Dynamo experiments and simulations

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Planetary Interiors

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Recommended reading

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A brief history

1950s	Bullard and Gellman (1954)	First attempt at dynamo simulations
1960s	Lowes and Wilkinson (1963, 1968)	First dynamo experiments
	Malkus (1968)	First precession experiments
1990s	Glatzmaier and Roberts (1995); Kageyama et al. (1995)	First successful Earth-like simulations

A brief history

2000	Riga experiment (Gailitis et al., 2000)	Ponomarenko flow
2001	Karlsruhe experiment (Stieglitz and Müller, 2001)	G. O. Roberts flow
2002	VKS experiment (Bourgoin et al., 2002)	Von Kármán swirling flow
2005	First precession simulations (Tilgner, 2005)	First non-convective dynamo simulations
2006	Dynamo scaling laws (Christensen and Aubert, 2006)	

Why experiments?

- ✔ Observations and experiments are reality

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- ✘ More difficult to maintain
- ✘ "There are no save games in real life"

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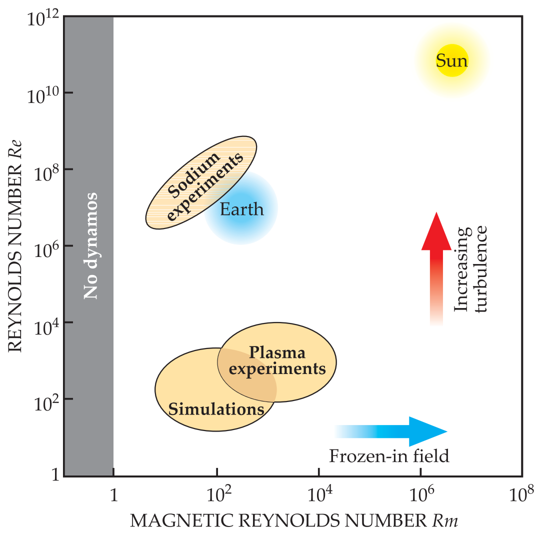
Parameter space



$$Re = \frac{UL}{\nu}$$

$$Rm = \frac{UL}{\eta}$$

Liquid sodium experiments

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Liquid sodium experiments

$$Rm = \frac{UL}{\eta}$$

$U \rightarrow$ More power

$L \rightarrow$ Make the experiment larger

$\eta = 1/\mu_0\sigma \rightarrow$ Make the fluid more conductive

Liquid sodium experiments

$$Rm = \frac{UL}{\eta}$$

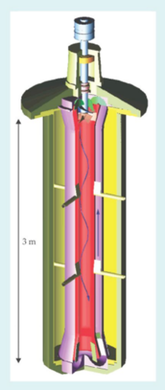
- Liquid sodium is the best electrically conducting liquid affordable in large volumes
- Magnetic diffusivity and viscosity similar to core conditions, $\eta \approx 0.1\,\mathrm{m}^2/\mathrm{s}, \nu \approx 10^{-6}\,\mathrm{m}^2/\mathrm{s}$
- It melts at $97^\circ\,\mathrm{C}$, so the experiments need a high operating temperature
- Hazardous to handle, highly reactive, requires specific set up, e.g.: water proof environment, fire extinguishing system, stainless steel flooring, dedicated alarm system etc.

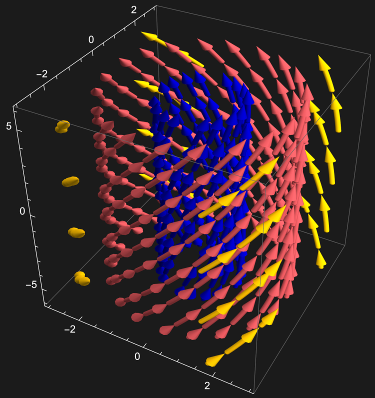
Liquid sodium experiments

$$Rm = \frac{U\,L}{\eta}$$

- Power requirements: "idealized" experiments (flow geometry forced to be very efficient at generating dynamos) create dynamos when $Rm > 100$. Typical size $L = 1\,\mathrm{m}$ and flow speed $U = 10\,\mathrm{m/s}$ requires $\sim 100\,\mathrm{kW}$ of power.
- $P \propto Rm^3$
- To reach astrophysical Rm, we would need $\sim 100\,\mathrm{MW}$ of power!

