The Unresolved Problem with Deriving Lunar Thermal Profiles When Including Heat Producing Elements

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ABSTRACT

Despite more than four decades of research, first-order knowledge about lunar evolution and structure remains unresolved, including: (a) the dynamic development of the interior through lunar history starting from crystallization of an early magma ocean; and (b) the presence of a low-rigidity basal mantle layer, a potential remnant of an overturned Fe-Ti-rich layer that formed below the crust and sank to the core-mantle boundary. Understanding the thermal state of the present-day lunar interior is a primary challenge for improving estimates of internal structure. The existing estimates of thermal profiles (selenotherms) derived from inversions of seismic, gravity, and electromagnetic data differ by ~800 °C; too broad to discriminate between proposed petrologic stratigraphies.

Constraining the heat-producing element (HPE) concentrations and distribution in the various reservoirs of the Moon would directly inform the thermal state of the interior. Estimates of bulk lunar mantle HPE concentrations can range from that of an ordinary chondrite (U = 0.0068; Th = 0.025; K = 17 ppm) to higher estimates (U = 0.039; Th = 0.15; K = 212 ppm) based on measurements of Apollo pyroclastic glasses that might represent the least fractionated, near-primary lunar mantle melts. We show preliminary results of selenotherms and their corresponding mantle properties from lunar interior models. The selenotherms were calculated by incorporating the HPE estimates into a 1D thermal conduction equation. The total mass and moment of inertia of each interior model were calculated through the Birch-Murnaghan equation of state and compared to observations.

Here we illustrate the difficulties of producing an HPE-based selenotherm that falls within geophysically based estimates, as well as highlight future effort to address these problems. Our preliminary search has found selenotherms on the hot edge of or hotter than this range. At the extreme, the higher HPE concentration estimates yield an impossibly hot mantle with temperatures in excess of 4,000 K, melting large portions of the mantle. This study emphasizes the need for future in-situ observations and sample analysis to better inform modeling of the selenotherm within the Moon's interior.

KEY TAKEAWAYS

- Need new bounds for lunar thermal profiles.
- New method calculates a thermally conductive profile *for each lunar interior model* and includes radioactive heat production.
- Previous low sigma/best fit lunar interior models are revised when switching from an imposed thermal profile to a thermally conductive profile.
- The *fitness* of a lunar interior model when paired with a thermal profile is measured by comparing the model material properties to observed values or independent estimates.
- This is an important problem. Here we show revised lunar interior models that are paired with a conductive thermal profile.

FUTURE DIRECTIONS

- Iterative testing of new interior models and thermal conductive profiles
- Geodynamic modeling
- Lateral (3D) heterogeneity
- Additional seismic constraints
- Other rocky planetary bodies

References:

