Exploring Enceladus: Internal Structure Models and Moment of Inertia

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Introduction

Enceladus, the sixth-largest moon of Saturn with a radius of 252.0±0.2 km [1] was observed by NASA's Cassini spacecraft in 2005. During its close flybys, Cassini's imaging science subsystem captured images revealing a region of intense geological activity near Enceladus' South Pole [2] found to be the source of fine icy particles that form Saturn's E ring [3]. This suggests the existence of a subsurface water ocean [2]. Enceladus' density of 1608±5 kg/m³ and its icy surface [2] indicates an ice-rich bulk composition. Additionally, the moment of inertia coefficient, known from Cassini radio science, ranging from 0.33 to 0.34 (2σ confidence level), suggests a differentiated body [4] with a rocky core beneath an H_2O mantle [5].

Goal

We are investigating different modeled internal structures of Enceladus and their corresponding moment of inertia (MOI) coefficients to identify which best matches bulk density and the MOI derived from spacecraft radio science data.

Methodology

Foundation:

This study expands upon the Neumann-Kruse model [5], which explored Enceladus' thermal evolution and differentiation by incorporating three distinct types of rock rheology—wet olivine, dry olivine, and antigorite (hydrated, layered silicate mineral)—and a partially porous core. Figure 1 illustrates a schematic of the interplay between the processes and parameters considered in these models, as outlined in [5].

