Planetary magnetic fields.

Observations, theory, models.

Julien Aubert

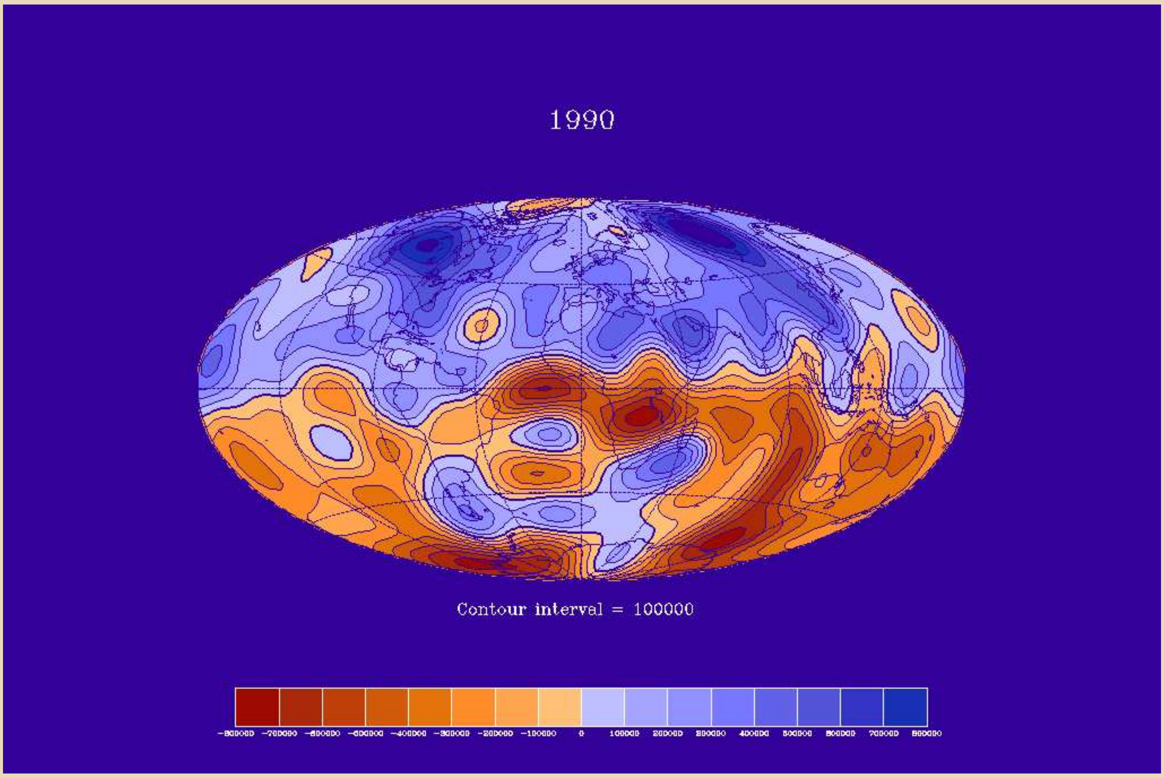
1– Intro

- **Magnetic field as a signal carrying information about**
  constitution
  dynamics of the interior
  thermal history of a planetary system.
- **Planetary dynamo modelling aims at**
  retrieving information by confronting numerical models and observations
  investigating the theoretical difficulties of the dynamo problem.

2– Plan

- The geodynamo: where it all started
- Mars: mysteries of the lost dynamo
- Uranus/Neptune: remote is exotic
- Jupiter/Saturn: zonal flows and dynamos

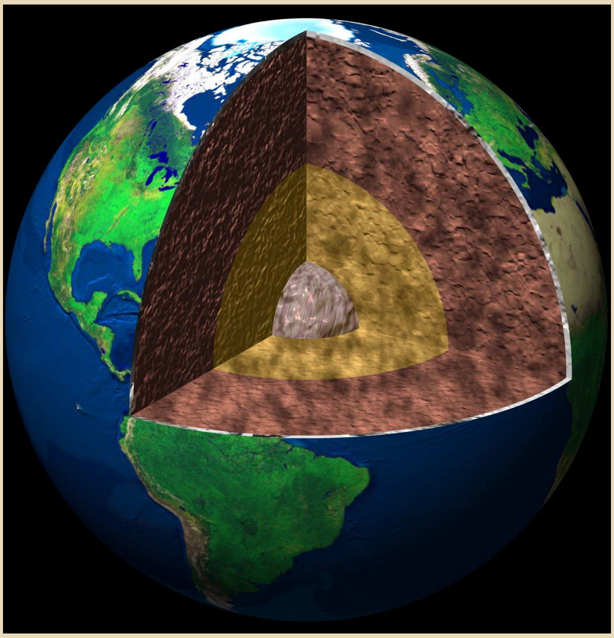
3– Earth: the most comprehensive dataset



Finlay & Jackson

4– Modelling

- Spherical shell geometry, rotation and magnetic induction are the 3 essential ingredients. One source of kinetic energy (most likely convection) is required.



