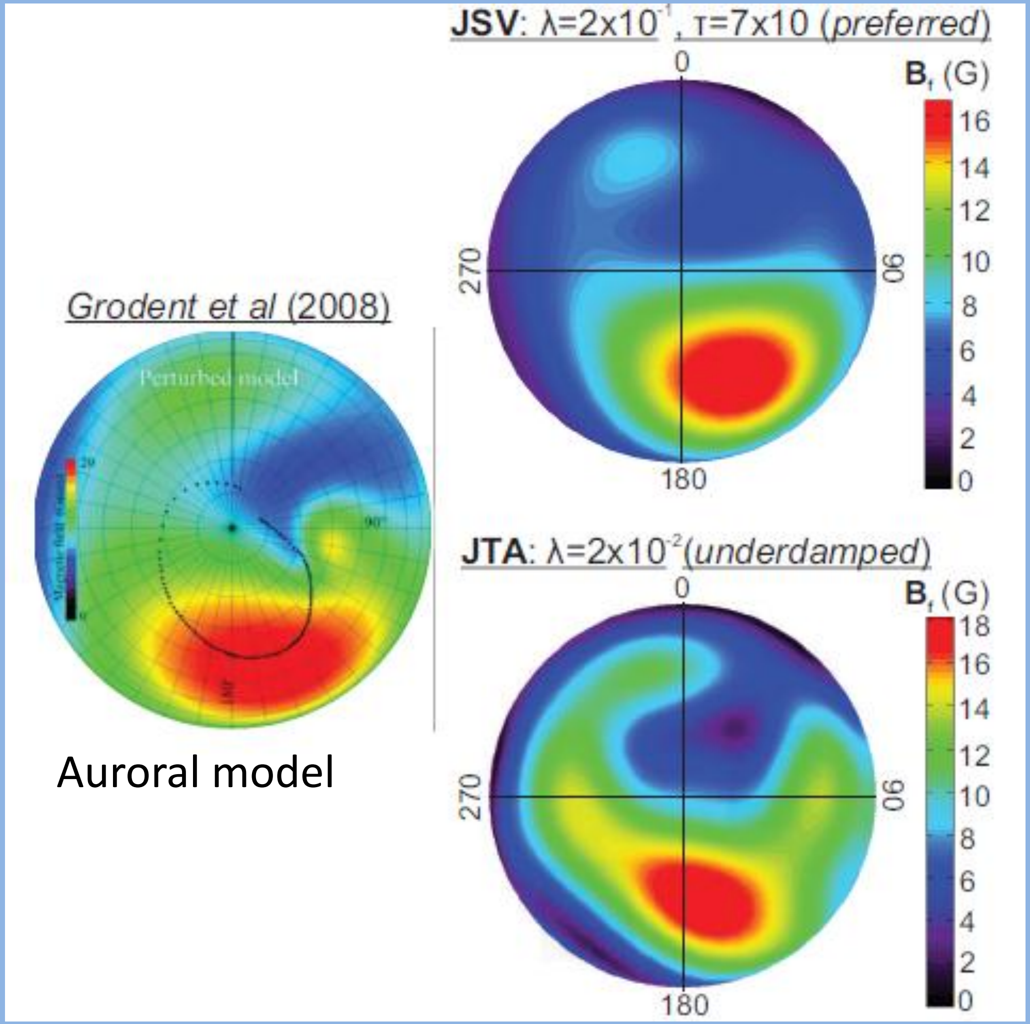
# Magnetic field constraint from Aurora

- Auroral structure and Galilean moon magnetic footprints provide high resolution field information
- Example from Hubble Space Telescope



# Is there more detail in the data?

- Models with auroral constraint higher resolution near the poles
- Compare models from satellite data alone
- Underdamped model not "fully converged" but features match higher-resolution auroral model
- More information in the data than we had thought?



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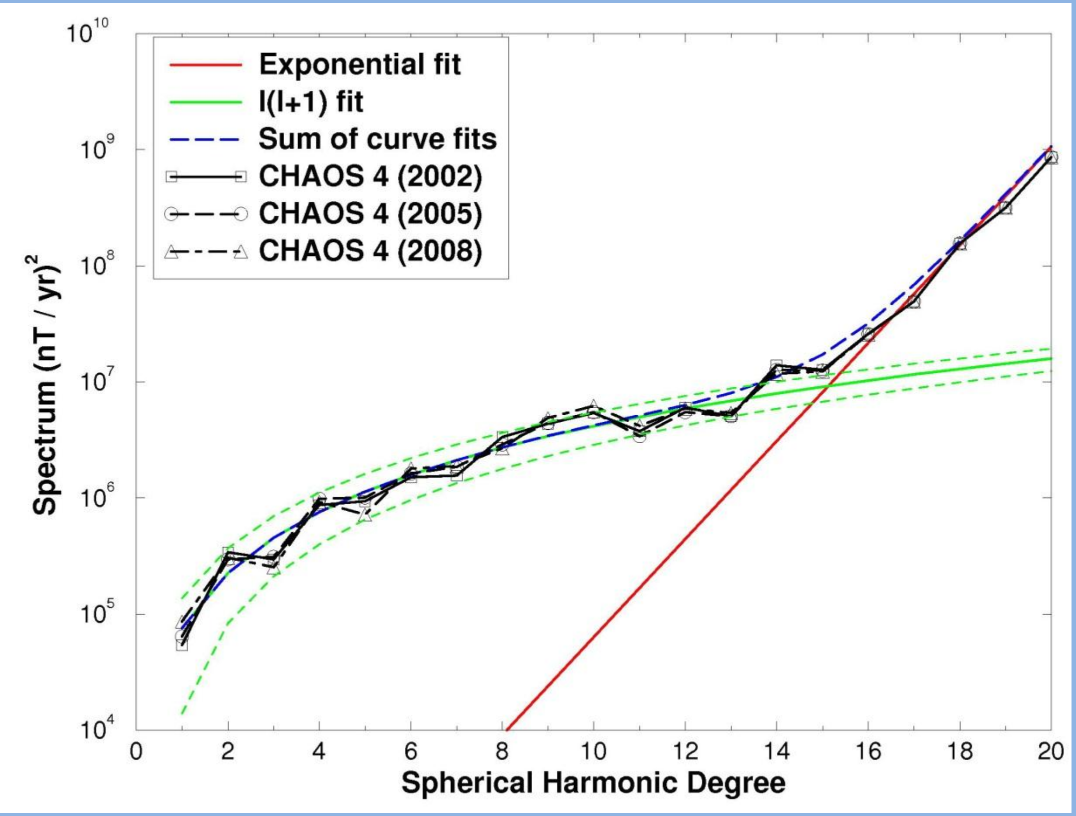
# Secular Variation Spectrum, CMB

