New Insights from MESSENGER Data on Mercury's Tidal Response and Internal Structure

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Introduction

Mercury is a key target for interior modelling because of its unusually large core, thin silicate mantle, and its spin–orbit resonance of 3:2. Geophysical constraints from MESSENGER including total mass (M) [1] , normalized moment of inertia (C/MR^2) [2-3] , the crust–mantle inertia ratio (C_m/C) [3], and bulk density (ρ_{bulk}) [1] provide non-unique insights into its interior. Forthcoming measurements from BepiColombo are expected to refine these constraints [4].

To address the Mercury's structure, we use a trans-dimensional Bayesian approach based on Reversible Jump Markov Chain Monte Carlo (RJMCMC) [5]. Unlike MCMC methods with a fixed number of mantle layers, RJMCMC allows the degree of stratification to vary during sampling, enabling a direct assessment of model complexity. Core densities are drawn from Fe–S–Si–C equations of state, while mantle densities are tied to mineralogical compositions (forsterite/enstatite) with the possibility of low-density sulfide (MgS–CaS) anomalies [6]. Rheological parameters are explicitly sampled to ensure mechanically consistent viscoelastic responses.

This framework yields posterior distributions for core size, mantle layering, crustal thickness, and tidal responses, offering new probabilistic constraints on Mercury's deep interior consistent with present and future geodetic and tidal data.

Methodology

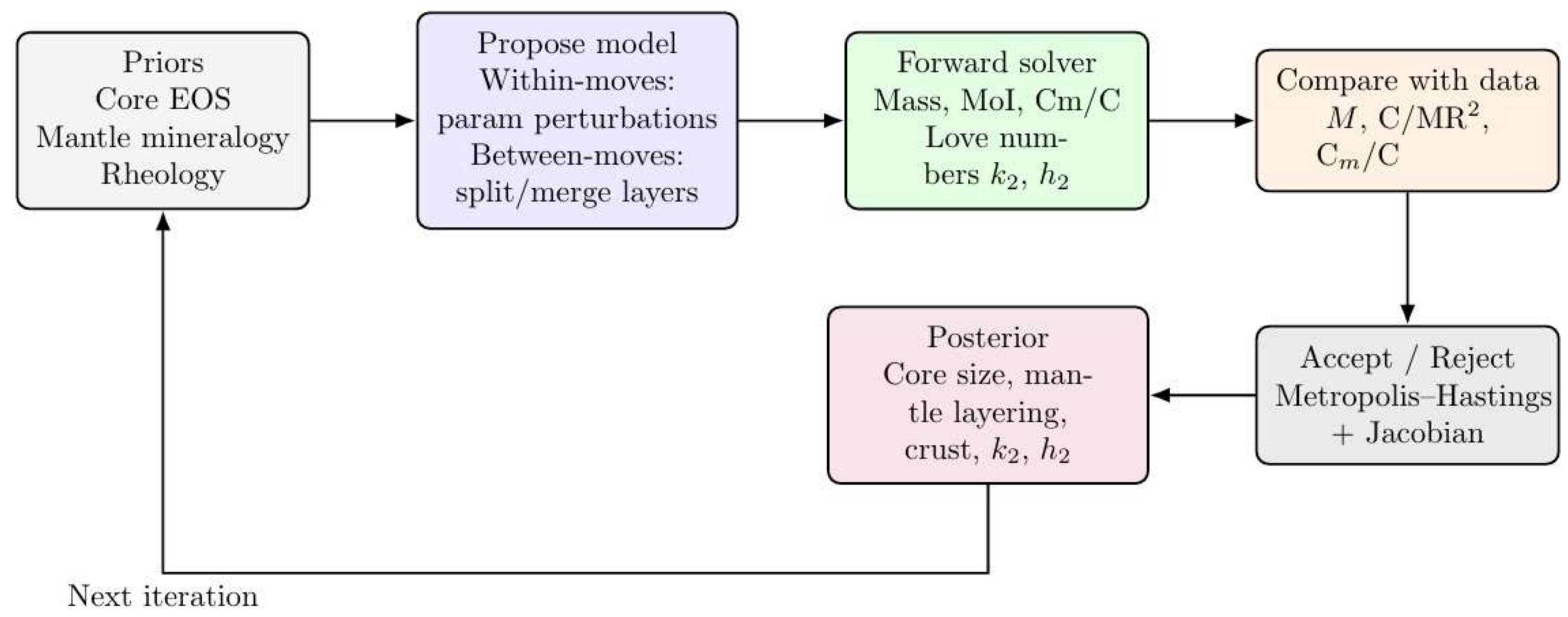


Fig.1: Workflow of the RJMCMC approach applied to Mercury's interior for one chain. Within-moves perturb model parameters, while split/merge moves allow the number of mantle layers to vary. A Jacobian correction ensures valid acceptance probabilities across dimensions. Posterior distributions provide probabilistic constraints on Mercury's core, mantle, crust, and tidal Love numbers.