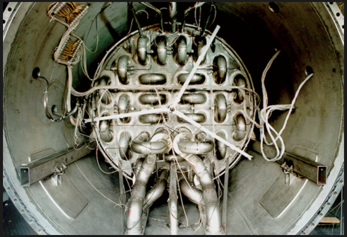
Riga experiment, 2000

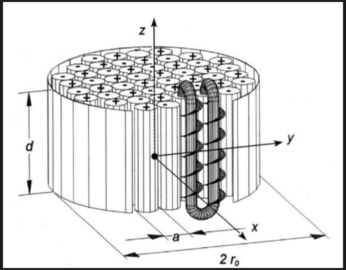


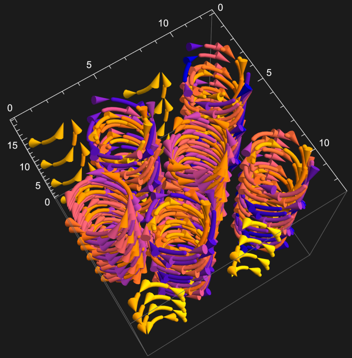


- First successful dynamo experiment with a liquid
- Based on “Ponomarenko flow”

Karlsruhe experiment, 2001

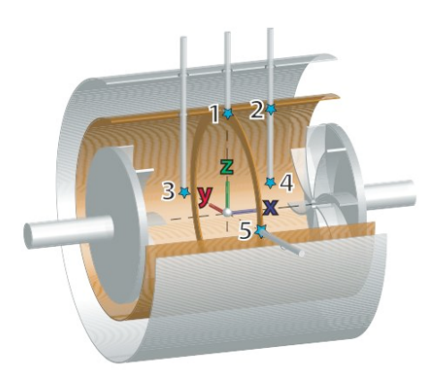






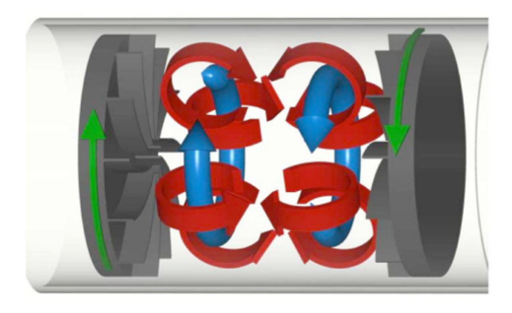
Based on “G. O. Roberts flow”

VKS experiment, Cadarache, 2002



- Also known as “French washing machine”
- A homogeneous cylinder instead of pipes, but uses propellers to drive the flow

VKS experiment, Cadarache, 2002

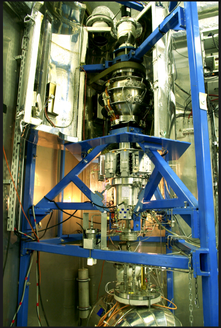


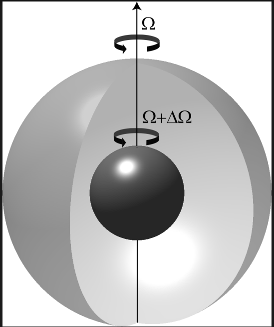
- VKS exhibited intermittent and steady dynamo states and chaotic Earth-like reversals
- Resulting dipolar field cannot be explained by mean (large scale) flows
- Dynamo action a result of differential rotation combined with coherent small-scale vortices at the edges of the propeller blades. Also needed to make the blades ferromagnetic to get dynamo action.

DYNAMO EXPERIMENTS

THE NEXT GENERATION

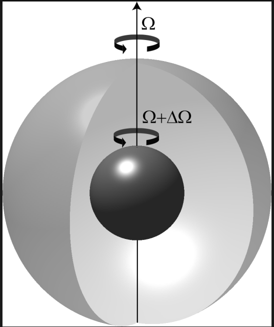
DTS experiment, Grenoble, France





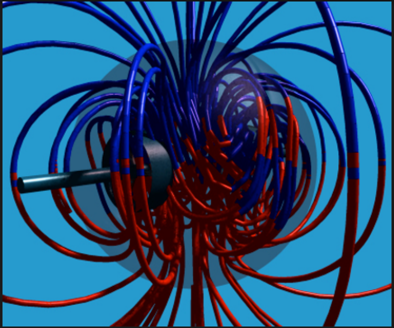
- Spherical shell (40 cm diameter) of liquid sodium surrounding highly magnetised inner solid sphere
- Uses "spherical Couette flow" - no propellers
- Has shown a wide variety of wave modes and jets due to Lorentz forces, but no self-excited dynamo