- Secular variation - field time rate of change
- CMB spectrum:

$$\sum_{l=1}^{\infty}(l+1)\left(\frac{a}{c}\right)^{2l+4}\sum_{m=0}^{l}\left(\left(\dot{g}_l^m\right)^2+\left(\dot{h}_l^m\right)^2\right)$$

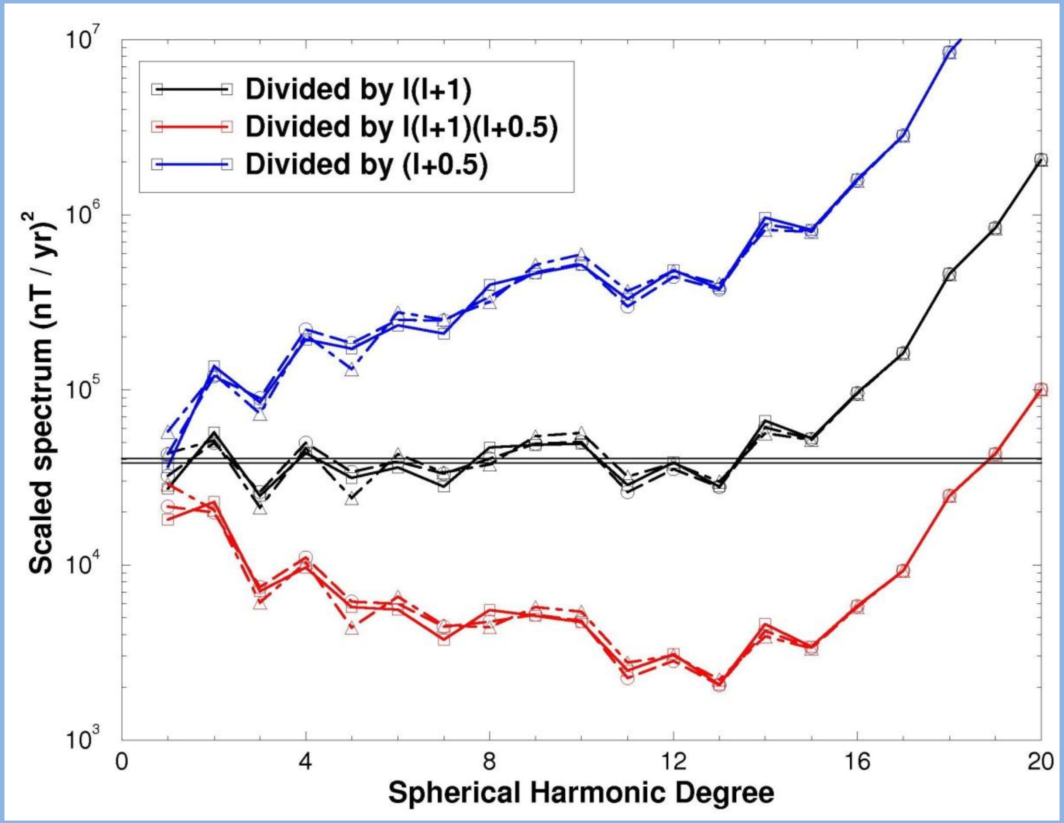
- Spectrum fit nicely by simple function of degree
- Fit so good tells us something about origin



# Other Possible Fits

- Single parameter fits proportional to
  - l(l+1)(2l+1)
  - l(l+1) (or $(2l+1)^2$)
  - (2l+1)
- Theory to suggest top two (Voorhies)
- Third suggested from dynamo models
- All look good on log plots!
- l(l+1) strongly preferred

Scaled Spectrum to test possible parameterisation



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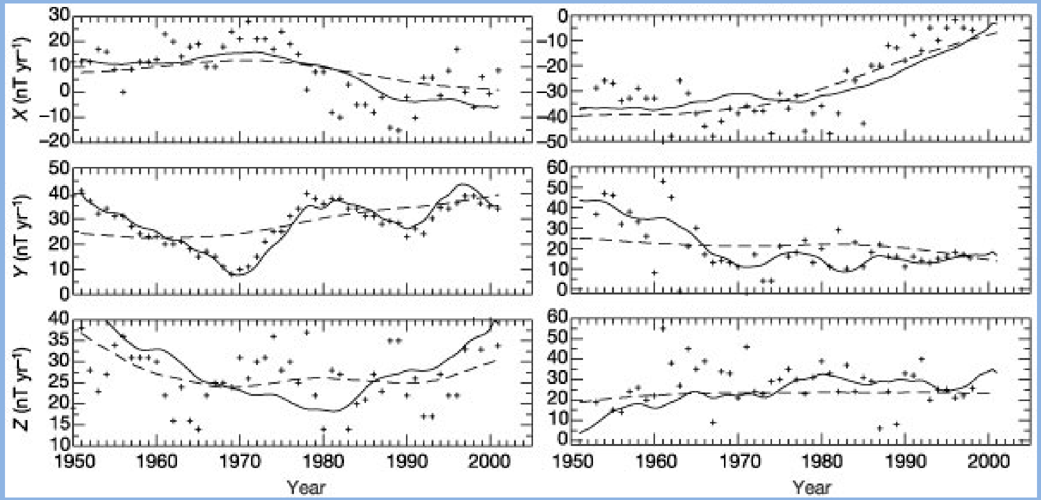
# Stable Stratification and Secular Variation

Niemegk Macquarie Island




Dashed line – steady flow
Solid line – + torsional oscillations

(Bloxham, Zatman and Dumberry, 2002)