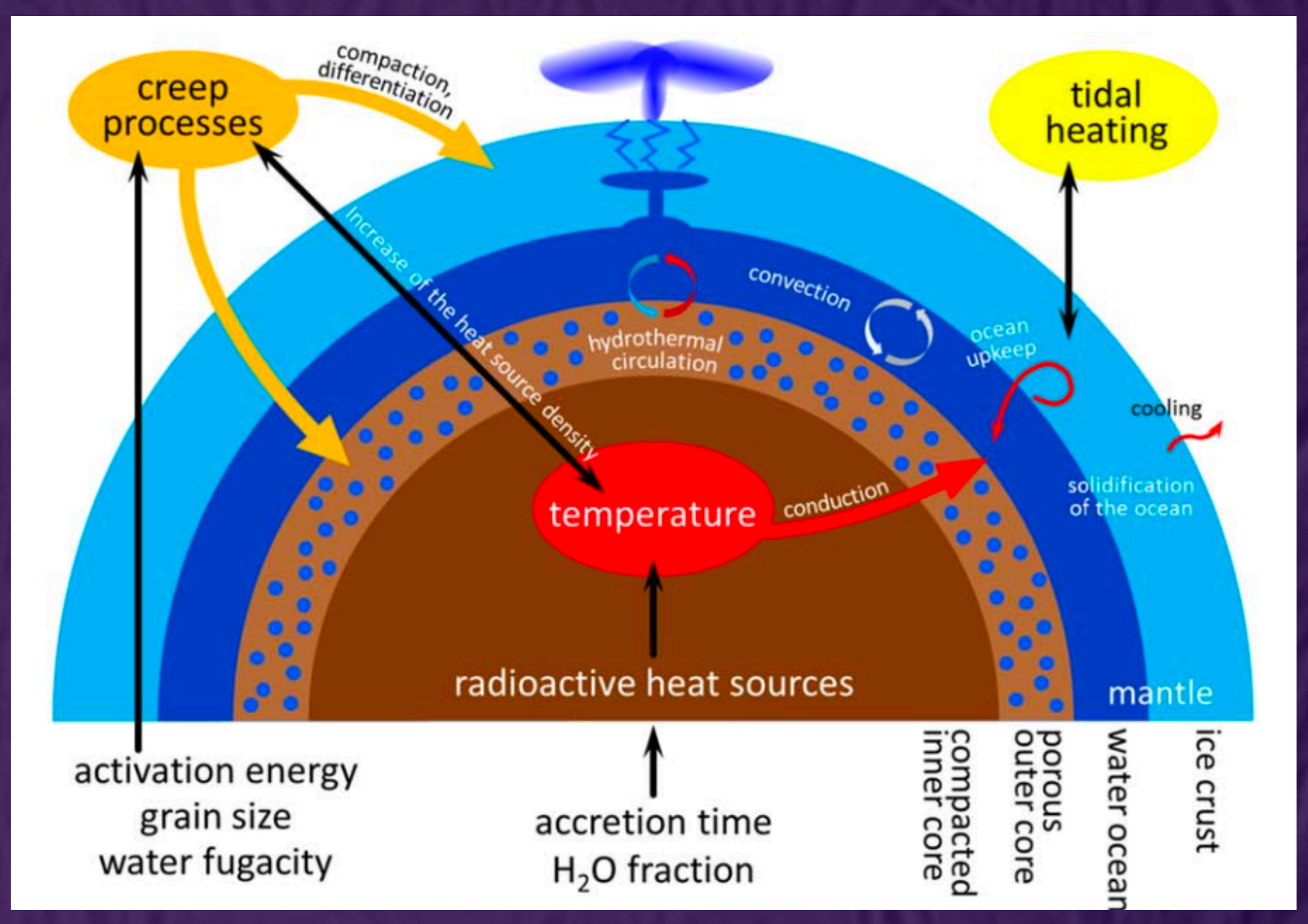

Figure 1. The sketch depicting the interaction of key processes and parameters involved in Enceladus' evolution, with the south pole positioned at the top.

Neumann-Kruse Model Outputs:

- Core radius: ≈185–205 km
- Porous core layer: ≈2–80 km
- Subsurface ocean: ≈10–27 km
- Ice-rock crust: ≈30–40 km
- Accretion time: 1.3–2.3 million years post-CAIs.

calculates thermal evolution and water-rock separation of an initially homogeneous Enceladus

Alternative Input Parameters:

- Incorporated subduction of rock material from the undifferentiated ice-rock crust above the core.

water ice, including some void space

- Adjusted crust densities: 850 kg/m³ [1], 918 kg/m³, 925 kg/m³ [6,7].
- This resulted in an increased core radius

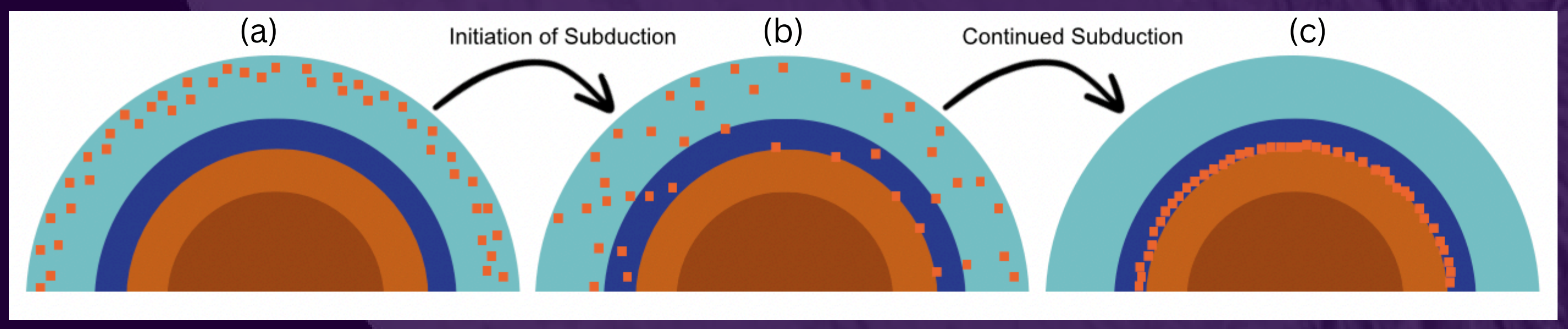

Figure 2. (a) shows the pre-subduction phase with a mixed ice-rock crust (light blue with orange dots), differentiated ice crust (light blue), subsurface ocean (dark blue), hydrated outer core (light brown), and consolidated inner core (dark brown). proposed by [5]. (b) depicts active subduction with ice descending toward the upper core. (c) illustrates the post-subduction phase, with only an icy crust remaining.

Moment of Inertia Calculation:

- MOI is calculated for both the original and adjusted models using (1), where ρ(r) denotes the density as a function of the radial coordinate. r, and θ and ϕ are the polar and azimuthal angles, respectively.

$$\Theta = \int_0^R \int_0^\pi \int_0^{2\pi} \rho(r) r^4 \sin^3(\theta) d\phi d\theta dr \qquad (1)$$

- The MOI coefficient can be calculated using (2), where M is the total mass and R is the radius of Enceladus.

$$I = \frac{\Theta}{MR^2} \qquad (2)$$

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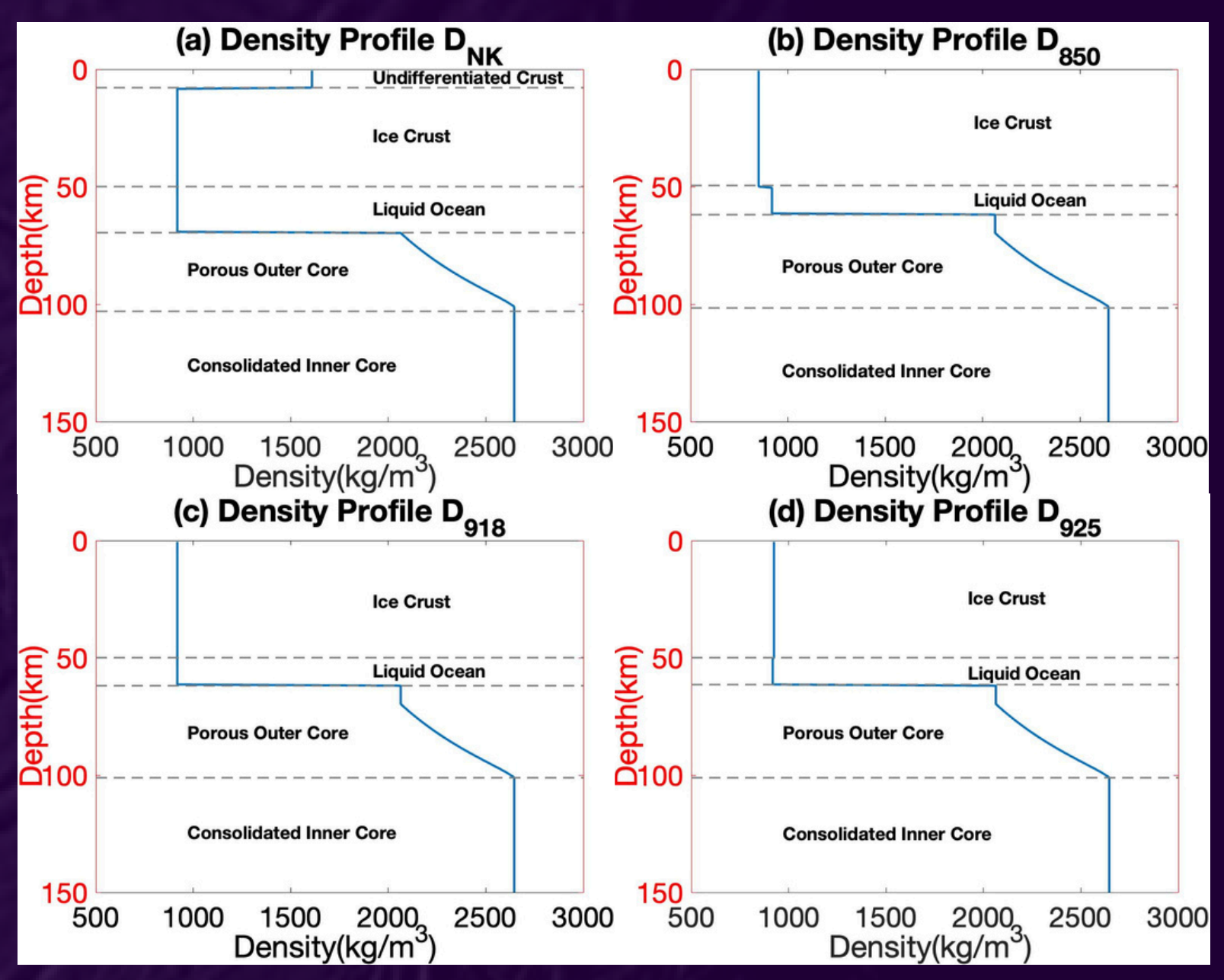
Results and Discussion

