Core-mantle boundary processes: Investigating geodynamo models with lateral variations in electrical conductivity at the core-mantle boundary

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Motivation

❖Seismic tomography of the lower mantle has revealed large scale anomalously slow wave-speed features, especially below the Pacific and Africa [1,2].

❖These **seismically slow anomalies** could be structures of either thermal or thermochemical origin and are thought to be hotter than the ambient mantle [3,4].

❖Some studies have suggested that the **LLVPs and ULVZs might be partially molten** and/or contain Fe-rich melts [5].

❖ The presence of (metallic/silicate) **melt can increase the electrical conductivity** at the CMB [6] → the lower mantle is **not** a perfect insulator (maybe at least on short timescales)

Question:

What spatial and temporal changes will we see in the Earth's magnetic field if the mantle has a finite electrical conductivity?

How will flows at the top of the core be affected in the presence of an electrically conducting layer?

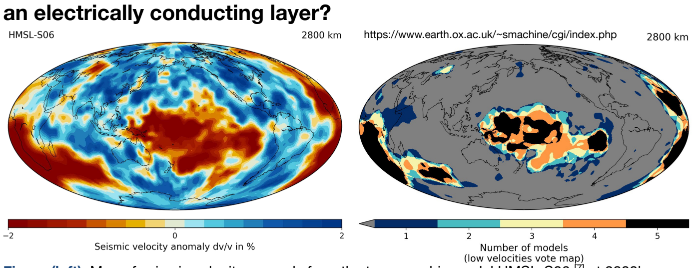
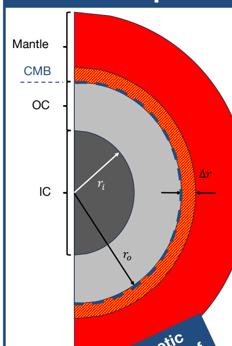


Figure (left): Map of seismic velocity anomaly from the tomographic model HMSL-S06 [7] at 2800km below the Earth's surface.
Figure (right): Areas where five different seismic velocity models agree on the position of slow seismic anomalies at 2800km below the Earth's surface.

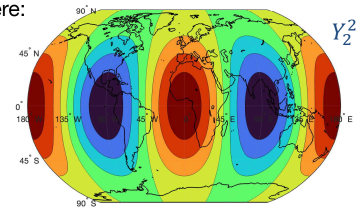
Model Setup – Geodynamo Simulations in XSHELLS [8]



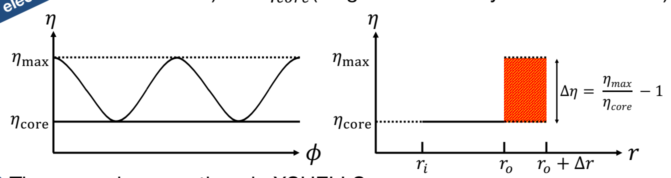
Remember that magnetic diffusivity (η) is the inverse of electrical conductivity (σ)

❖Add a thin layer of conductivity at the top of the CMB (shown on the left)

❖Include a Y_2^2 pattern of lateral heterogeneity at the top of the core to mimic the large scale pattern of the seismic anomalies, shown here:



❖The Y_2^2 pattern is implemented as an oscillating layer of Δr thickness between η_{max} (imposed diffusivity threshold) and η_{core}(magnetic diffusivity of the outer core):



❖The governing equations in XSHELLS are:

$$\partial_t \boldsymbol{u} + (2\boldsymbol{\Omega} + \nabla\times\boldsymbol{u})\times\boldsymbol{u} = -\nabla p^* + \nu\nabla^2\boldsymbol{u} + (\nabla\times\boldsymbol{b})\times\boldsymbol{b} + T\nabla\Phi_0$$
$$\partial_t \boldsymbol{b} = \nabla\times(\boldsymbol{u}\times\boldsymbol{b} - \eta\nabla\times\boldsymbol{b})$$
$$\partial_t T + \boldsymbol{u}\cdot\nabla(T + T_0) = \kappa\nabla^2 T$$
$$\nabla\cdot\boldsymbol{u} = 0 \qquad \nabla\cdot\boldsymbol{b} = 0$$