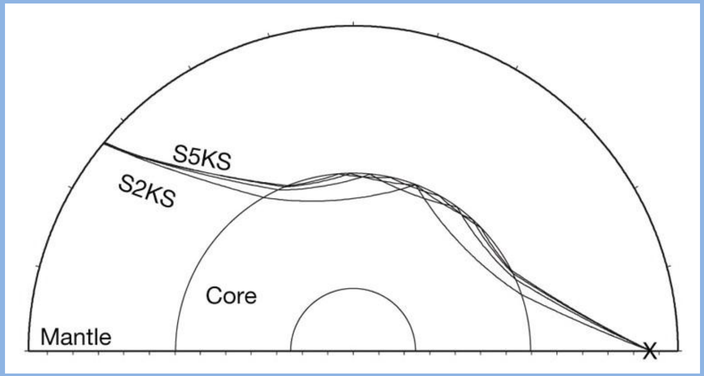
- Torsional motions – zonal toroidal, equatorially symmetric - consistent with stable stratification and tangential geostrophy
- Steady flow cannot explain "geomagnetic jerk", but additional torsional modes can do so
- Cannot explain other features of SV (including other jerks) – need more complex motions
- What other motions can be supported with stable stratification?

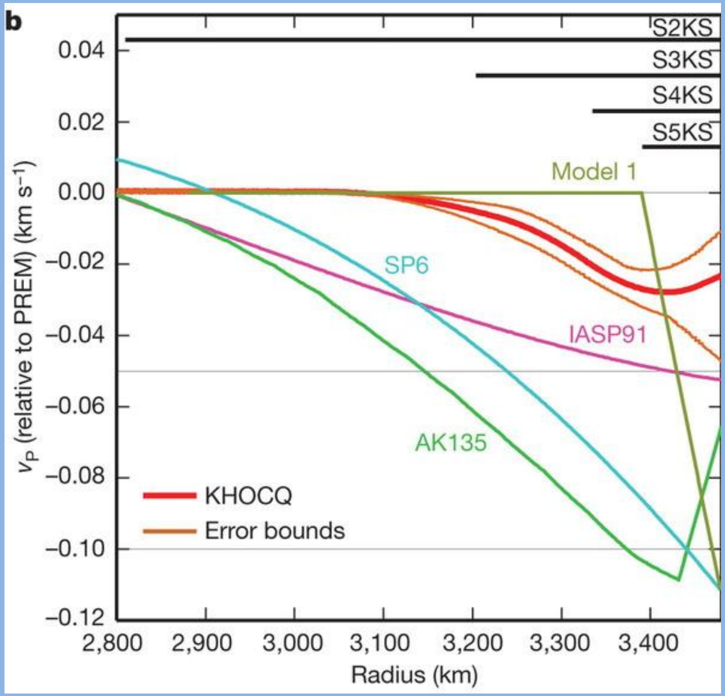
# Stable Stratification at top of Core

- Seismological evidence - Helffrich and Kaneshima argue for reduced seismic velocities near top of core
- Pozzo et al, 2012 – first principles calculations, increased thermal conductivity . **BUT**
- Zhang et al, 2015 – other first principles calculations suggest thermal conductivity estimate was correct
- Seismological evidence still implies stable stratification


- Seismological evidence - Helffrich and Kaneshima argue for reduced seismic velocities near top of core
- Pozzo et al, 2012 – first principles calculations, increased thermal conductivity :


"The presence of a stable layer, and the effects associated with an increased electrical conductivity, have significant implications for our understanding of the geomagnetic secular variation."



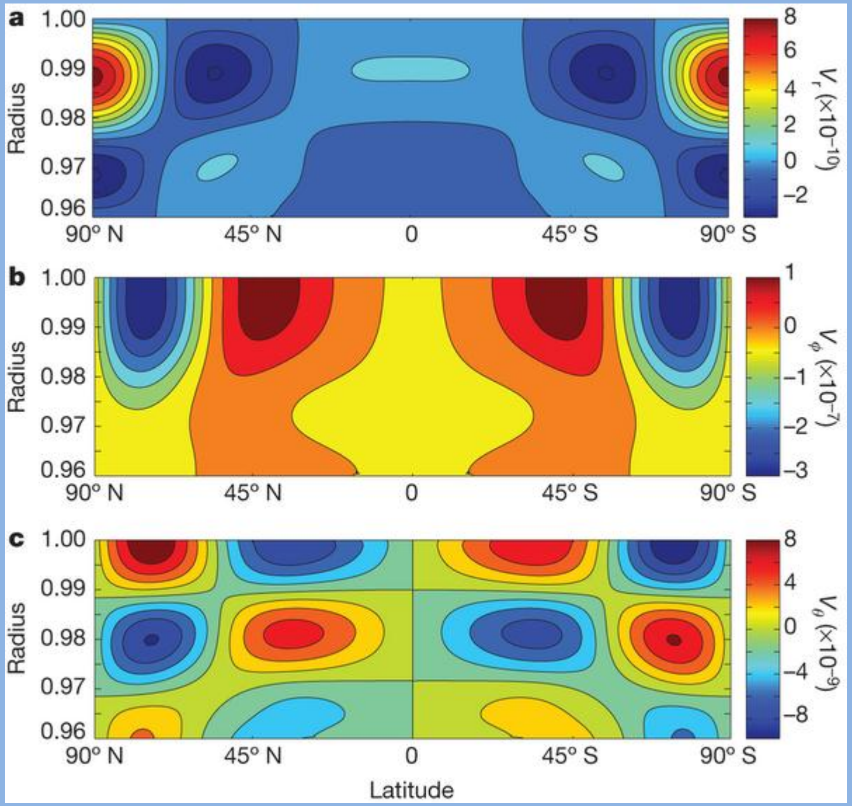
# Stable Stratification?