- Models without crust subduction show the least agreement with the derived MOI from the gravity field [4].
- When the undifferentiated crust subducts and an icy crust with a density of 925 kg/m³ forms, most models fall within the accepted MOI coefficient range (0.33-0.34) at a 2σ confidence level as recommended by [4].
- Higher crust densities require higher core densities, while lower crust densities need lower core densities to match the observed MOI values.
- Outer Porous Core Thickness for accepted models (MOI: 0.33-0.34) [4]:
  - Dry Olivine Rheology:
    - + Thickness Range: ≈ [3,73] km.
    - + ≈60% of models: < 10 km.
    - + ≈80% of models: < 20 km.
  - Wet Olivine Rheology:
    - + Thickness Range: ≈ [2,80] km.
    - + ≈50% of models: < 10 km.
    - + ≈65% of models: < 20 km.

Figure 3. Density profiles for the model corresponding to a MOI of 0.3329 in the Neumann-Kurse model with an undifferentiated crust (a), and the corresponding density profiles with subduction of rock in crustal models with crust densities of 850 kg/m³ (b), 918 kg/m³ (c), and 925 kg/m³ (d), which result in MOIs of 0.3190, 0.3237, and 0.3252, respectively. The figure demonstrates that only the undifferentiated crust model falls within the accepted MOI range (0.33-0.34) as derived by [4], while the others do not meet this criterion.