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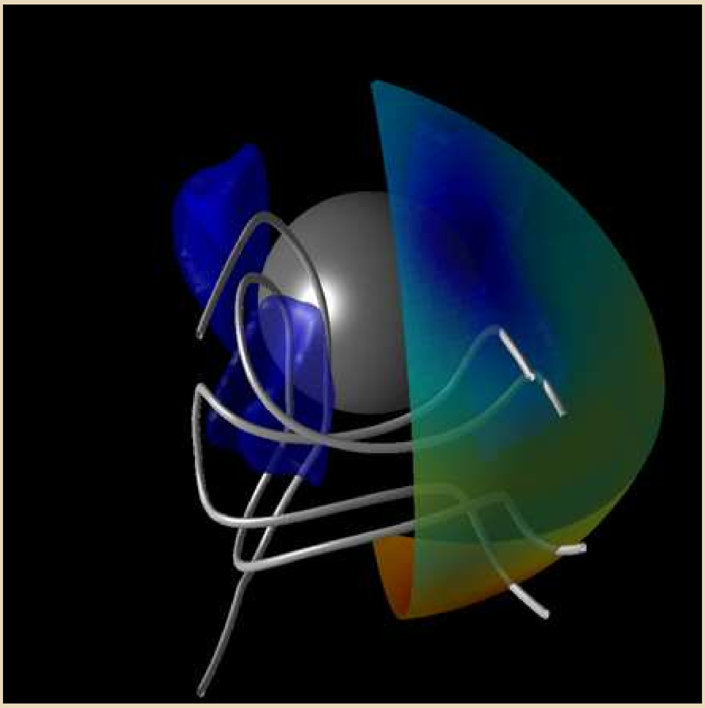
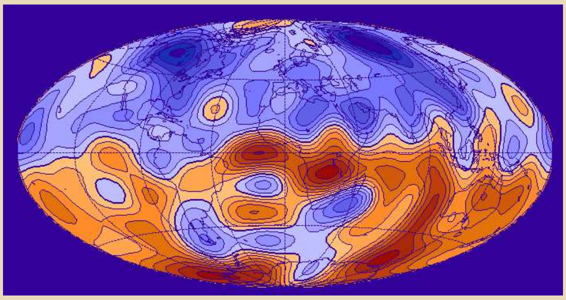
5– Solving the equations

- Navier Stokes (Boussinesq) equations + Maxwell equations = magnetohydrodynamic model

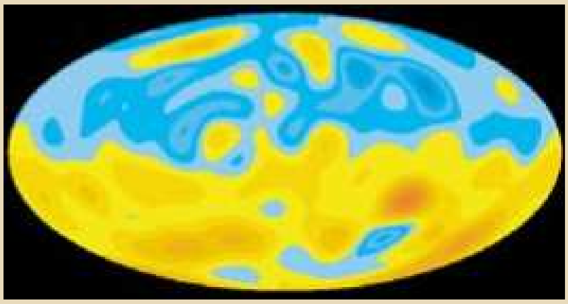


6– Success

- **explains the large scale space (> 1000 km) and time (>100 yrs) features of the geodynamo**