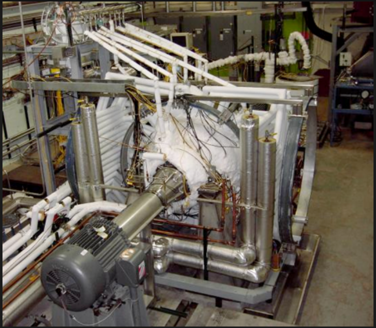
Maryland experiments



- spherical shells with increasing diameters (30 cm to 3 meter) have shown turbulent induction, and waves and modes restored by Coriolis and Lorentz forces
- the 3 meter experiments contains about 15 tons of liquid sodium
- no self-excited dynamo yet
- baffles installed on inner sphere for better coupling with the sodium

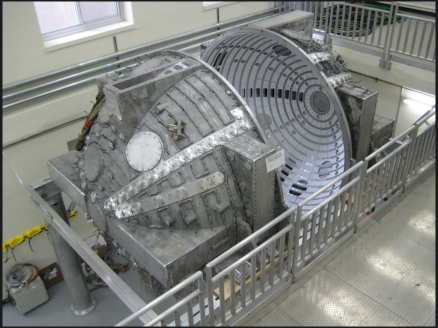
Wisconsin experiments

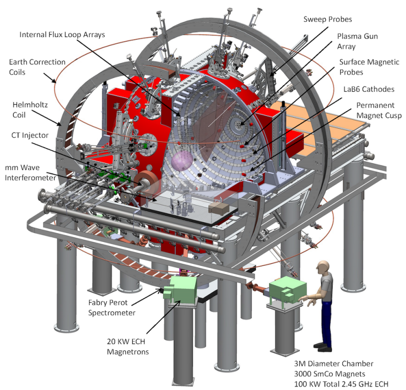




- spherical shell (1 meter diameter) drives flow with 2 propellers just at opposite poles
- goal is to achieve critical Rm for self-excitation
- hasn't reached it yet, but has shown how turbulence increases effective diffusivity thereby repressing field generation

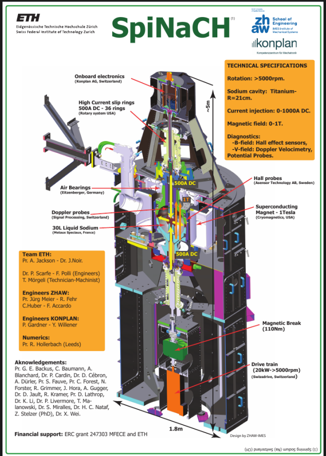
Big Red Ball (BRB), Madison, Wisconsin





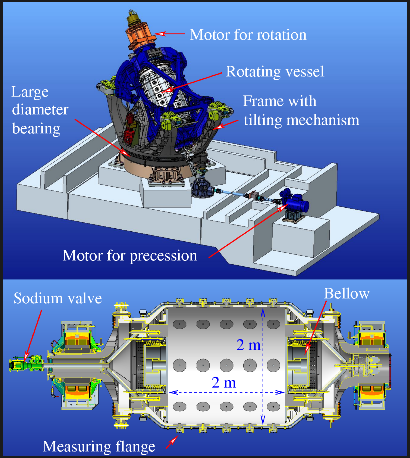
- 3 meter diameter experiment, earlier called MPDX (Madison Plasma Dynamo Experiment), now a multipurpose facility
- Uses plasma instead of liquid metal and can thus control the conductivity of fluid and thus η

SpiNaCH, ETH Zürich



Liquid sodium in a 42 cm diameter spherical cavity, capable of running at 5000 rpm

DRESDYN, Dresden, Germany



Liquid sodium in a precessing cylinder, 2 meter in both diameter and height

Experiments : summary

- no spherical (i.e. planet/star-like) geometry experiment has generated a self-sustained dynamo yet
- none of the experiments use buoyancy to drive the flow
- there are some smaller hydrodynamic experiments of convection in hemispheres that use centrifugal forces to mimic gravity
- lots of exciting progress to be made in the near future