❖We start with an existing insulating mantle case to see the effect of applying the heterogeneity. Their (and our) parameter space and initial conditions are below:

$$Ek = \frac{\nu}{\Omega D^2} = 10^{-3}$$
$$Pm = \frac{\nu}{\eta_{core}} = 5$$
$$Ra = \frac{\alpha g \Delta T D}{\nu\Omega} = 100$$
$$Pr = \frac{\nu}{\kappa} = 1$$

$$T = \frac{r_o r_i}{r} - r_i + \frac{21}{\sqrt{17920\pi}}\times(1 - 3x^2 + 3x^4 - x^6)\sin^4\theta\cos 4\phi$$
$$b_r = \frac{5}{8}\left(8r_0 - 6r - 2\frac{r_i^4}{r^3}\right)\cos\theta$$
$$b_\theta = \frac{5}{8}\left(9r - 8r_0 - \frac{r_i^4}{r^3}\right)\sin\theta$$
$$b_\phi = 5\sin\big(\pi(r - r_i)\big)\sin 2\theta$$

$$\boldsymbol{u} = \boldsymbol{0}$$
$$x = 2r - r_i - r_0$$

Parameters from Christensen et al, 2001[9]

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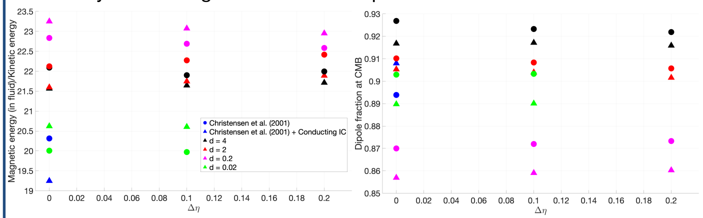
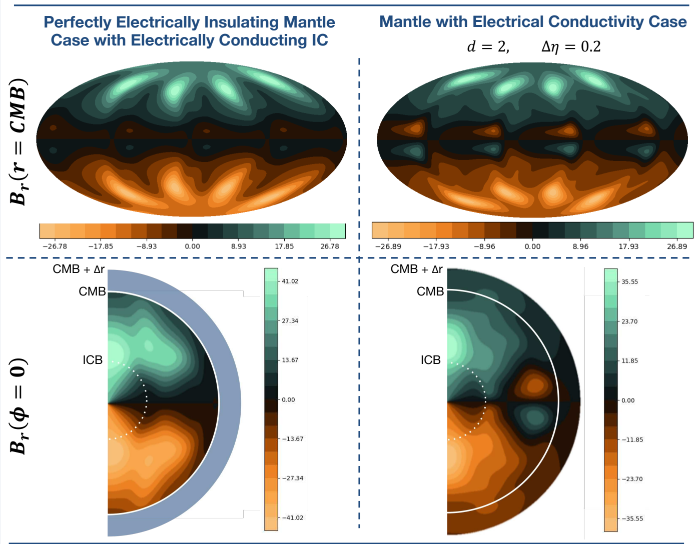
Preliminary Results

We investigated the parameter space by varying the amplitude of the heterogeneity and the thickness of the electrically conducting layer:

Variables		Boundary Conditions
$\Delta\eta$	$d\ (= \frac{13 * \Delta r}{r_0 - r_i})$	No slip and fixed temperature at CMB and ICB
0 , 0.1 , 0.2 , 0.4 , 0.6 , 0.8	0.02 , 0.2 , 2 , 4	

The resulting outputs indicate that the presence of an electrically conducting layer at the CMB seems to increase the ratio of magnetic energy to kinetic energy within the fluid region, and whether the simulations have an electrically conducting inner core can impact the results:





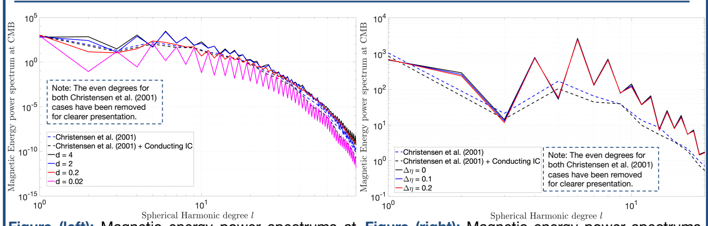


Figure (left): Magnetic energy power spectrums at the CMB for constant $\Delta\eta (= 0.1)$ but varying d. **Figure (right):** Magnetic energy power spectrums at the CMB for constant $d (= 2)$ but varying $\Delta\eta$.

Future Directions

❖Cross-verification of results with other dynamo codes

❖Explore larger parameter space e.g. lower Ek and Pm, larger Ra, different spatial patterns in electrical conductivity variations

❖Combine and contrast lateral variations in heat flux and electrical conductivity at the CMB.

❖Investigate in more depth how these heterogeneities can affect geomagnetic reversal frequencies, field strength, and secular variations

❖Consider whether stronger electromagnetic coupling between the core and lower mantle can increase ohmic dissipation in the Earth

References

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