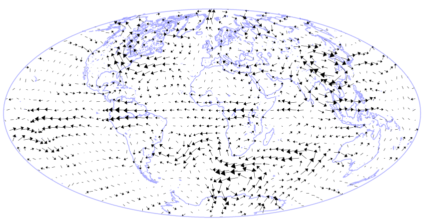


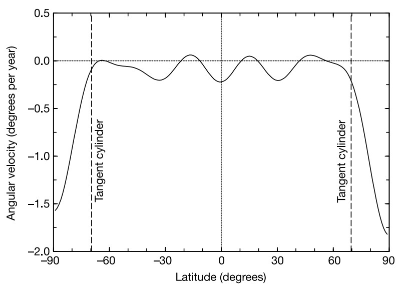
Model gufm1 for 1990



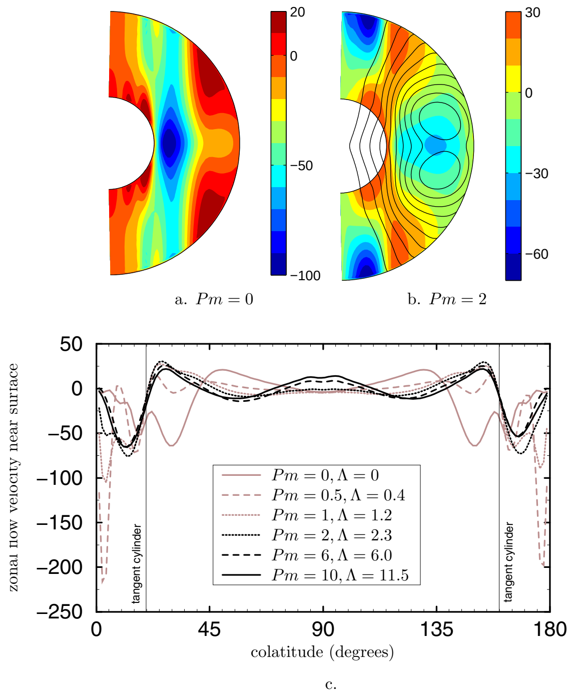
Glatzmaier-Roberts simulation

7– Invert for innner structure?





Hulot et al.

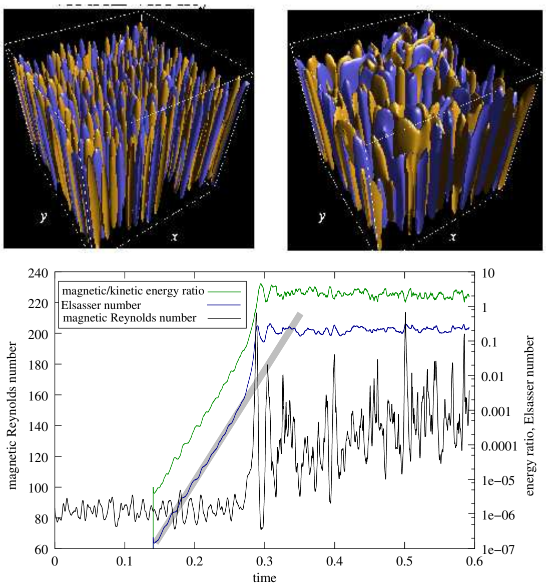


- **Surface measurement allows to infer inner magnetic structure and confirm dynamo mechanism.**

8– Challenges for future modelling

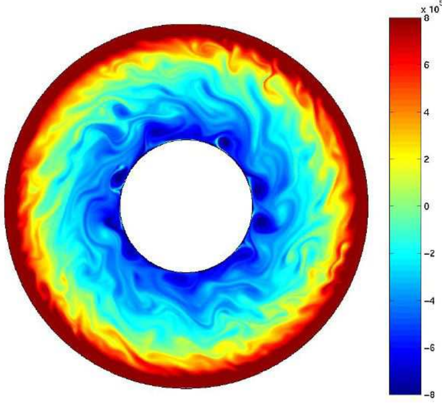
- **Are models wrong or lowpass-filtering reality? Need to have accurate ratio between viscous, thermal, compositional, magnetic time scales.**