Dynamo simulations

Equations, Boussinesq approximation

Momentum: $$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\nabla p - 2\Omega \hat{\boldsymbol{z}} \times \boldsymbol{u} + \alpha g T \hat{\boldsymbol{r}} + \frac{1}{\mu_0 \rho}(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} + \nu \nabla^2 \boldsymbol{u} \quad (1)$$

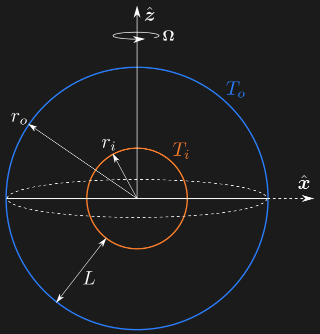
Induction: $$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{u} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B} \quad (2)$$

Energy: $$\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla T = \kappa \nabla^2 T + Q \quad (3)$$

Continuity + Maxwell: $$\nabla \cdot \boldsymbol{u} = 0, \nabla \cdot \boldsymbol{B} = 0 \quad (4)$$

- $\boldsymbol{u}$: velocity
- p : modified pressure
- Ω : rotation rate
- α : thermal expansion coefficient
- g : acceleration due to gravity
- T : temperature
- $\boldsymbol{B}$: magnetic field
- ν : viscosity
- η : magnetic diffusivity
- κ : thermal diffusivity
- Q : heat source/sink

Equations, Boussinesq approximation



Time scale : $\tau_\nu = L^2/\nu$

Length scale : $L = r_o - r_i$

Velocity scale : $L/\tau_\nu = \nu/L$

Temperature scale : Either $\Delta T = T_i - T_o$ or LdT/dr at a boundary

Equations, Boussinesq approximation

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\nabla p - \frac{2}{E}\hat{\boldsymbol{z}} \times \boldsymbol{u} + \frac{Ra}{Pr} T \left(\frac{r}{r_o}\right) \hat{\boldsymbol{r}} + \frac{1}{EPm}(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} + \nabla^2 \boldsymbol{u} \tag{5}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{u} \times \boldsymbol{B}) + \frac{1}{Pm}\nabla^2 \boldsymbol{B} \tag{6}$$

$$\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla T = \frac{1}{Pr}\nabla^2 T + Q \tag{7}$$

$$\nabla \cdot \boldsymbol{u} = 0, \nabla \cdot \boldsymbol{B} = 0 \tag{8}$$

Equations, Boussinesq approximation

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\nabla p - \frac{2}{E} \hat{\boldsymbol{z}} \times \boldsymbol{u} + \frac{Ra}{Pr} T \left(\frac{r}{r_o} \right) \hat{\boldsymbol{r}} + \frac{1}{EPm} (\nabla \times \boldsymbol{B}) \times \boldsymbol{B} + \nabla^2 \boldsymbol{u} \tag{9}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{u} \times \boldsymbol{B}) + \frac{1}{Pm} \nabla^2 \boldsymbol{B} \tag{10}$$

$$\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla T = \frac{1}{Pr} \nabla^2 T + Q \tag{11}$$

$$\nabla \cdot \boldsymbol{u} = 0, \nabla \cdot \boldsymbol{B} = 0 \tag{12}$$

Non-dimensional parameters

Parameter	Earth's core	Giant planets	Sun
Ekman number, $E = \dfrac{\nu}{\Omega L^2}$	10^{-15}	10^{-18}	10^{-15}
Rayleigh number, $Ra = \dfrac{\alpha_o g_o \Delta T L^3}{\nu\kappa}$	10^{27}	10^{30}	10^{24}
Prandtl number, $Pr = \dfrac{\nu}{\kappa}$	0.1	0.1	10^{-6}
Magnetic Prandtl number, $Pm = \dfrac{\nu}{\lambda}$	10^{-6}	10^{-7}	10^{-3}
Elsasser number, Λ (Lorentz/Coriolis)	1	1	?
Local Rossby number, Ro_l (Inertia/Coriolis)	10^{-2}	10^{-3}	1
Magnetic Reynolds number, Rm	1000	10^5	10^9
Reynolds number, Re	10^9	10^{12}	10^{12}