Buffett (2014) – evidence of MAC waves in time dependent zonal toroidal flow

Linear superposition of waves can account for $V_\phi$

Makes predictions for $V_\theta$

Flow zonal toroidal *and* poloidal




Model of MAC wave

# Stable Stratification?

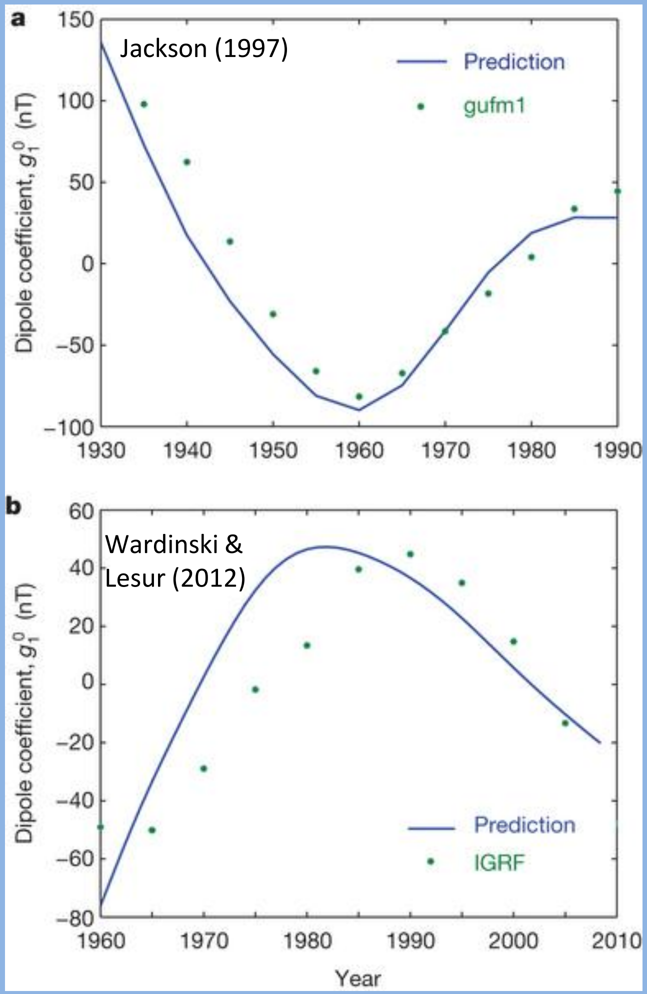
Buffett (2014) – evidence of MAC waves in time dependent zonal toroidal flow from 1930-1990

Linear superposition of waves can account for $V_\phi$

Makes predictions for $V_\theta$

Dipole field variation

- Explained for 1930-1990
- *Predicted* for 1960-2010




dipole fluctuations

# Core Flow Modelling

Radial component of induction equation
(frozen-flux approximation)

$$\frac{\partial B_r}{\partial t} + \nabla_H (B_r \mathbf{u}) = 0$$

Flow obtained by inverting observed secular variation.

Additional assumptions needed to reduce non-uniqueness. Standard:

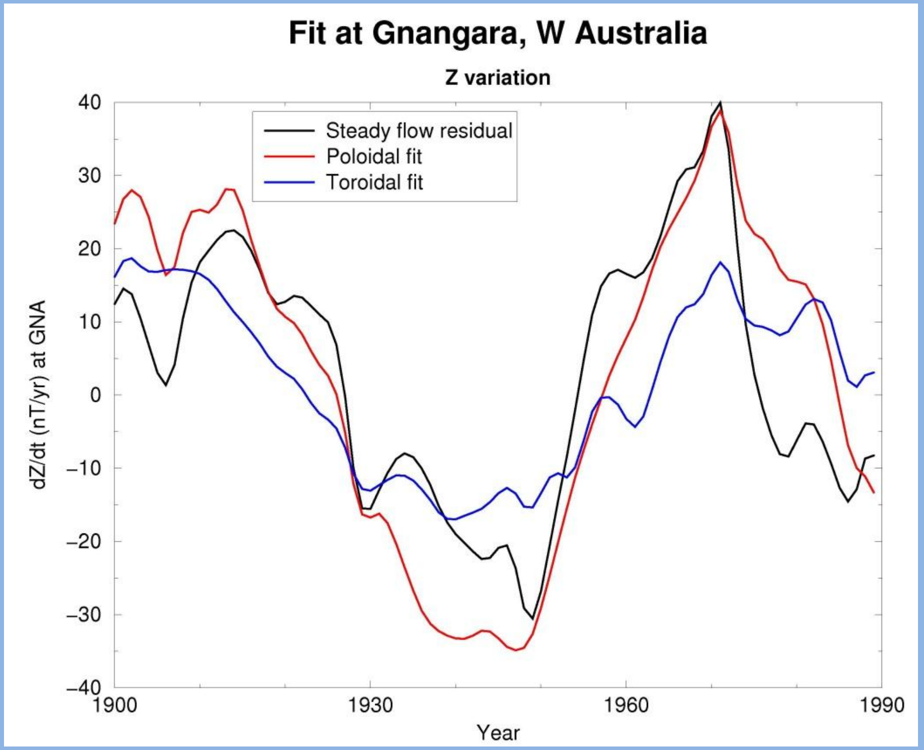
- steady
- purely toroidal
- tangentially geostrophic