local (box) model

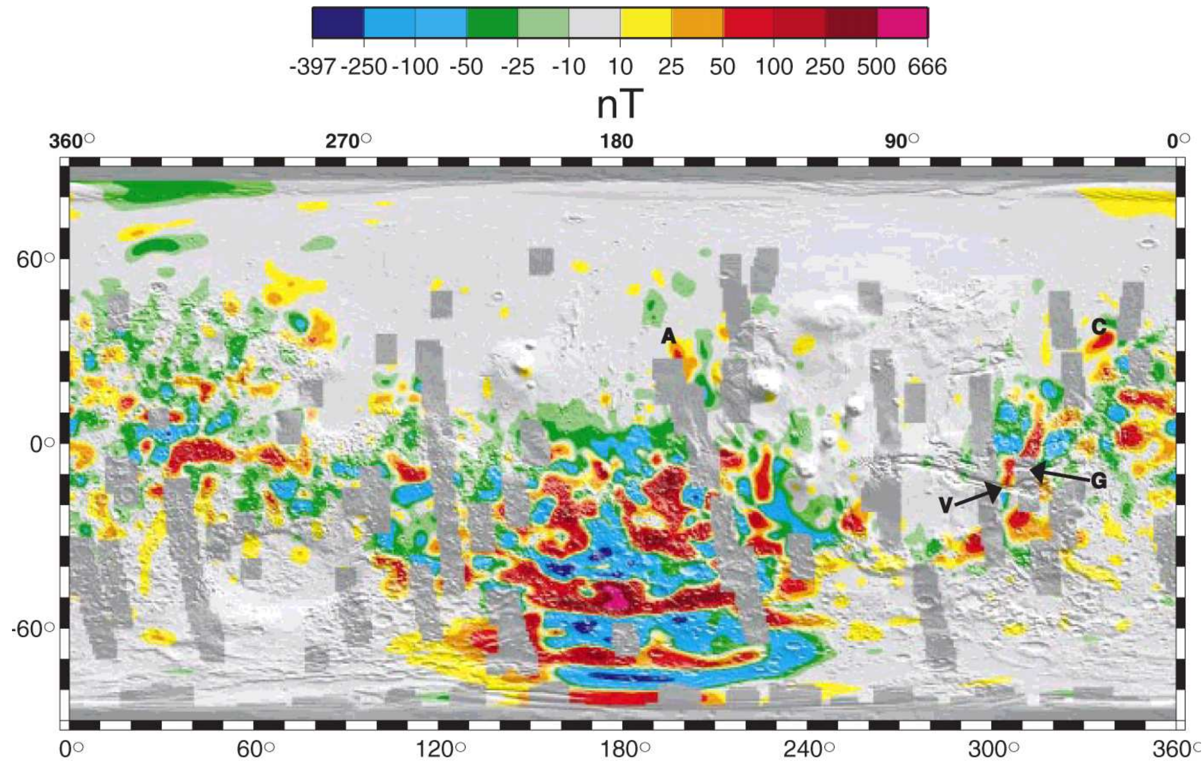


Stellmach et al.

global model with 2D approximation



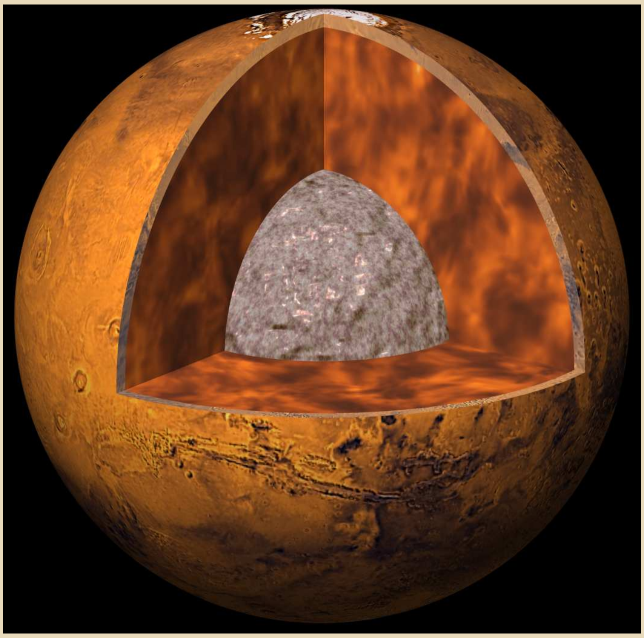
9– Mars: an ancient, short lived dynamo?



Mars Global Surveyor at 200 km altitude, Purucker et al.

10– Interior of Mars

- Mars has half the Earth's radius and an iron core which is at least partially liquid.



