Behavior at the boundaries of our world:
What can we learn about core and mantle dynamics
from long and short period seismology?

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Earth’s outer core

Important role in Earth’s dynamics:
• Generation of the geodynamo;
• Provides heat to the mantle – part of the power source for plate tectonics.
• Is there stratification at the top? If so, why, when and how?

Existing seismological models of the outer core are not perfect. They are:
• Parameterized for simplicity, not grounded in physics;
• Based on older data;
• Show disagreement between body wave and normal mode based models;
• Therefore less useful for other scientists.

Velocity models published 1975–2010. Based on modes & body waves, or body waves alone.

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- Look for the outer core's Equation of State, relating its bulk modulus and molar volume → we get velocity and density.
- We end up with a physics based parameterisation.
- We can also use new data!
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Inversion for EoS & Seismic Parameters

Mode $S_3$ 
period ~ 18 minutes
Inversion for EoS & Seismic Parameters

Mode $_1S_3$
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Goal: isentropic Vinet EoS & seismic model which best describe the data.

Mode $\nu S_3$
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(1) Choose values of $K_{0S}$, $K'_{0S}$, and $V_0$ using PyMc
(molar mass assumed to be 0.05kg)

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(2) Using these EoS parameters, predict the outer core’s $v_p$, $\rho$, using Burnman.

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Elastic Parameters of the Outer Core: EPOC–Vinnet

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Uppermost outer core structure – an E' layer?
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- A large number of E' velocity models exist, nearly all are slower than PREM.
- Some of these models suggest a seismically anomalous layer. Our model explains the mode data with a smooth curve. But a layer might still be present!
Uppermost outer core structure – an E’ layer?

- The name E’ follows Bullen’s layer-naming convention
- Called the “Hidden Ocean of the Core” by Braginsky
- Buffett (2014, figure right) shows that estimates of flow at the surface of the outer core are predicted well by MAC waves; a 140 km thick layer works.
- May be the cause of signals in satellite observations of Earth’s magnetic field (Vidal and Schaeffer, 2015); and present in geomagnetic ‘jerk’ data (Chulliat et al., 2015).
- Other studies prefer no stratification, or cannot see its effect.

Figure 1 | Schematic illustration of the wave motion. Radial motion $V_r$ causes a pressure perturbation, which drives an azimuthal flow $V_\theta$ in the stratified layer. The presence of a radial magnetic field opposes $V_w$ and induces a meridional flow $V_h$. The fluid velocities reverse direction over a full cycle of the wave.
Permitting variation in D'' properties and an E' layer

EPOC–Vinet has 3 parameters
Permitting variation in D'' properties and an E' layer

- Using the same methodology, we can:
  - allow a distinct E’ layer, where $v_p$ and $\rho$ diverge from those of the well mixed outer core
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  - allow a distinct E' layer, where \( v_p \) and \( \rho \) diverge from those of the well mixed outer core
  
  and

  - let the seismic properties of the D\textasciitilde (\( \rho \), \( v_s \) and \( v_p \)) vary away from PREM towards the CMB.
Permitting variation in D" properties and an E' layer

- $v_s$ and $v_p$ in the D" decrease
- Need to see what body waves prefer
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- Immisible melts at OC conditions (eg Averson et al, 2019, figure right; but also Helffrich & Kaneshima 2004)
Uppermost outer core structure – an E' layer?

But what should it look like seismically?

Figure from Buffett & Seagle, 2010
Uppermost outer core structure – an E' layer?

But what should it look like seismically?

Figure from Buffett & Seagle, 2010

Figure from Brodholt & Badro, 2018

Maybe slow & light is possible?
Moving up to the MTZ

- The question of how convection behaves in the mantle and whether layering is present has been tackled for decades – with insights from geochemistry, geodynamics and seismology.
Moving up to the MTZ – P'•d•P'

- Asymmetric P'•d•P' can be used to probe the mantle transition zone.

Wu, Ni & Irving, Science, 2019
Moving up to the MTZ – $P' \circ d \circ P'$

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Wu, Ni & Irving, Science, 2019
• Asymmetric $P' \cdot d \cdot P'$ can be used to probe the mantle transition zone.

Wu, Ni & Irving, Science, 2019
Moving up to the MTZ – $P'dP'$

- We found very significant scattering from the ‘660 km’ discontinuity — it is much rougher than the free surface.

Wu, Ni & Irving, Science, 2019
We model the signal as coming from a 660 with substantial topography, but a thin layer of strong scatterers could produce a similar signal.
P'\(d\)P' and mantle convection

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Wu, Ni & Irving, Science, 2019
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Wu, Ni & Irving, Science, 2019
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Previous studies disagree about the genesis of the Bermudian Islands. We are looking under Bermuda using receiver functions.

We’re also developing a new receiver function metric to help assess receiver function quality.

Burky, Irving & Simons, in prep
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- We find that Bermuda is underlain by a deeper than average ‘410’ km discontinuity, and a complex ‘660’ km.

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See Alex Burky’s AGU presentation for more details!

Burky, Irving & Simons, in prep
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Project GuyotPhysics
Behavior at the boundaries of our world:
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Project GuyotPhysics

With Profs
Frederik Simons, Princeton &
Alain Plattner, U Alabama
Long and short period seismology can be applied to look at the physical properties of the Earth at geodynamically important boundaries.

At the ‘660’, we see evidence of roughness, indicating imperfect mixing. This does not mean that material flow through the ‘660’ is absent, but it may be imperfect.

At the uppermost outer core, our EPOC outer core model reduces the need to have a slow E’, but when one is permitted it is favored. This suggests that there may be a compositionally distinct reservoir at the top of the outer core. The genesis mechanism for such a layer is still open.
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Trade-offs with D'' properties
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- Using the same methodology, we can let the seismic properties of the D'' vary away from PREM towards the CMB. In this example we fix how $v_p$ and $\rho$ vary as $v_s$ changes.
- In this case the velocity changes a little but $\rho$ changes more.
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\[ K_0, K'_0, V_0 \]

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Body wave predictions for an E' layer

- Travel time anomalies are too extreme for rays which spend most of their time very close to the CMB → these model predictions may be too slow at the CMB when an E' layer is included.
What if we had used a Birch Murnaghan formulation?

- Velocity & density models obtained from the ensemble of Birch–Murnaghan EoS parameters are very close to those of EPOC–Vinet:
  \[ |ΔV_p| \leq 0.02 \text{km/s} \quad \text{and} \quad |Δρ| \leq 0.001 \text{g/cm}^3. \]
- Different formulations give different extrapolations from core to ambient conditions result in different values for the EoS parameters.

Irving, Cottaar & Lekić, Science Advances, 2018
Why a linearized inversion might be problematic

- Non-linearity of the relationship between mode center frequency and elastic parameters of the core.
- Each symbol corresponds to a different mode used, and its size is proportional to the mode's sensitivity to outer core structure (%).
- Symbol color represents the magnitude of the non-linearity of mode frequency shift due to a 1% perturbation to outer core $v_p$, compared to uncertainty on the measurement due to mantle structure (which is nearly always greater than measurement error).

Irving, Cottaar & Lekić, Science Advances, 2018
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EPOC–Vinet is homogeneous and stable

Irving, Cottaar & Lekić, Science Advances, 2018
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Selected References

- Mode data:

- Other outer core models: