Characterizing Jupiter's dynamo radius using its magnetic energy spectrum

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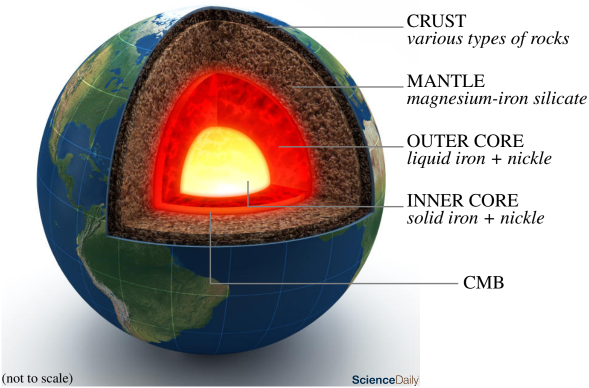
Let's start on Earth . . .



- **core-mantle boundary** (CMB): sharp boundary between the non-conducting mantle and the conducting outer core
  $\Rightarrow$ *fluid flow and dynamo action confined in the same region*
- **dynamo radius** $r_{\rm dyn}$: top of the dynamo region $\approx r_{\rm cmb}$
- one way to deduce $r_{\rm cmb}$ from observation at the surface: magnetic energy spectrum

Gauss coefficients g_{lm} and h_{lm}

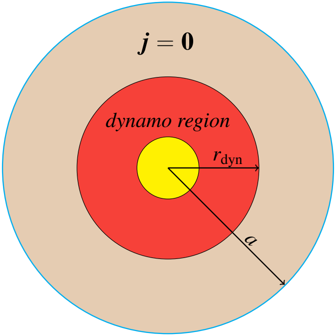
- Outside the dynamo region, $r > r_{\text{dyn}}$:

$$\boxed{\boldsymbol{j} = \mathbf{0}}$$

$$\nabla \times \boldsymbol{B} = \mu_0 \, \boldsymbol{j} = \mathbf{0} \implies \boldsymbol{B} = -\nabla\Psi$$

$$\nabla \cdot \boldsymbol{B} = 0 \implies \nabla^2\Psi = 0$$

$a =$ *radius of Earth*



- Consider only internal sources,

$$\Psi(r,\theta,\phi) = a \sum_{l=1}^{\infty} \sum_{m=0}^{l} \left(\frac{a}{r}\right)^{l+1} \hat{P}_{lm}(\cos\theta)(g_{lm}\cos m\phi + h_{lm}\sin m\phi)$$

$\hat{P}_{lm}$: *Schmidt's semi-normalised associated Legendre polynomials*

- g_{lm} and h_{lm} can be determined from magnetic field measured at the planetary surface $(r \approx a)$

The Lowes spectrum

- *Average magnetic energy* over a spherical surface of radius r

$$E_B(r) = \frac{1}{2\mu_0}\frac{1}{4\pi}\oint |\boldsymbol{B}(r,\theta,\phi)|^2 \sin\theta \, \mathrm{d}\theta \, \mathrm{d}\phi$$

- Inside the current-free region $r_{\mathrm{dyn}} < r < a$,

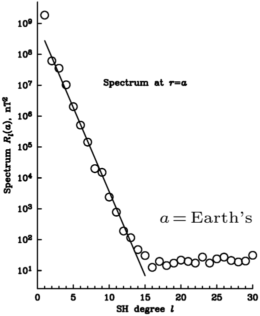
$$2\mu_0 E_B(r) = \sum_{l=1}^{\infty}\left[\left(\frac{a}{r}\right)^{2l+4}(l+1)\sum_{m=0}^{l}\left(g_{lm}^2 + h_{lm}^2\right)\right]$$

- **Lowes spectrum** (magnetic energy as a function of l):

$$R_l(r) = \left(\frac{a}{r}\right)^{2l+4}(l+1)\sum_{m=0}^{l}\left(g_{lm}^2 + h_{lm}^2\right)$$

$$= \left(\frac{a}{r}\right)^{2l+4} R_l(a) \qquad \text{(downward continuation)}$$

Estimate location of CMB using the Lowes spectrum



(Robert Parker, UCSD)

$$R_l(r_{\text{cmb}}) = \left(\frac{a}{r_{\text{cmb}}}\right)^{2l+4} R_l(a)$$

- downward continuation from a to r_{cmb} through the mantle ($\boldsymbol{j} = \mathbf{0}$):