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3. Hagerty, J. J., Shearer, C. K., & Vaniman, D. T. (2006). Heat-producing elements in the lunar mantle: Insights from ion microprobe analyses of lunar pyroclastic glasses. Geochimica et Cosmochimica Acta, 70(13), 3457–3476. https://doi.org/10.1016/j.gca.2006.04.013
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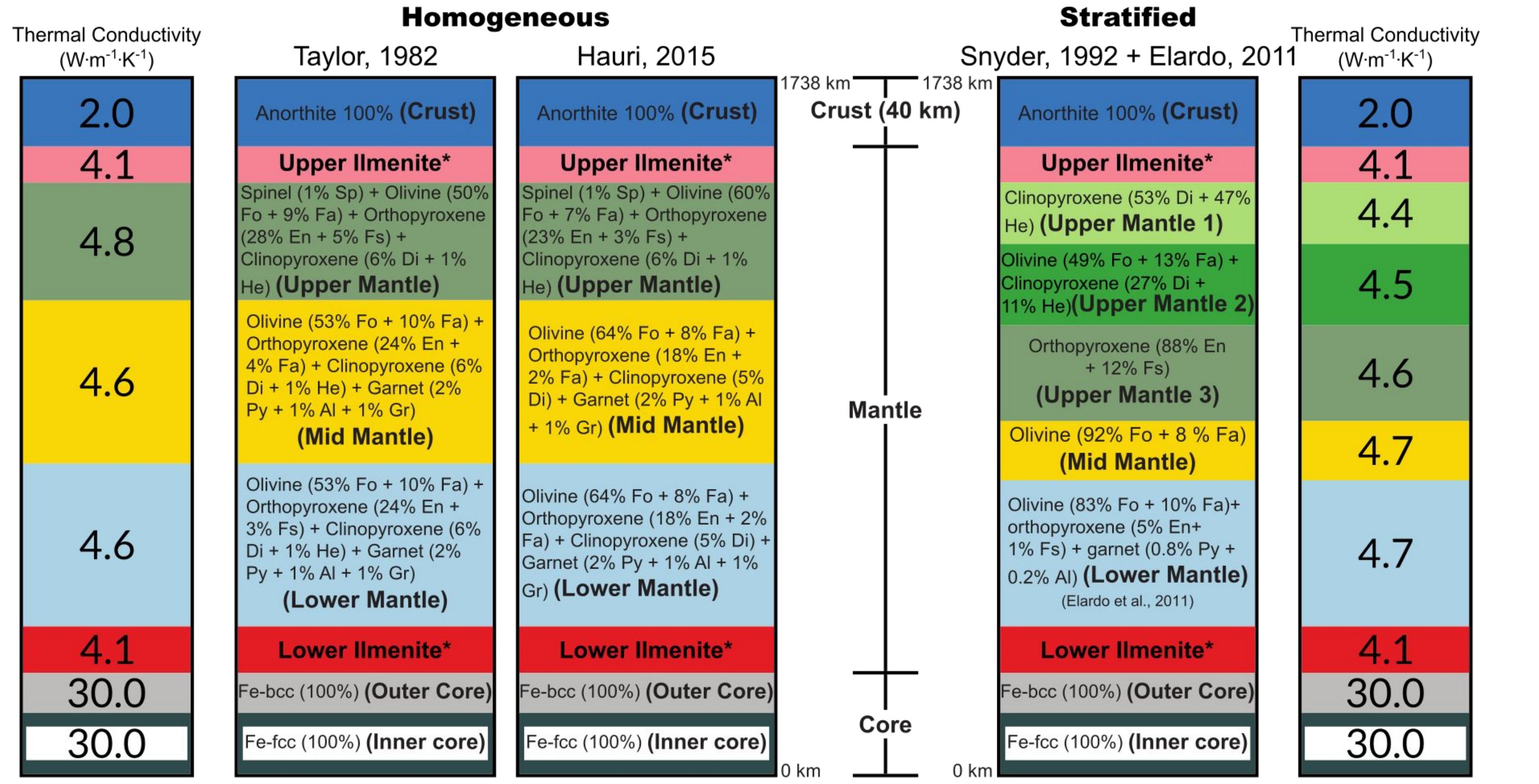
PROCESS

Figure 1. Specify a stratigraphic column of petrology and thermal conductivity.



*Upper and lower ilmenite-bearing layers used in Stratified: Clinopyroxene (60% He + 14% Di) + Ilmenite (23%) + Anorthite (2%) *(van Orman and Grove, 2000)*.
Upper and lower ilmenite-bearing layers used in Homogenous: Olivine (18% Fa + 2% Fo) + Cpx (12% He + 4% Di) + 42% An + 12% Ilm + 10% Sil *(from Charlier et al., 2018)*.
Sp - Spinel; Fo - Forsterite; Fa - Fayalite; En - Enstatite; Fs - Ferrosilite; Di - Diopside; He - Hedenbergite; Py - Pyrope; Al - Almandine; Gr - Grossular;
Fe-bcc, Fe-fcc - Iron-Body Centered Cubic, Face-Centered Cubic; An - Anorthite; Sil - Silica/Quartz; Ilm - Ilmenite.

Figure 2. Process to create and evaluate lunar interior models. Lunar interior models are a stratigraphic type (from Figure 1) with specified layer thicknesses.