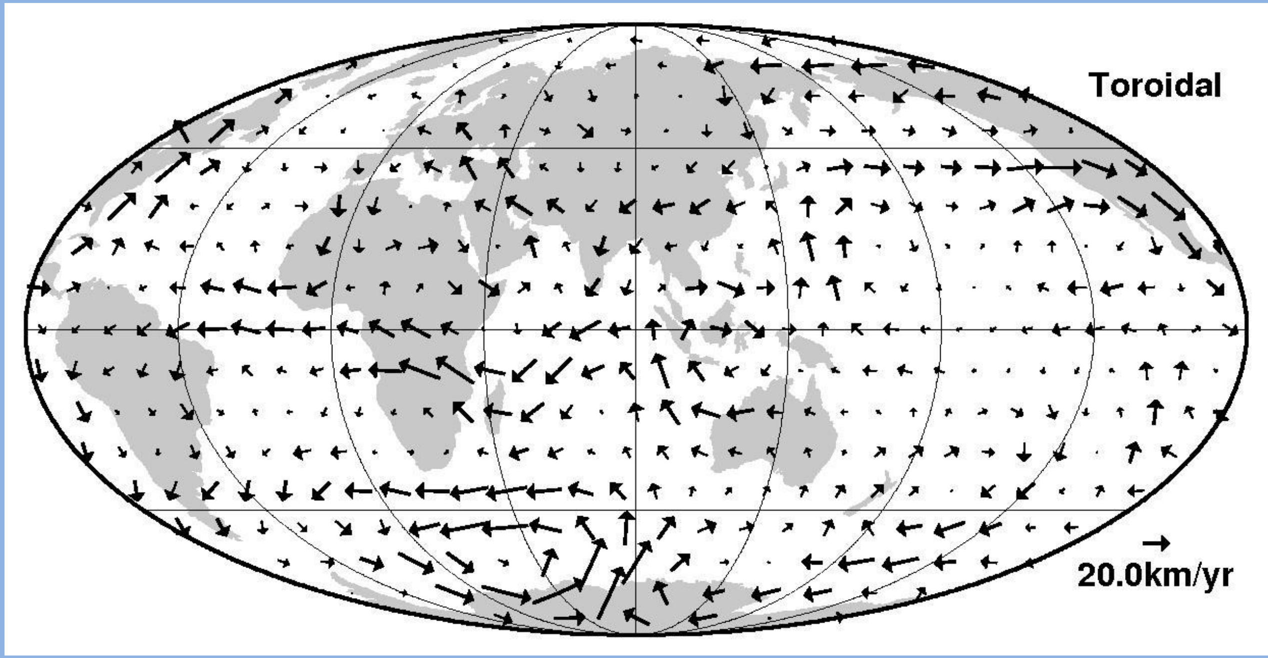
} no zonal poloidal flow

BUT: MAC wave solution has a time varying zonal flow with both toroidal *and poloidal* flows

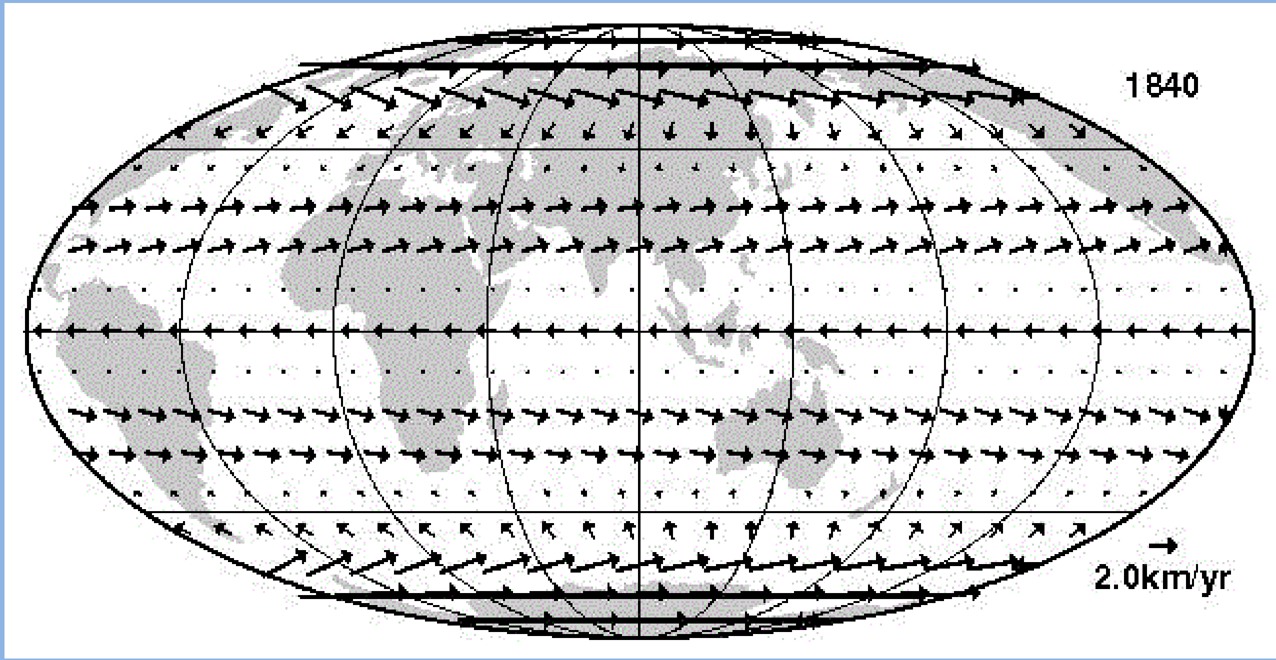
# New Flow Modelling

- Recover a constant toroidal steady flow
- Seek time varying flows to account for residual SV
  - Zonal
  - Equatorially symmetric
  - Toroidal, or toroidal and poloidal
- Including poloidal flows explains much additional SV (southern hemisphere geomagnetic jerks)