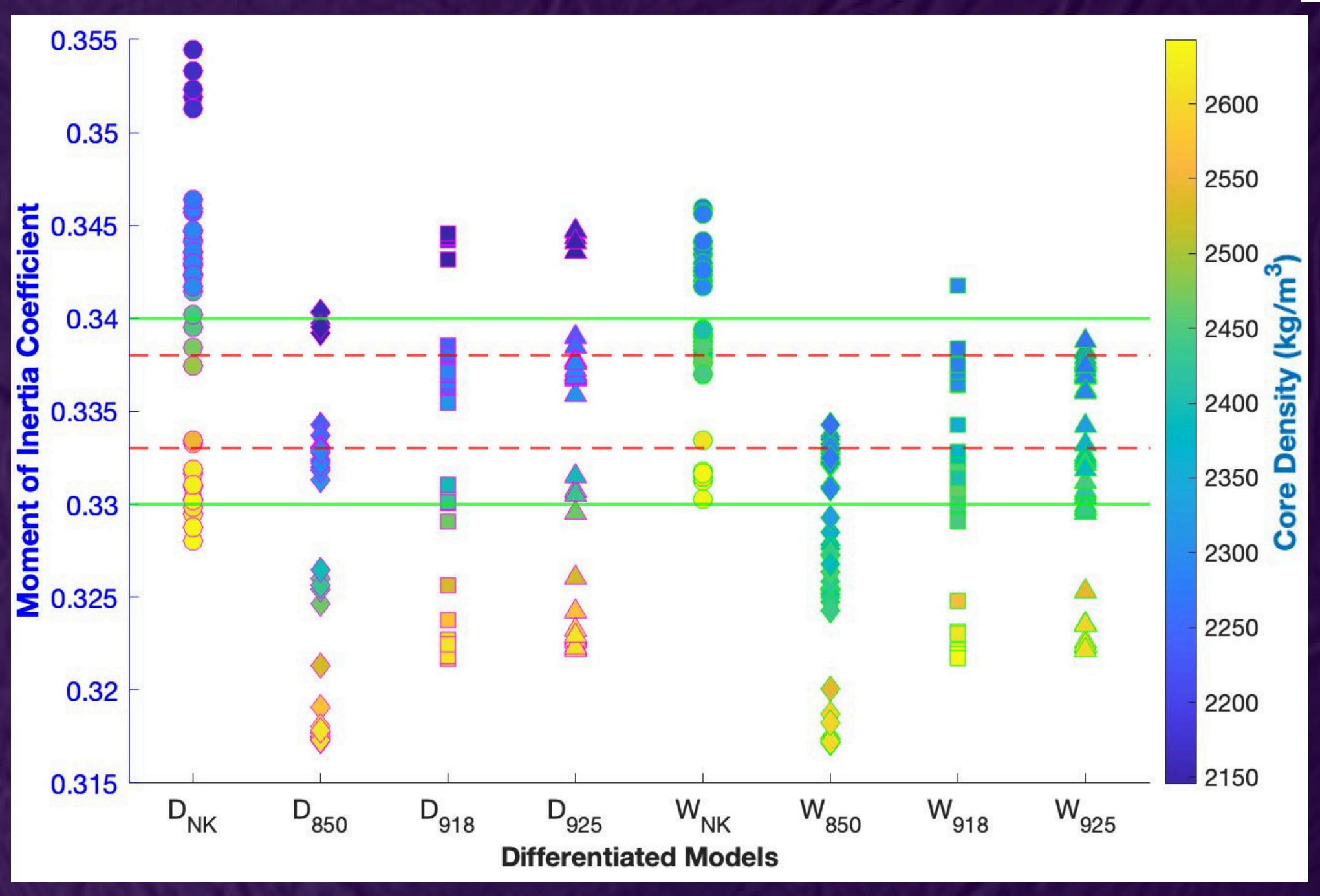


Figure 4. Results for the MOI coefficient. "D" and "W" refer to dry and wet olivine core rheologies. "NK" indicates a crust density of 1609 kg/m³ based on Neumann-Kruse models, while subscripts "850," "918," and "925" represent crust densities of 850 kg/m³, 918 kg/m³, and 925 kg/m³, respectively. The solid green line marks the MOI coefficient range of 0.33-0.34 (2σ confidence level), while the red line shows the 0.333-0.338 range (1σ confidence level) derived from gravity data [4].

Core Structures Based on Different Studies:

Core Structures and Corresponding MOI Based on Different Studies

Core Structure	Core Density (kg/m³)	Moment of Inertia
Partially Porous Core - This Study, [5]	[2146,2643]	[0.3171,0.3544]
Consolidated core [8]	3527.5	0.31
Fragmented Core [9]	[2170,2710]	[0.320,0.344]
Porous Core [10]	2870	0.345
Hydrated Unconsolidated Core [11]	[2450,2600]	0.33

const den
boulders with water in between
core with porous and water
loose material bounded together wit

- As shown in the above table, the MOI coefficients for a partially porous core proposed by [5], a fragmented core [9], and a hydrated unconsolidated core [11] all fall within the 2σ confidence interval of the MOI range derived by [4].

Conclusions

- Our study builds upon the differentiated internal structure with partially porous core models proposed by [5], which were initially based on a rock-ice crust model. We further refined these models by incorporating a differentiated crust with varying densities.
- Most models, with a crust density of 925 kg/m³, align with the MOI range of 0.333-0.338 with a 1σ range confidence level, suggested by [4] regardless of whether the core rheology is dry or wet olivine.
- Lower crust densities result in lower average MOI coefficients.
- Approximately 54% of the models fall within the accepted 2σ range of MOI, suggesting their compatibility with observed gravity data.

References

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