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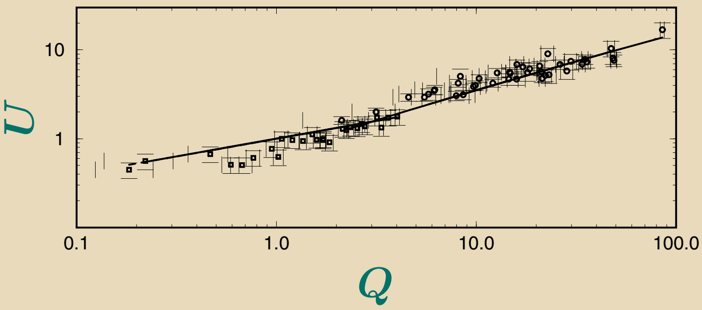
11– Scaling of dynamo constraints: velocity amplitude

- Magnetic Reynolds number $Re_m = UD/\lambda$ has to exceed 100 for a dynamo to work.
- convective velocities U have been scaled with heat flux Q in lab experiments:

$$U = \left(\frac{\alpha g}{\rho C_p \Omega D^3}\right)^{2/5} Q^{2/5}$$



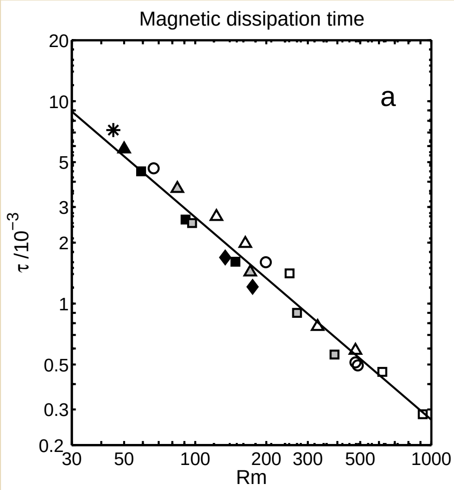
- dynamo condition implies $Q > 1$ GW which is very little above adiabatic, much less than typical adiabatic heat flux (~ 1 TW).
- So if there is core convection, a dynamo is extremely likely!

12– Scaling of dynamo constraints: Ohmic losses

- A working dynamo produces a lot of ohmic heat.
- Joule heating power Q_J has been scaled in numerical models:

$$\tau = \frac{E_m}{Q_J} \propto \frac{1}{Rem}$$

An asymptotic regime is reached (independant of the kinematic/magnetic diffusivity ratio): small-scale eddies dissipate a large-scale field.



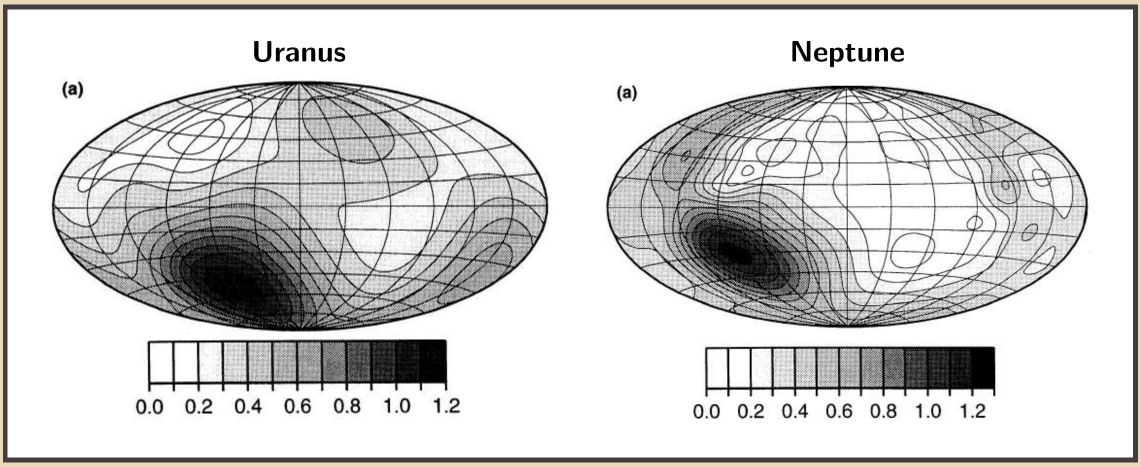
Christensen 2004

- $Q_J = 1 - 10$ TW has to be extracted from the energy sources. The onset of a dynamo is coincident with a sudden "power hunger" (cf Karlsruhe experiment).

13– Possibilities?

- Why hasn't Mars a dynamo today while Earth has one?
- Death of convection? Possible if plate tectonics stopped, if inner core formation was delayed in comparison to the Earth.
- Possible later turn-on of the dynamo, stopped due to a frozen core.
- In any case the thermal history of the core needs to be clarified. Q_J is a central unknown for this history.
- Scaling will help to better estimate dissipation from surface observations.
- Present models have a high potential because they show unexpected asymptotic convergence, a hint of the closeness with the physics of real systems.