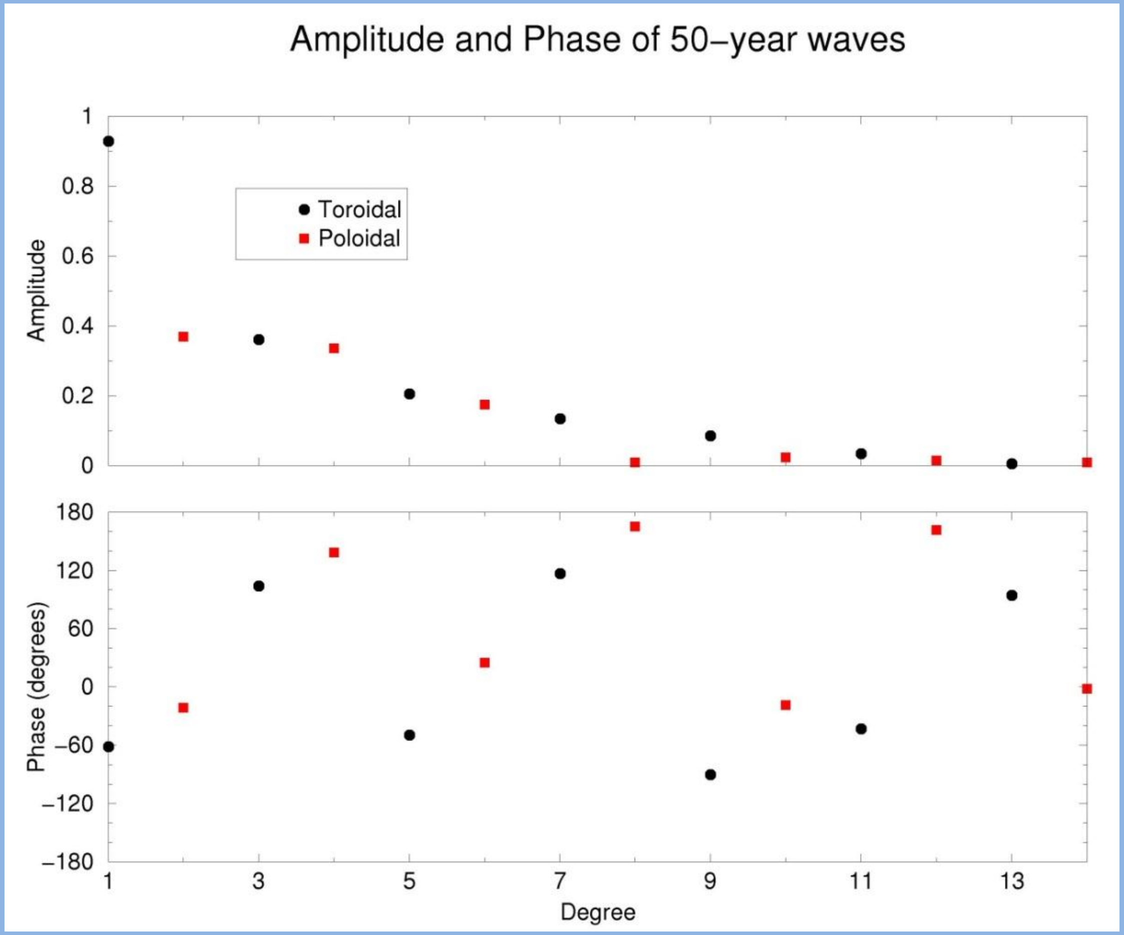



Steady toroidal flow




Time varying component

# Wave fit to different components



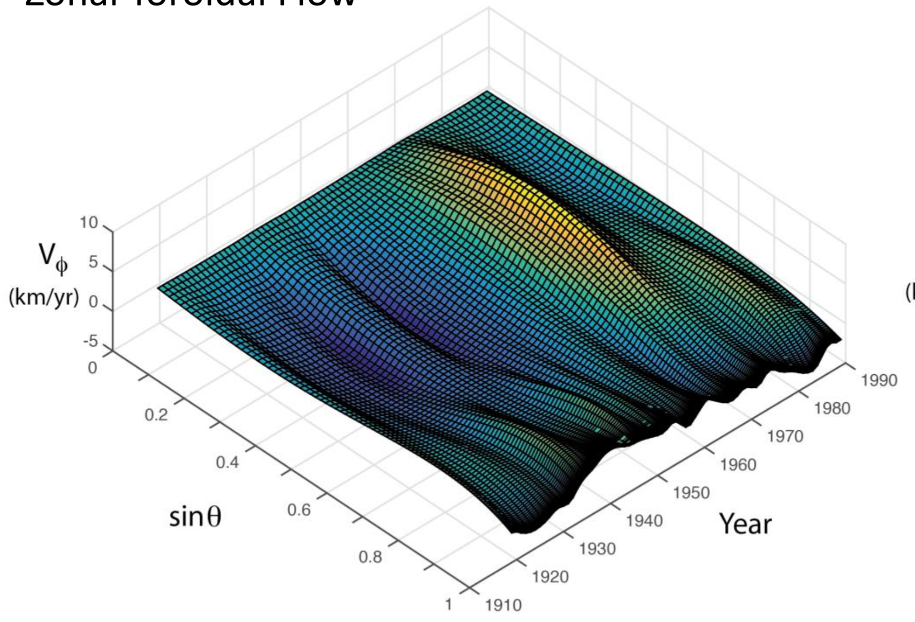

- Fit sine waves to different flow modes
- Best common fit at T ≈ 50 years
- Fall in amplitude with complexity
- Structure in phase difference between toroidal and poloidal components