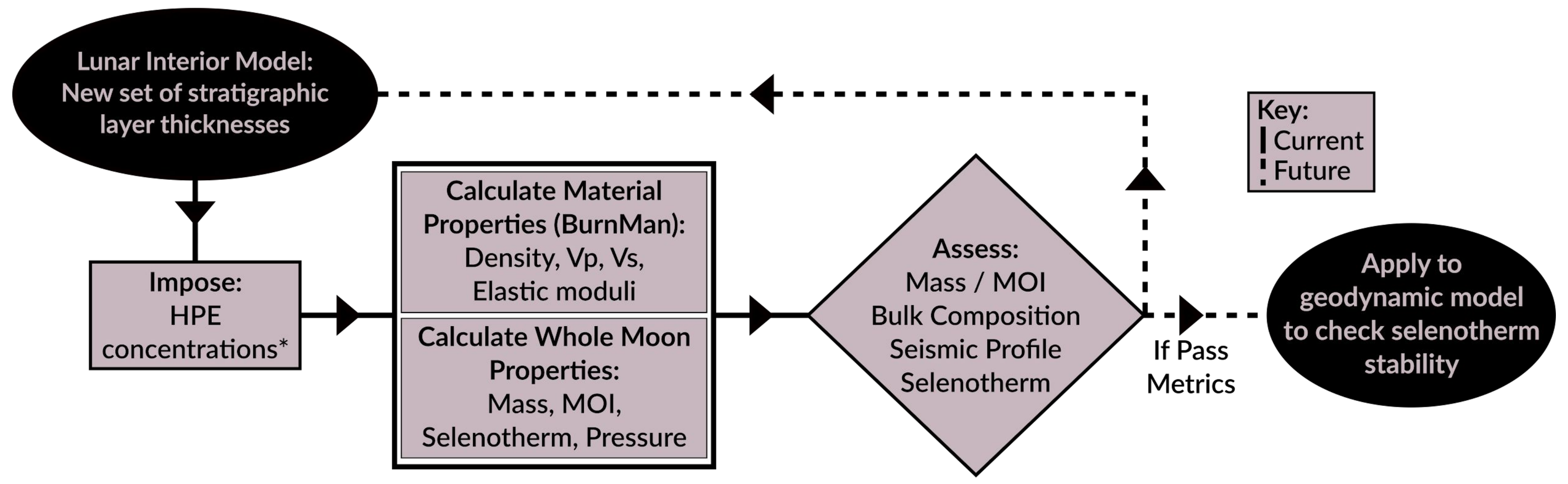
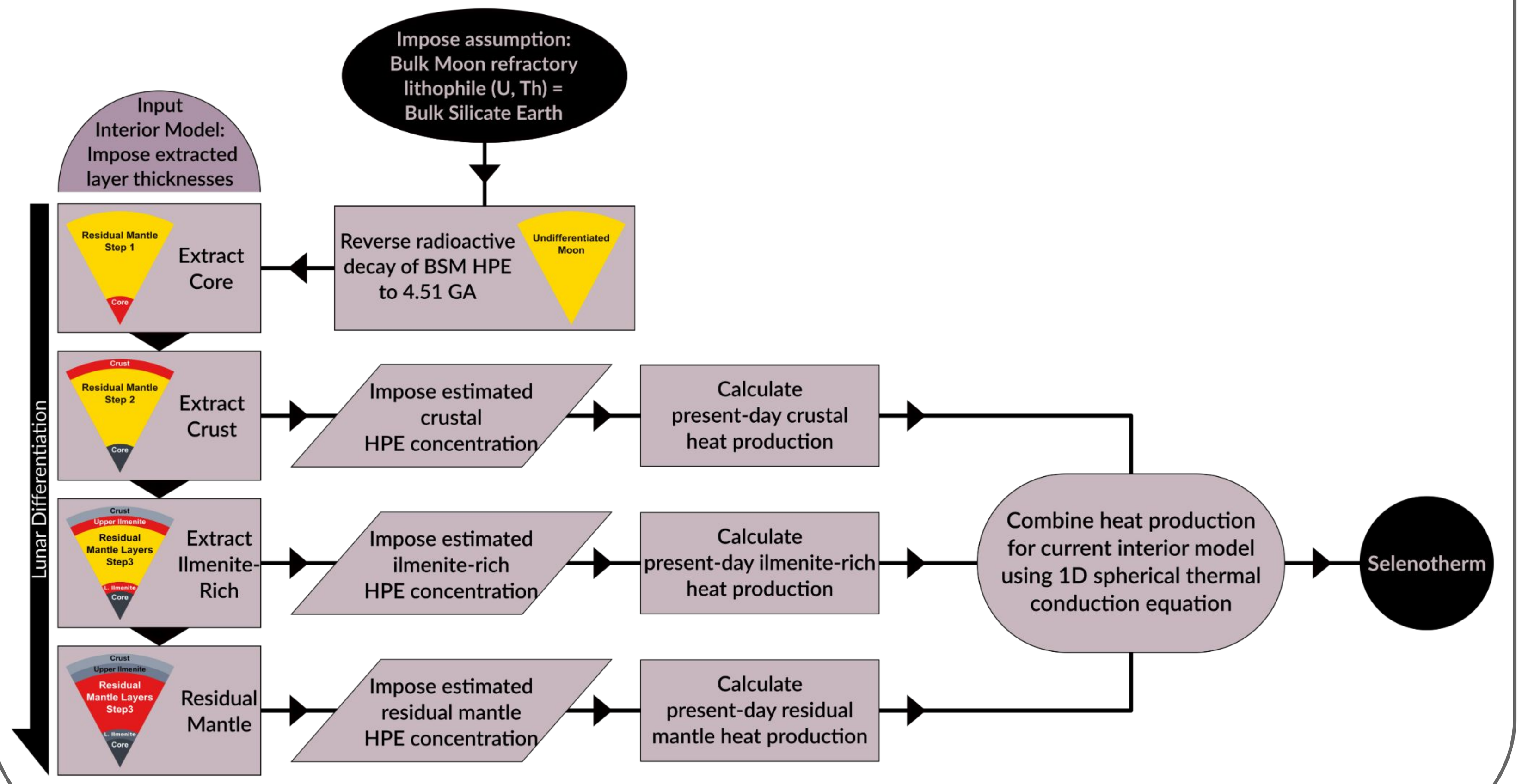