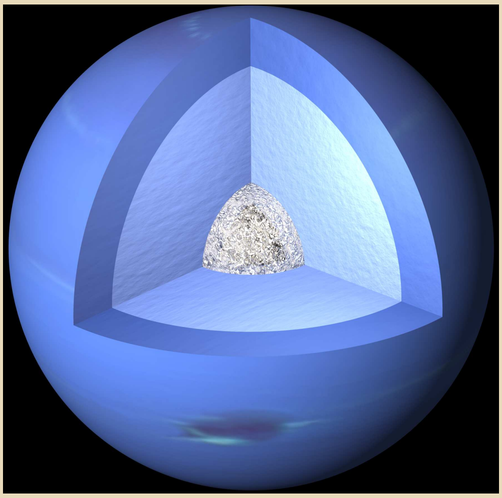
14– Remote & exotic: Uranus and Neptune

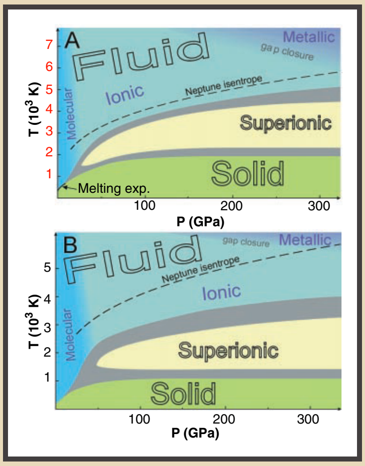


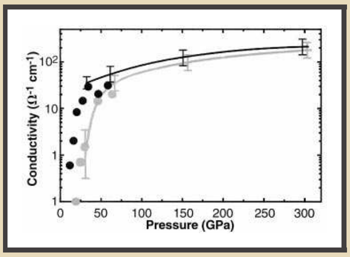
surface radial fields in gauss, Holme and Bloxham, Voyager II.

- Surface fields have a singular equatorial dipole + multipoles content.
- two instances mean that we are not “catching” a reversal.

15– Interior of Uranus/Neptune







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Cavazzoni et al.

- Dynamo action could take place in the middle conducting fluid ice layer.

16– The Elsasser Number mystery

- Planetary dynamos are believed to work in a

  Coriolis force $\sim$ Lorentz force

  equilibrium regime.

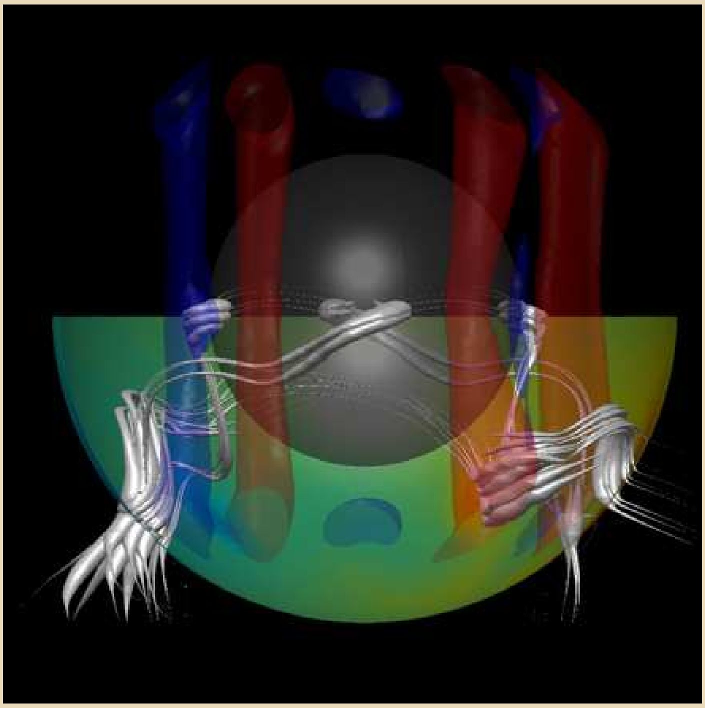
- The Elsasser number

  $$\Lambda = \frac{\sigma B^2}{\rho \Omega}$$

  measures the ratio of the two. This should always be of order 1 and provide a convenient way of scaling planetary magnetic fields...

- ... but $\Lambda \sim 1$ in the Earth, $\Lambda \sim 0.01$ in Uranus/Neptune. How can this be? More generally, how does an equatorial dipole dynamo work?