Similar behavior expected for MAC waves

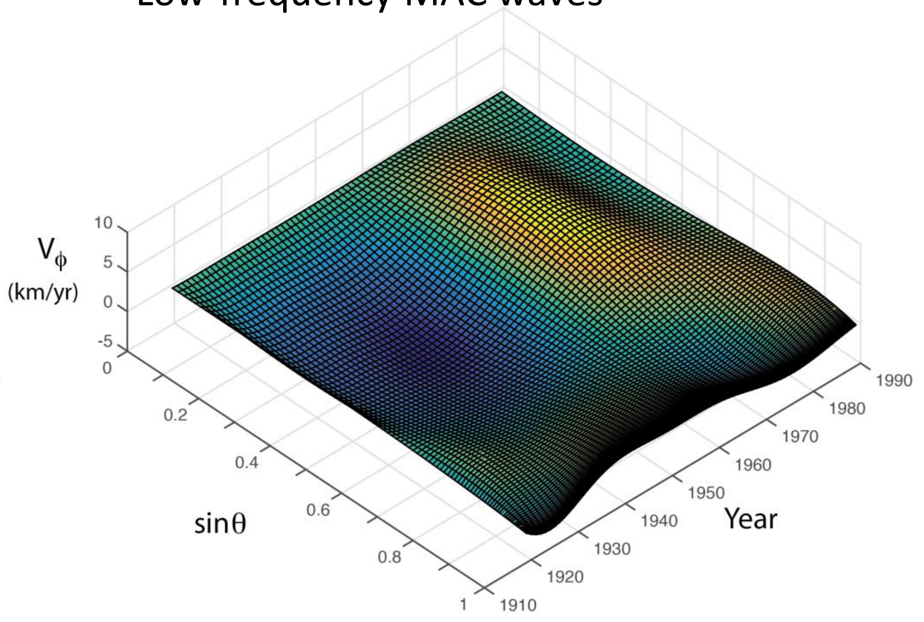
# Linking theory and observations

Fit MAC waves to zonal toroidal flow -> compare predictions for poloidal flow

Zonal Toroidal Flow




Low-frequency MAC waves

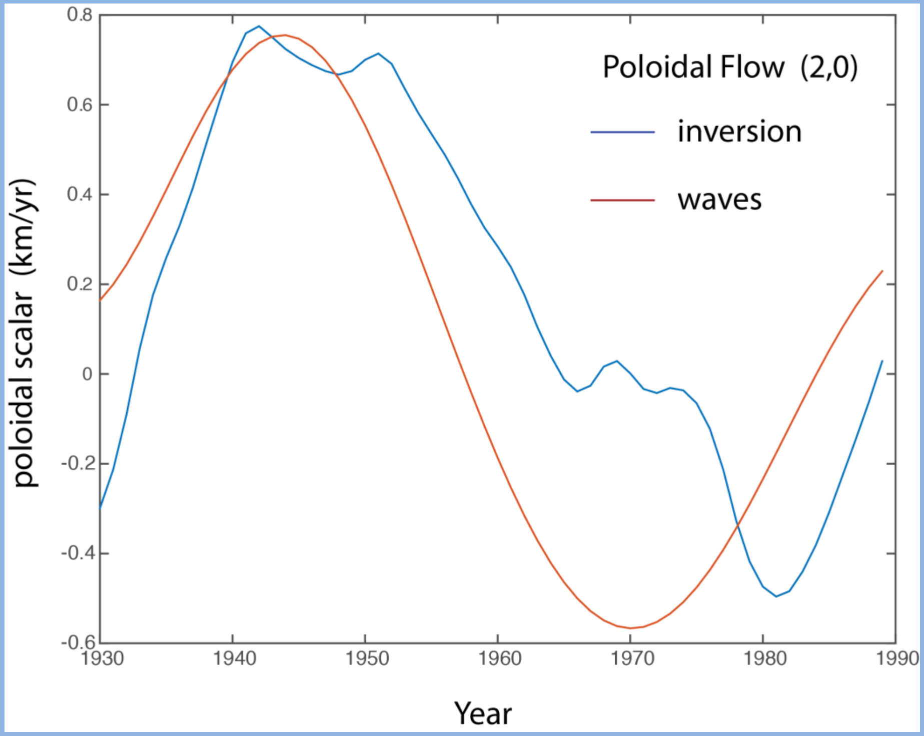



buoyancy frequency N ~ Ω

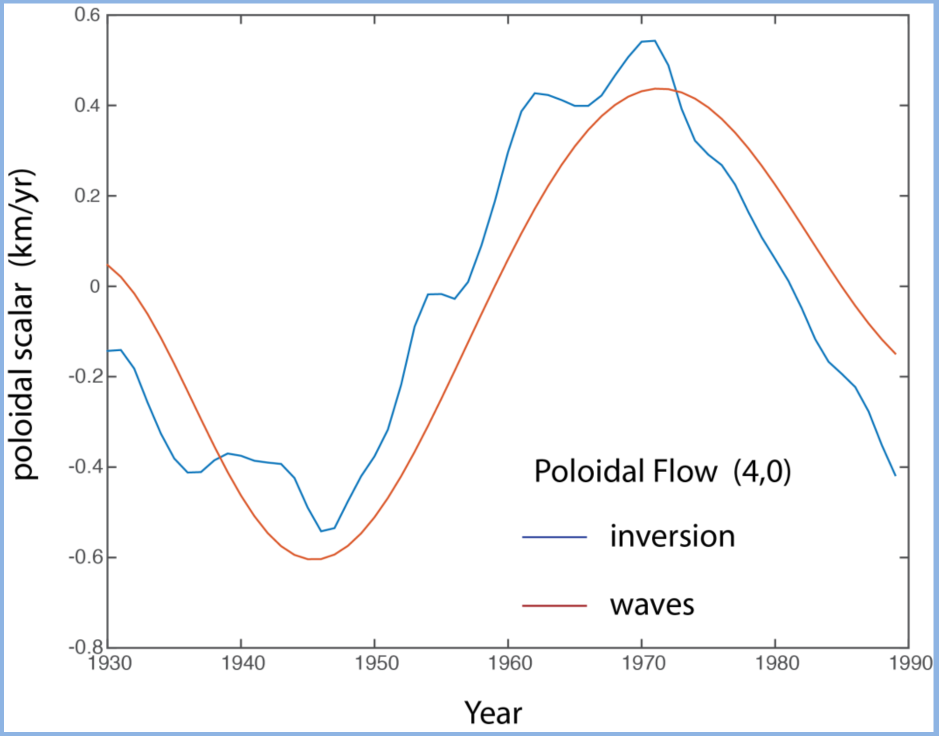
# Predicting Poloidal Flow

- Fit MAC waves to zonal toroidal flow
- -> predictions for poloidal flow  fit observations