Non-dimensional parameters

Parameter	Earth's core	Tractable	Most extreme
Eman number, $E = \frac{\nu}{\Omega L^2}$	10^{-15}	$\geq 10^{-6}$	10^{-7}
Rayleigh number, $Ra = \frac{\alpha_o g_o \Delta T L^3}{\nu \kappa}$	10^{27}	$\leq 10^{12}$	10^{12}
Prandtl number, $Pr = \frac{\nu}{\kappa}$	0.1	0.1 - 10	1
Magnetic Prandtl number, $Pm = \frac{\nu}{\lambda}$	10^{-6}	0.1	0.1
Elsasser number, Λ (Lorentz/Coriolis)	1	1	3.7
Local Rossby number, Ro_l (Inertia/Coriolis)	10^{-2}	10^{-3} - 10^{-1}	0.01
Magnetic Reynolds number, Rm	1000	1000	514
Reynolds number, Re	10^9	100 - 1000	5140

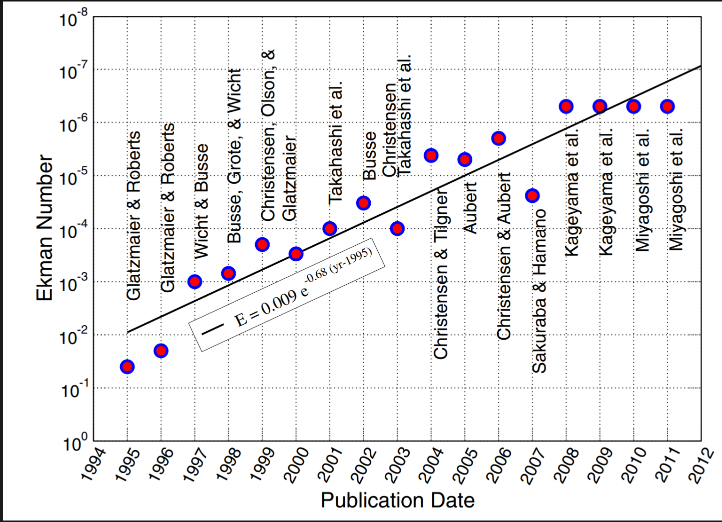
Non-dimensional parameters

Parameter	Earth's core	Simulations	Experiments
Eman number, $E = \frac{\nu}{\Omega L^2}$	10^{-15}	$\geq 10^{-6}$	$> 10^{-8}$
Rayleigh number, $Ra = \frac{\alpha_o g_o \Delta T L^3}{\nu \kappa}$	10^{27}	$\leq 10^{12}$	?
Prandtl number, $Pr = \frac{\nu}{\kappa}$	0.1	0.1 - 10	0.02 - 10
Magnetic Prandtl number, $Pm = \frac{\nu}{\lambda}$	10^{-6}	0.1	$> 10^{-5}$
Elsasser number, Λ (Lorentz/Coriolis)	1	1	< 1
Local Rossby number, Ro_l (Inertia/Coriolis)	10^{-2}	10^{-3} - 10^{-1}	> 0.1
Magnetic Reynolds number, Rm	1000	1000	$< 10^7$
Reynolds number, Re	10^9	100 - 1000	0 - 100

What can we get right?

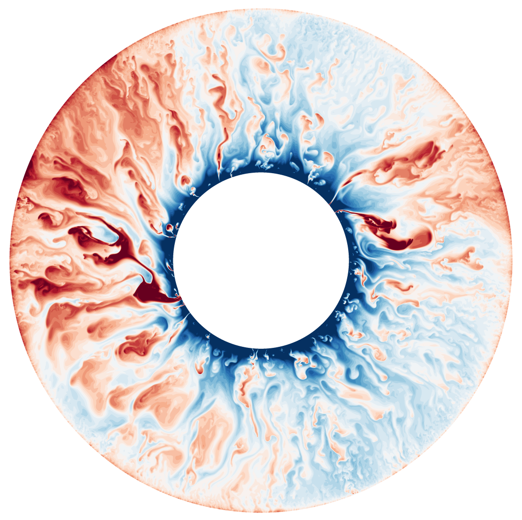
- Viscosity & thermal diffusivity too large compared to magnetic diffusivity
- Rotation too slow, much less turbulent
- Hope that if we are getting the force balances right, then models might be telling us something about core dynamics
- Scaling laws suggest this is happening (e.g. Christensen, 2010)

Can we get to Earth-like values?