Figure 3. Process to calculate a thermally conductive selenotherm from radiogenic heat production. Heat production is determined for each major layer of the lunar interior as it is extracted (crystallized) from the early Moon magma ocean.



PRELIMINARY RESULTS

- We chose a subset of previously found low sigma lunar interior models to test pairing with a new conductive thermal profile, calculated on-the-fly for each model.
- Each of the chosen lunar interior models was previously constructed with one of the three stratigraphic petrology types (Figure 1) and paired with an imposed thermal profile (Figure 4).
- Out of ~400k interior models, **187** previously fit total lunar mass (Mass) and moment of inertia (MOI) within 3 standard deviations [2].
- **The left column shows the previous results, the right column shows the new revised results of the lunar interior models paired with a conductive thermal profile based on 4 HPE scenarios.**

Figure 4. Three thermal profiles we previously imposed that outline the envelope of geophysically derived selenotherms: MaxT, MeanT, and MinT. This previous method bypassed the need to consider parameters like thermal conductivity by just assuming the true thermal profile is within the envelope. Included for reference are solidus curves for major lunar mantle minerals. Fo92: forsterite. FeTi: ilmenite-rich cumulate. Perid: peridotite.

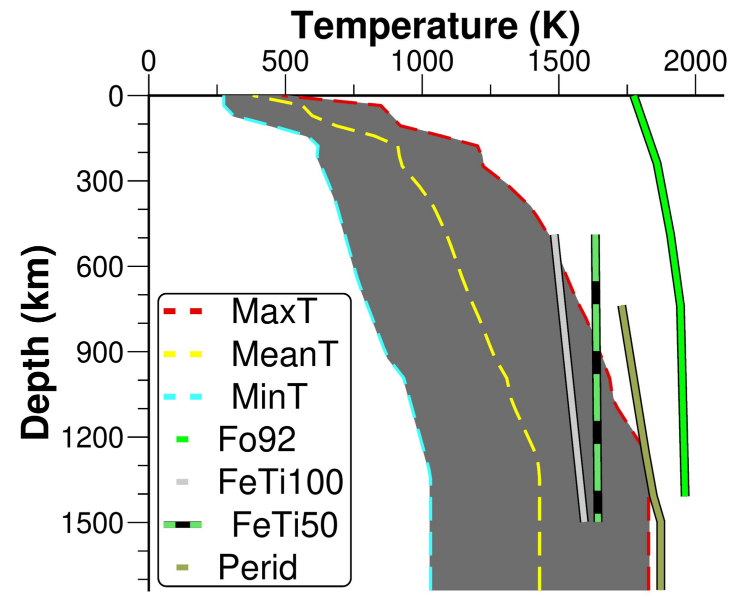


Figure 5. Calculated values of Mass and MOI for each of the 187 lunar interior models with reference to GRAIL observations [Williams et al. 2014].