17– Equatorial dipole dynamo model



Magnetic tension in the normal/tangential vector basis

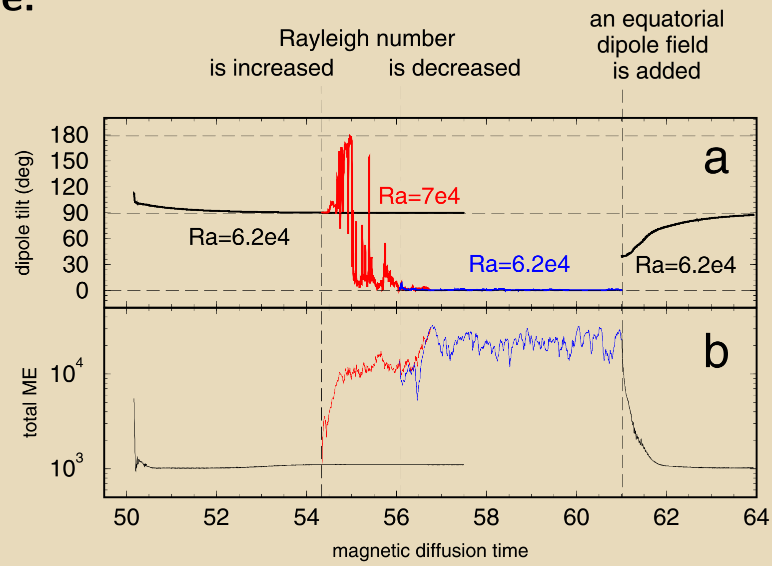
$$T = \frac{B^2}{R_c}\mathrm{e}_n + \frac{\partial}{\partial s}\left(\frac{B^2}{2}\right)\mathrm{e}_s$$

In this representation field line thickness is weighted with B^2.

- Where thickness varies, or where thick lines are curved, work is done against magnetic tension.

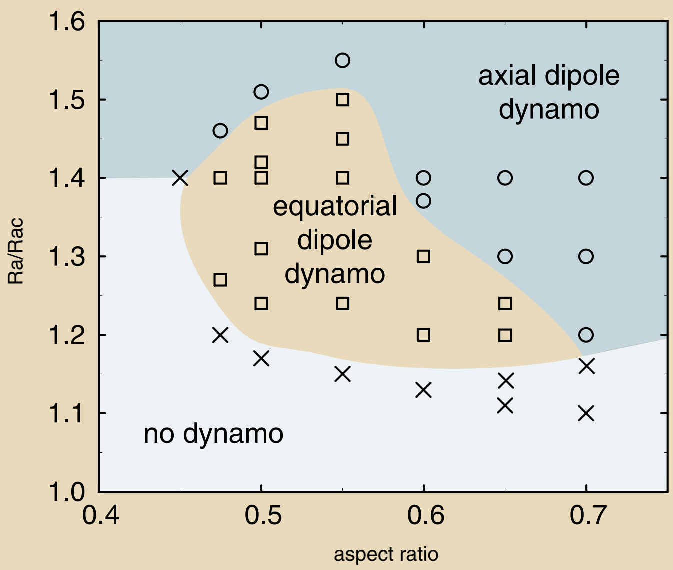
18– Model predictions

- **This model can be perturbed to yield either an axial, or an equatorial dipole.**



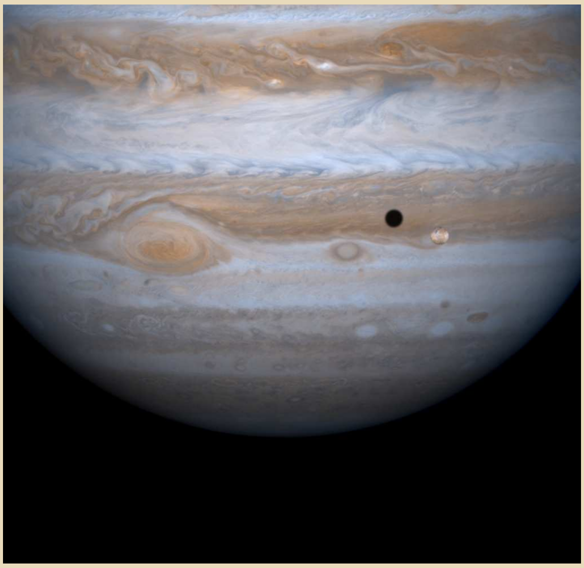
- **Dynamo is not efficient when dipole axis and rotation axis are orthogonal because of field line shear by vortices. Hence** $\Lambda_e/\Lambda_a = 0.05$.