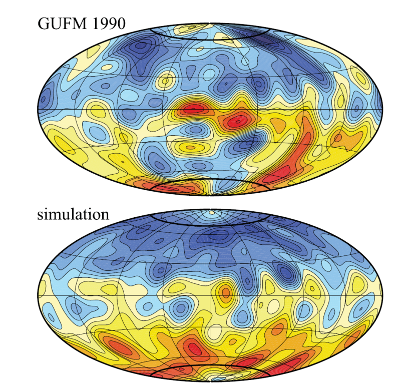
(Roberts and King, 2013)

Flow/field characteristics

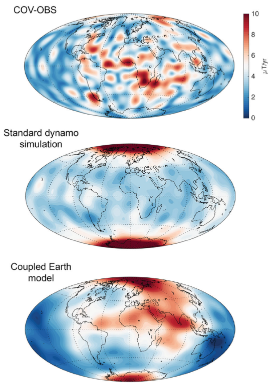


(Schaeffer et al., 2017)

Comparison with observations



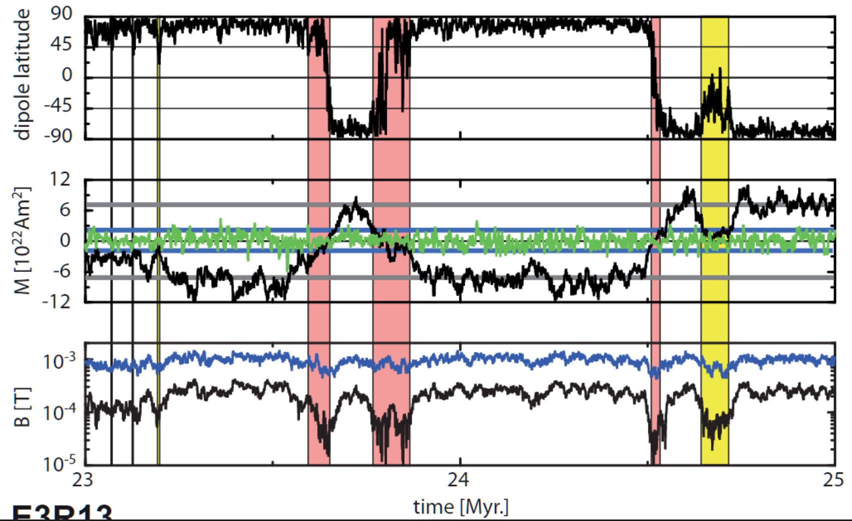
Surface field



Secular variation

(Wicht and Sanchez, 2019)

Comparison with observations



(Wicht and Meduri, 2016; Meduri et al., 2021)

Why does it work?

Why does it work?

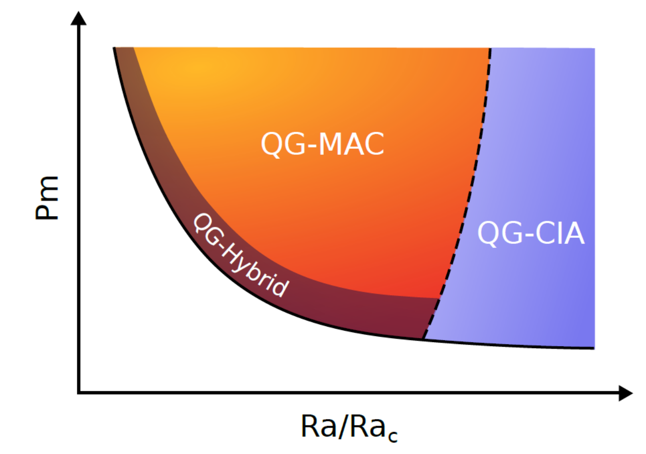
- Importance of rotation
- Force balance

Force balance

Importance of forces : Coriolis (C), Buoyancy (A), Magnetic (M), Inertia (I), Pressure and Viscosity