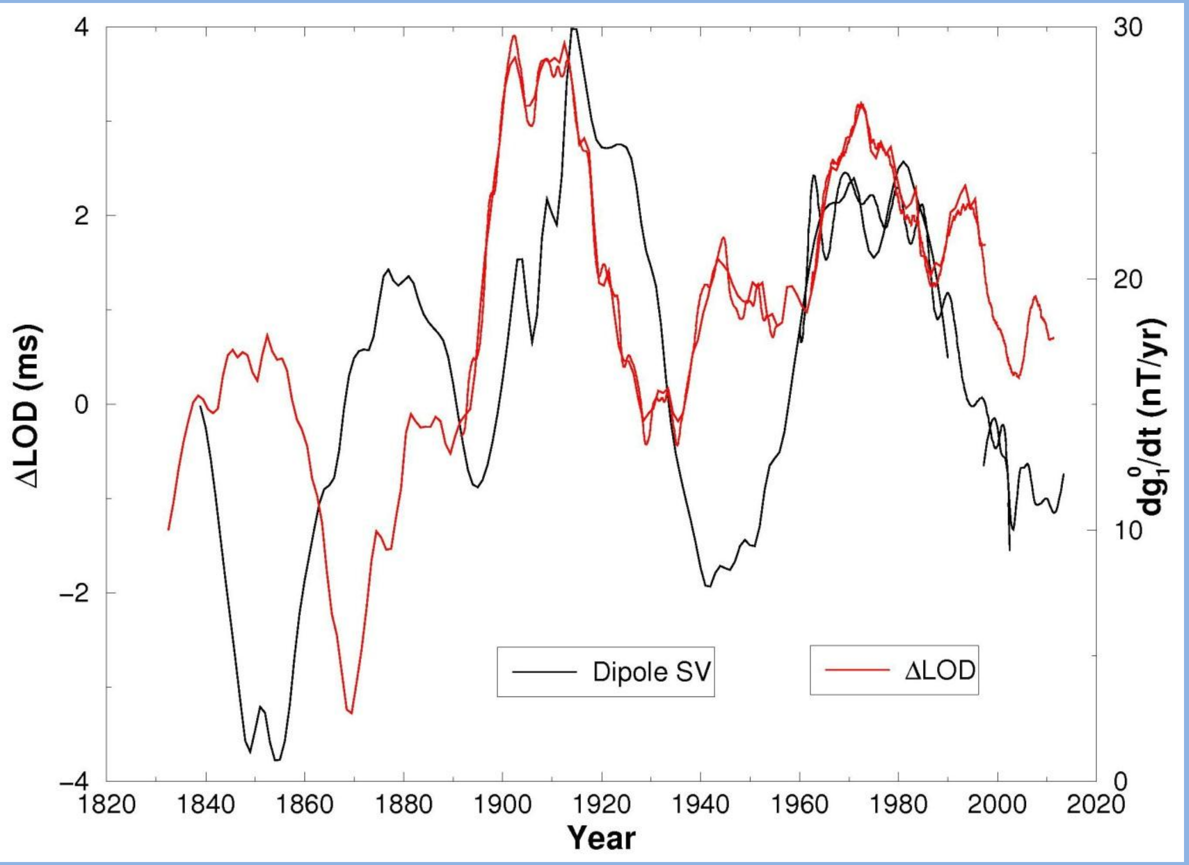
Degree 2




Degree 4



# Comparing ΔLOD and Axial Dipole SV




- Axial dipole and ΔLOD both have "60yr" variation
- But zonal toroidal flows don't give axial SV
- "Geomagnetic jerks" in axial SV – not from torsional oscillations
- This is either profoundly important or completely irrelevant!

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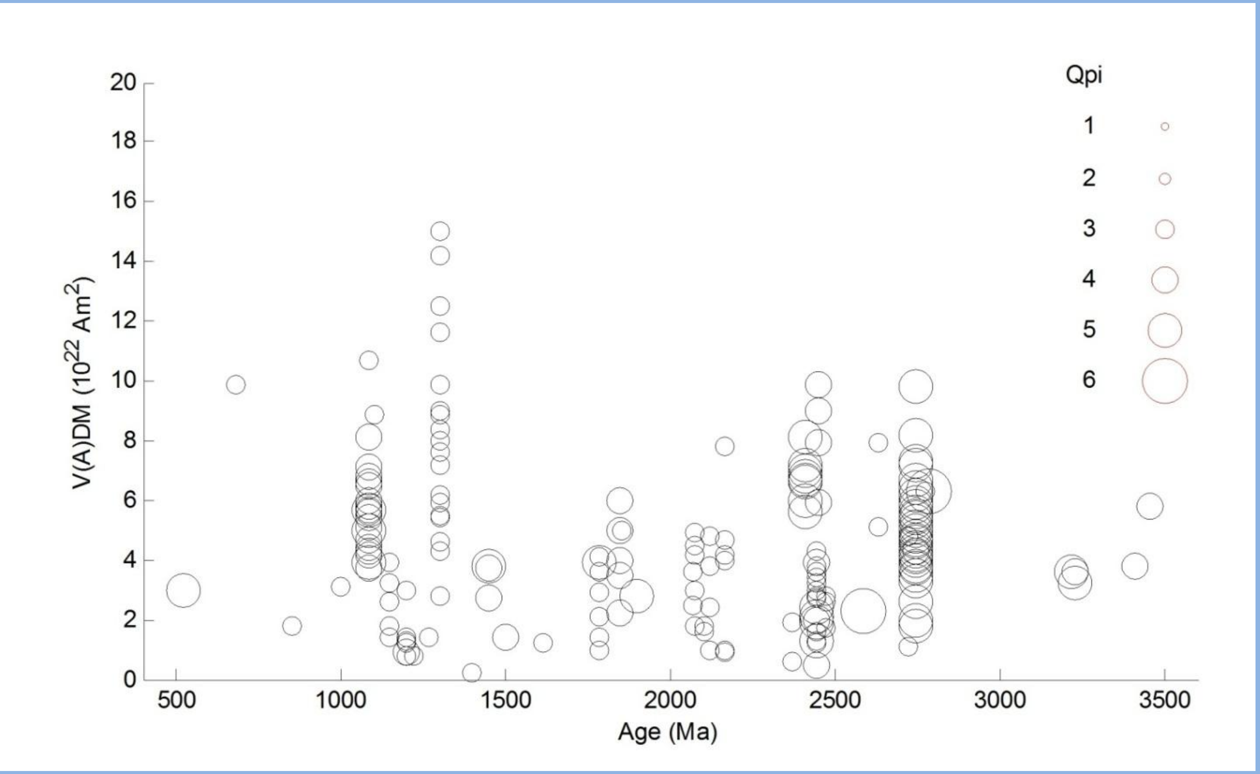
# Implications for Inner Core Growth

- Dipole moment from very old palaeointensity results
  - more reliable data ⇦ larger symbols (Biggin et al 2015)




- Consistent with inner core origin approx. 1.4 Byr ago
- Easier to explain with traditional core conductivity
- Seismological evidence still implies stable stratification

# Conclusions

- Non-symmetry of fields of Uranus and Neptune
  - Treat data from models
- Magnetic field and secular variation of Jupiter
  - Perhaps more can be extracted from observations
  - Juno will test this!
- Geomagnetic secular variation spectrum
  - Very clean relation to test against dynamo models
- Stable stratification and waves at the top of the Core
  - Beware of getting too caught up in one “school” (QG)
- Palaeointensity and inner core initiation
  - Perhaps the “New Normal” isn’t…….