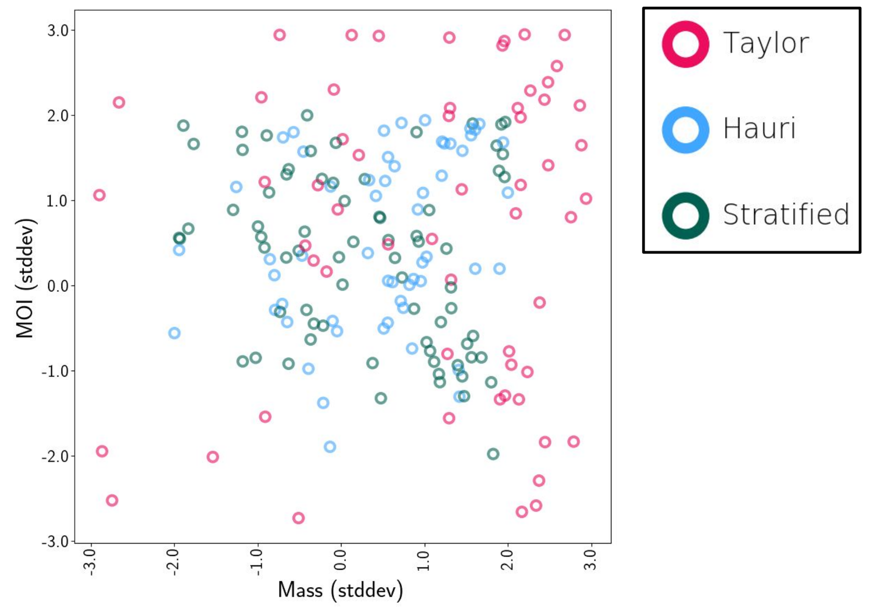


Figure 6. Calculated selenotherm and density, seismic velocities Vs, Vp profiles for each of the 187 best fit lunar interior models.

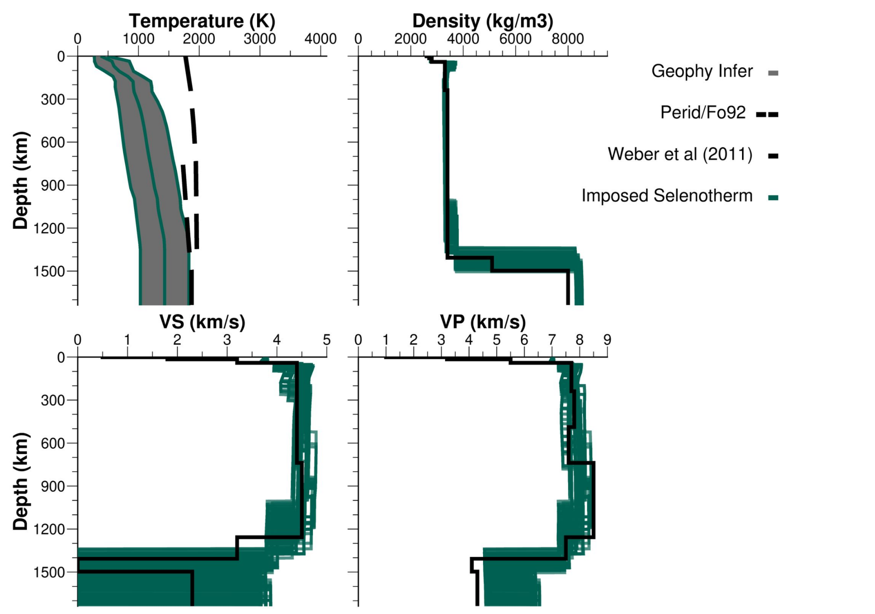


Figure 7. Results of applying conductive selenotherms to the 187 lunar interior models. Four different HPE scenarios are shown. BSE: Bulk Silicate Earth. FAN: Ferroan Anorthitic Crust. Hagerty et al. 2006.