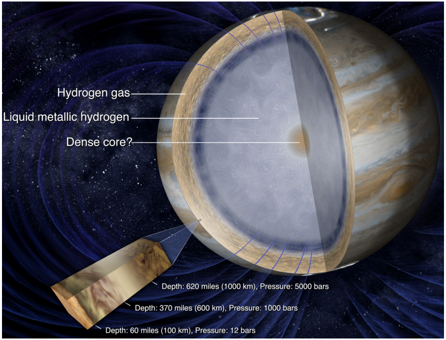
$$\ln R_l(a) = 2\ln\left(\frac{r_{\text{cmb}}}{a}\right) l + 4\ln\left(\frac{r_{\text{cmb}}}{a}\right) + \ln R_l(r_{\text{cmb}})$$

- **white source hypothesis**: turbulence in the core leads to an *even distribution of magnetic energy* across different scales l,

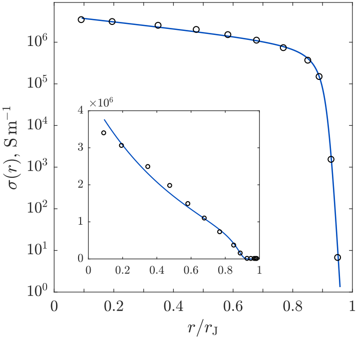
  $R_l(r_{\text{cmb}})$ is independent of l

- $r_{\text{cmb}} \approx 0.55a \approx 3486\,\text{km}$ agrees well with results from seismic waves observations

Interior structure of Jupiter



(NASA JPL)

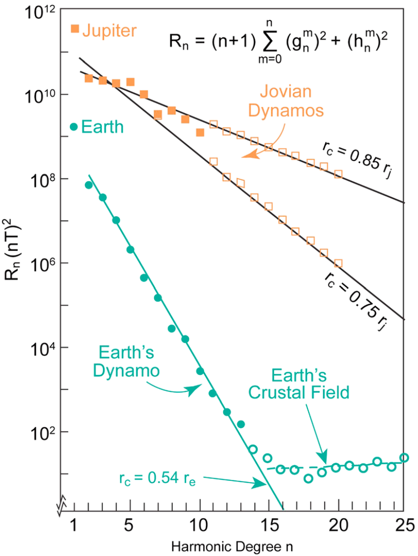


Theoretical $\sigma(r)$ by French et al. (2012)

- gaseous molecular H/He → liquid metallic H → core?
- transition from molecular to metallic hydrogen is continuous
- **conductivity** $\sigma(r)$ varies smoothly with radius r
- dynamo region $\neq$ region of fluid flow

At what depth does dynamo action start?

Lowes spectrum from the Juno mission



(Connerney et al. 2018)

- Juno's spacecraft reached Jupiter on 4th July, 2016
- currently in a 53-day orbit, until (at least) July 2021
- $R_l(r_J)$ up to $\boldsymbol{l = 10}$ from recent measurement (8 flybys)
- Lowes' radius: $r_{\text{lowes}} \approx 0.85\, r_{\text{J}}$ ($r_{\text{J}} = 6.9894 \times 10^7 \text{m}$)

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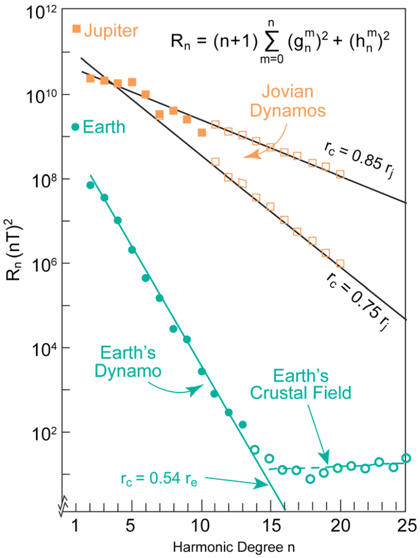

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Questions: with the conductivity profile $\sigma(r)$ varying smoothly,

- meaning of r_{lowes}? $r_{\text{lowes}} = r_{\text{dyn}}$?
- white source hypothesis valid?
- concept of "dynamo radius" r_{dyn} well-defined?

A numerical model of Jupiter

- spherical shell of radius ratio $r_{\text{in}}/r_{\text{out}} = 0.0963$ (small core)
- anelastic: linearise about a hydrostatic adiabatic basic state $(\bar{\rho}, \bar{T}, \bar{p}, \ldots)$
- rotating fluid with electrical conductivity $\sigma(r)$ driven by buoyancy
- convection driven by secular cooling of the planet
- dimensionless numbers: Ra, Pm, Ek, Pr

$$\nabla \cdot (\bar{\rho}\boldsymbol{u}) = 0$$

$$\frac{Ek}{Pm}\left[\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u}\right] + 2\hat{\boldsymbol{z}} \times \boldsymbol{u} = -\nabla\Pi' + \frac{1}{\bar{\rho}}(\nabla\times\boldsymbol{B})\times\boldsymbol{B} - \left(\frac{EkRaPm}{Pr}\right) S \frac{\mathrm{d}\bar{T}}{\mathrm{d}r}\hat{\boldsymbol{r}} + Ek\frac{\boldsymbol{F}_\nu}{\bar{\rho}}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla\times(\boldsymbol{u}\times\boldsymbol{B}) - \nabla\times(\eta\nabla\times\boldsymbol{B})$$

$$\bar{\rho}\bar{T}\left(\frac{\partial S}{\partial t} + \boldsymbol{u}\cdot\nabla S\right) + \frac{Pm}{Pr}\nabla\cdot\boldsymbol{\mathcal{F}}_Q = \frac{Pr}{RaPm}\left(Q_\nu + \frac{1}{Ek}Q_J\right) + \frac{Pm}{Pr}H_S$$

Boundary conditions: no-slip at r_{in} and stress-free at r_{out}, $S(r_{\text{in}}) = 1$ and $S(r_{\text{out}}) = 0$, electrically insulating outside $r_{\text{in}} < r < r_{\text{out}}$. (Jones 2014)

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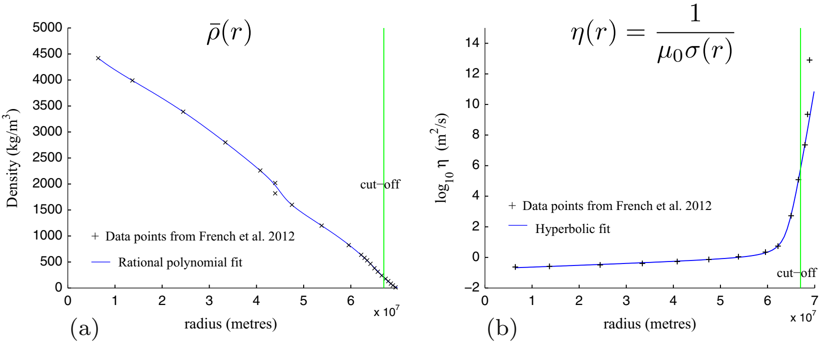
- **a Jupiter basic state:**

C.A. Jones / Icarus 241 (2014) 148–159

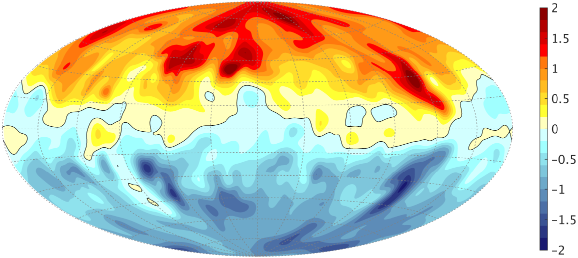


$Ra = 2 \times 10^7, \; Ek = 1.5 \times 10^{-5}, \; Pm = 10, \; Pr = 0.1$

radial magnetic field, $B_r(r, \theta, \phi)$

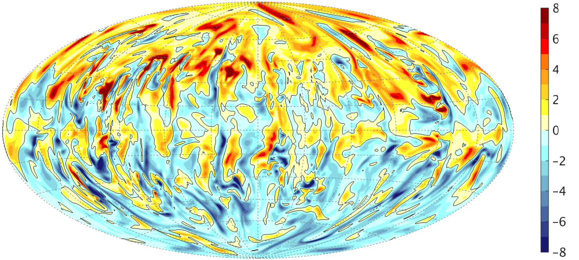
$r = r_{\text{out}}$

dipolar

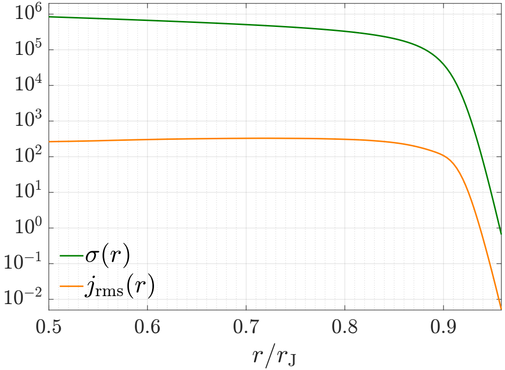


$r = 0.75 r_{\text{out}}$

small scales



Where does the current start flowing?



- average current over a spherical surface of radius r

$$\mu_0 \boldsymbol{j} = \nabla \times \boldsymbol{B}$$

$$j_{\rm rms}^2(r,t) \equiv \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi} |\boldsymbol{j}|^2 \sin\theta \, \mathrm{d}\theta \, \mathrm{d}\phi$$

- $j_{\rm rms}$ drops quickly but smoothly in the transition region, no clear indication of a characteristic “dynamo radius”

Magnetic energy spectrum, $F_l(r)$

- average magnetic energy over a spherical surface:

$$E_B(r) = \frac{1}{2\mu_0}\frac{1}{4\pi}\oint |\boldsymbol{B}(r,\theta,\phi)|^2 \sin\theta \, \mathrm{d}\theta \, \mathrm{d}\phi$$

- Lowes spectrum: recall that if $\boldsymbol{j} = \boldsymbol{0}$, we solve $\nabla^2\Psi = 0$, then

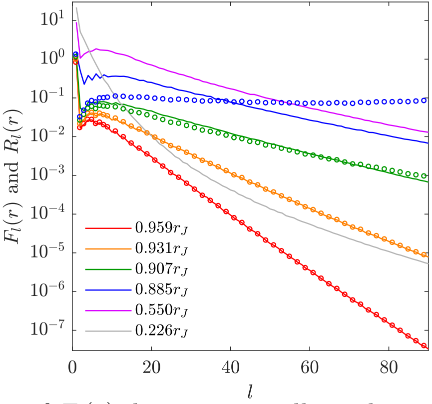
$$2\mu_0 E_B(r) = \sum_{l=1}^{\infty} \left[\left(\frac{a}{r}\right)^{2l+4} (l+1) \sum_{m=0}^{l} \left(g_{lm}^2 + h_{lm}^2\right) \right] = \sum_{l=1}^{\infty} R_l(r)$$

- generally, for the numerical model, $\boldsymbol{B} \sim \sum_{lm} b_{lm}(r) Y_{lm}(\theta,\phi)$,

$$2\mu_0 E_B(r) = \frac{1}{4\pi}\oint |\boldsymbol{B}(r,\theta,\phi)|^2 \sin\theta \, \mathrm{d}\theta \, \mathrm{d}\phi = \sum_{l=1}^{\infty} F_l(r)$$

$$\boldsymbol{j}(r,\theta,\phi) = \boldsymbol{0} \;\; \text{exactly} \implies R_l(r) = F_l(r)$$

Magnetic energy spectrum at different depth r



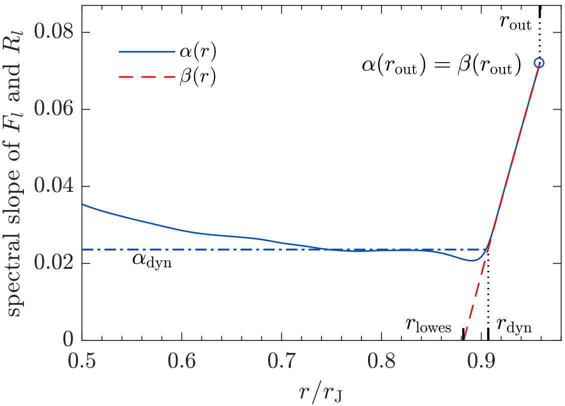
log–linear plot

$F_l(r)$: solid lines

$R_l(r)$: circles

- $r > 0.9r_\mathrm{J}$: slope of $F_l(r)$ decreases rapidly with r
  $r < 0.9r_\mathrm{J}$: $F_l(r)$ maintains the same shape and slope
  $\Rightarrow$ a shift in the dynamics of the system at $0.9r_\mathrm{J}$
- $r > 0.9r_\mathrm{J}$: $F_l(r) \approx R_l(r)$
  $r < 0.9r_\mathrm{J}$: $F_l(r)$ deviates from $R_l(r)$
  $\Rightarrow$ electric current becomes important below $0.9r_\mathrm{J}$
- suggests a dynamo radius $r_\mathrm{dyn} \approx 0.9r_\mathrm{J}$

Spectral slope of $F_l(r)$ and $R_l(r)$



$\log_{10} F_l(r) \sim -\alpha(r) l$

$\log_{10} R_l(r) \sim -\beta(r) l$

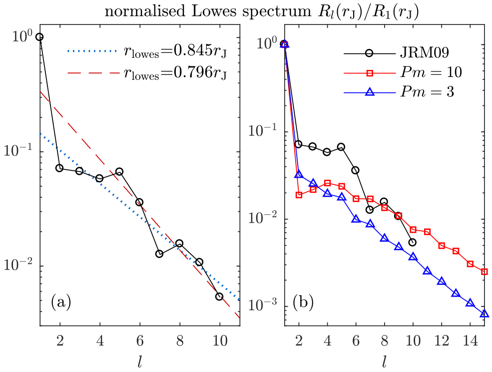
$R_l(r) = \left(\frac{r_{\rm out}}{r}\right)^{2l+4} R_l(r_{\rm out})$

$\beta(r) = \beta(r_{\rm out}) - 2\log_{10}\frac{r_{\rm out}}{r}$

- sharp transition in $\alpha(r)$ indicates $r_{\rm dyn} = 0.907 r_{\rm J}$
- $F_l(r)$ inside dynamo region is not exactly flat ($\alpha_{\rm dyn} = 0.024$): white source assumption is only approximate
- $r_{\rm lowes}$ provides a lower bound to $r_{\rm dyn}$: $\beta = 0$ at $r_{\rm lowes} = 0.883$

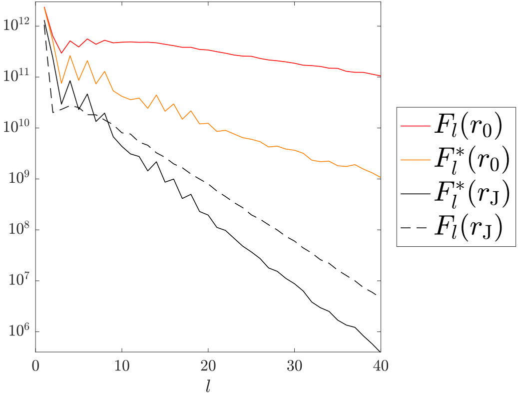
General picture: $\alpha(r_{\rm out})$ and $\alpha_{\rm dyn}$ control $r_{\rm dyn}$ and $r_{\rm lowes}$

Comparison with Juno data: a conundrum



- uncertainties in Juno data ⇒ slope depends on fitting range ($r_{lowes} \sim 0.8 - 0.85\, r_J$)
- spectrum of Pm=10 simulation ($r_{lowes} \sim 0.883\, r_J$) shallower than Juno observation
- reducing Pm leads to steeper spectrum ($r_{lowes} \sim 0.865$ at Pm=3)
- increasing Pm supposedly moves towards Jupiter condition !? Possible answers:
  - the actual electrical conductivity inside Jupiter is smaller than predicted by theoretical calculation?
  - our numerical model has more small-scale forcing than Jupiter does
  - the existence of a stably stratified layer below the molecular layer

Effects of a stable layer: a schematic



Imagine there is a stable layer between $r_0 = 0.89 r_J$ and $r_s = 0.91 r_J$

- $F_l(r_0)$ from $Pm = 10$ simulation
- filtering: $\mathbf{B}(r_0, \theta, \phi) * H_{low} \to F_l^*(r_0)$; $\quad \tilde{H}_{low} \sim \exp(-\gamma\sqrt{m})$
- $F_l(r_s) \equiv F_l^*(r_0)$; $\quad F_l^*(r_J) = \left(\frac{r_s}{r_J}\right)^{2l+4} F_l(r_s) \;\Rightarrow\; r_{lowes} = 0.85 r_J$

Tsang & Jones, Earth Planet. Sci. Lett. (2019). doi.org/10.1016/j.epsl.2019.115879