19– Constraint on the size of the dynamo region?



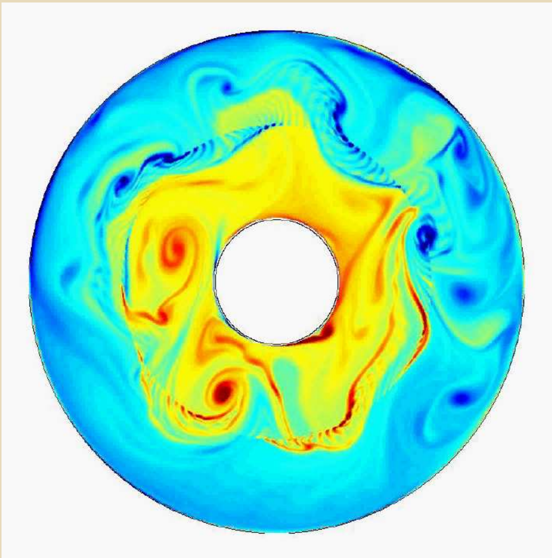
- **Exotic dynamos with equatorial dipoles and multipoles show when the dynamo shell is small. This could be a constraint for Uranus and Neptune.**

20– Zonal flows in the gas giants



- **The surface, and probably the deeper dynamo region of gas giants is swept by strong zonal flows.**

21– The origin of zonal flows



Potential vorticity

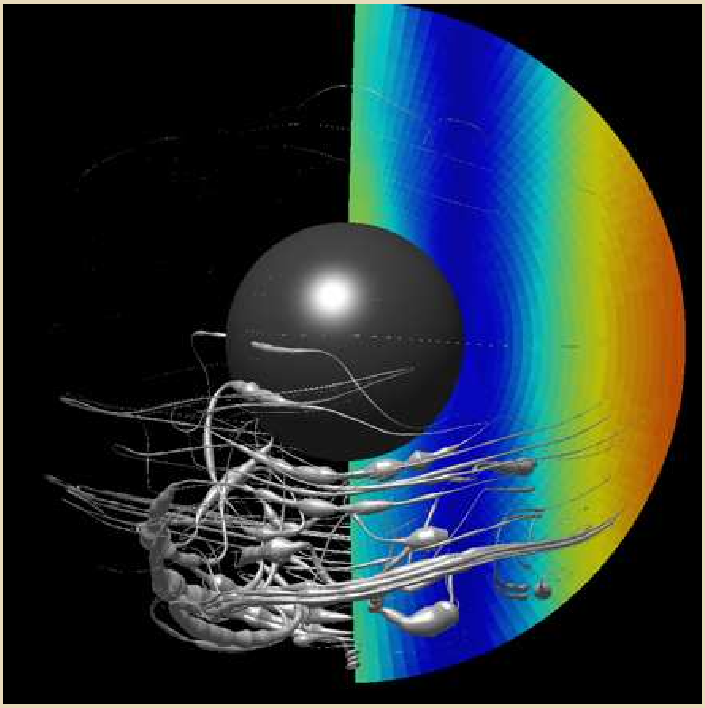
$$q = \frac{\omega + 2\Omega}{H}$$

q **is materially conserved and therefore develops regions with flat profiles. This means nonzero** ω **and therefore zonal flow.**

- **Zonal flows are the result of potential vorticity mixing by turbulence.**
- **This simply describes exchanges of angular momentum between the rotating frame and the fluid within.**

22– Dynamos with zonal flows

- The magnetic field of Saturn is highly axisymmetric, but Cowling theorem prevents dynamos producing axisymmetric fields.



- The surface field looks axisymmetric on surface,
- ...but is not deeper in the shell where dynamo action takes place.
- This dynamo requires free-slip boundaries and has a different mechanism from the previous models.

23– Finally...

- Other magnetic analyses have increased the payload of space missions, for instance the discovery of liquid water oceans under the surface of jovian satellites.
- Present numerical modelling has a large potential, especially with the upcoming planetary magnetic observations.
- The knowledge of the Earth dynamo benefits from this of other natural dynamos.
- Dynamo processes are intimely connected to surface and mantle geodynamics.