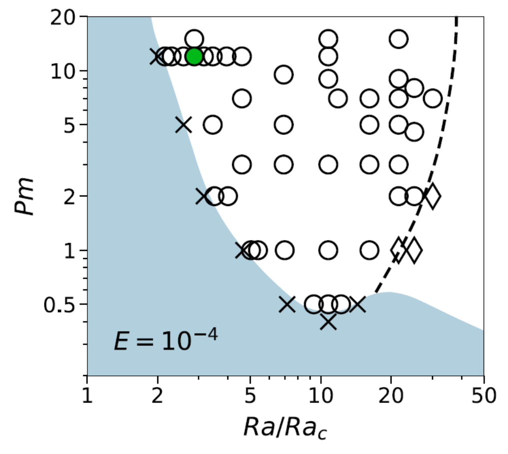
- Pressure and Coriolis forces form the leading order force balance : Quasi-geostrophy (QG)
- Other forces can lead to either MAC or a CIA balance
- Earth lies in a QG-MAC state (Aubert, 2020)
- Most advanced simulations progressively moving towards a better QG-MAC balance

Regime diagrams



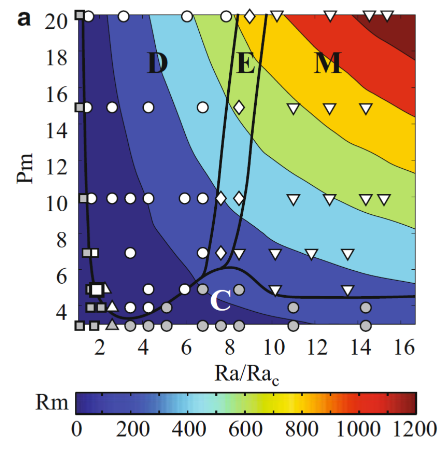
(Schwaiger et al., 2019)

Regime diagrams



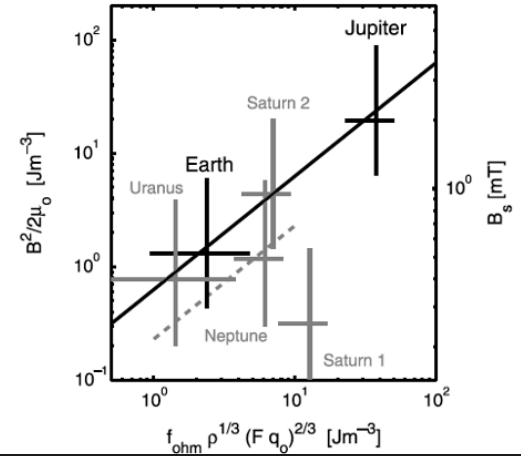
(Schwaiger et al., 2019)

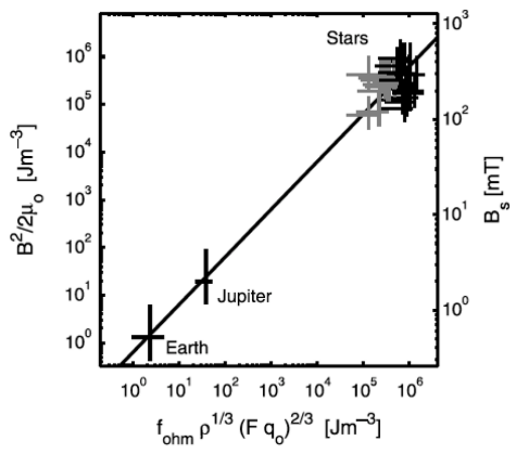
Regime diagrams



(Wicht et al., 2015)

Scaling laws

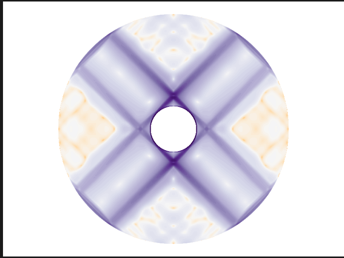




(Christensen, 2010)

Codes

MagIC
https://magic-sph.github.io/



XSHELLS
https://nschaeff.bitbucket.io/xshells

Rayleigh
https://rayleigh-documentation.readthedocs.io/

Simulations : summary

- Far away from planets in terms of parameters
- Can reproduce major features of planetary magnetic fields
- Correct force balance
- Can be used to obtain scaling laws applicable to planets and rapidly rotating stars
- Future of simulations lies in pushing more extreme parameters as well as adding new ingredients to models

Simulations : summary

- Several open source codes available!
- Feel free to download and run small models. :)

Summary

- Simulations and experiments complement each other
- Experiments provide observations that need to be reproduced by simulations
- Simulations can help understand experiments better by analysing the system in greater detail than experimentally possible (e.g. Barik et al., 2018)

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