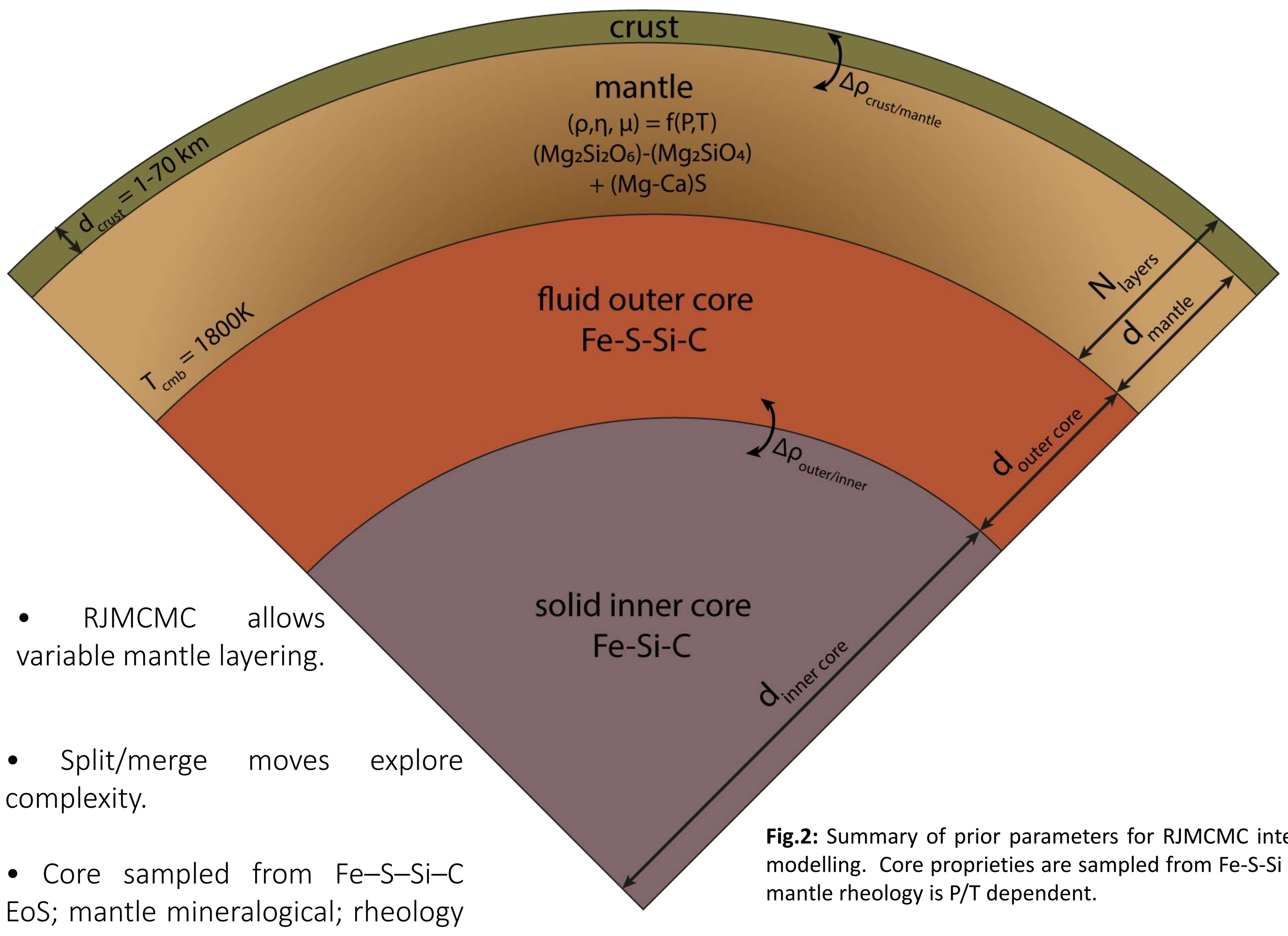
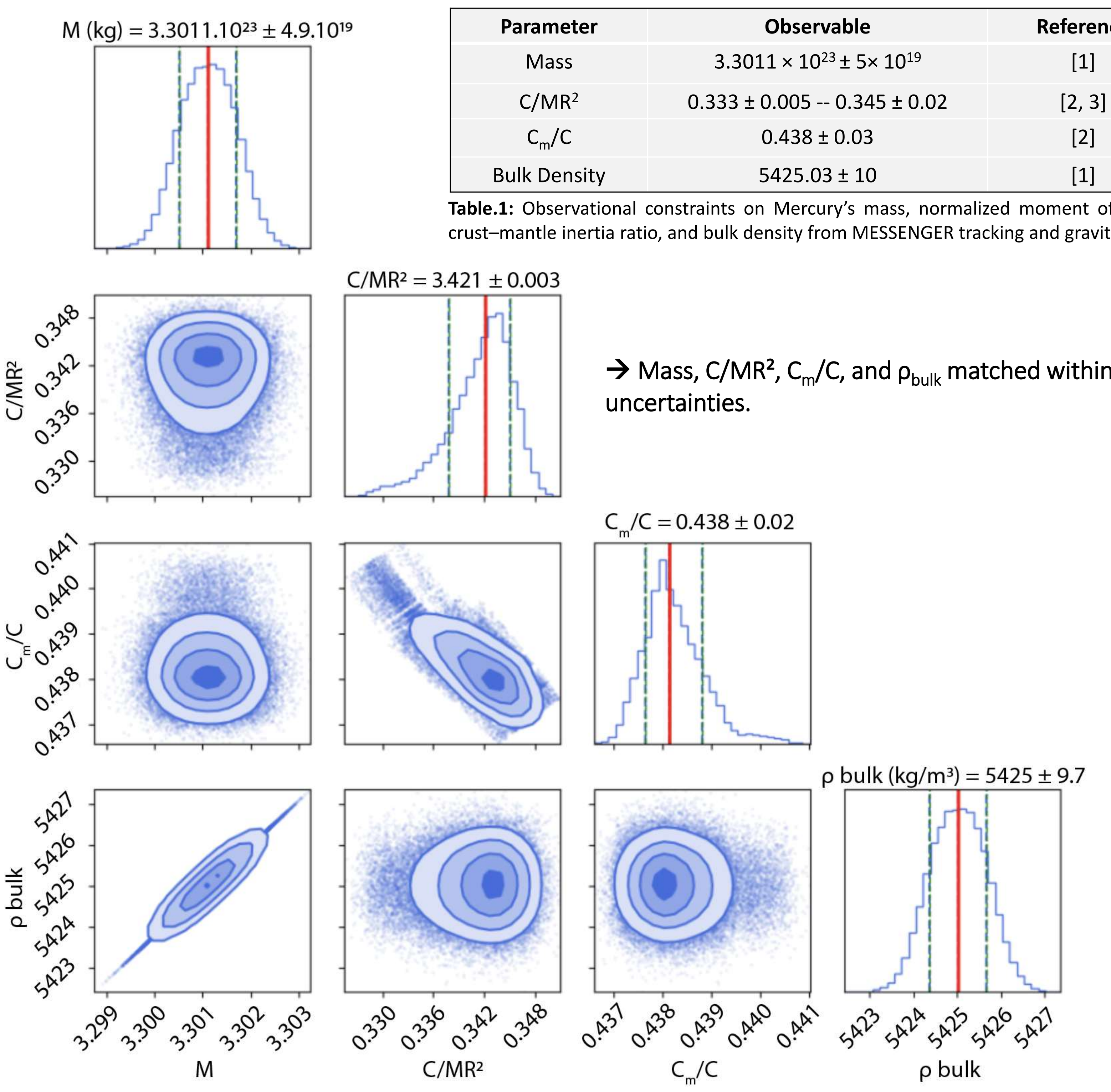


Fig.2: Summary of prior parameters for RJMCMC interior modelling. Core proprieties are sampled from Fe-S-Si EoS, mantle rheology is P/T dependent.

- RJMCMC allows variable mantle layering.
- Split/merge moves explore complexity.
- Core sampled from Fe–S–Si–C EoS; mantle mineralogical; rheology sampled

Parameter	Observable	Reference
Mass	$3.3011 \times 10^{23} \pm 5\times 10^{19}$	[1]
C/MR²	0.333 ± 0.005 -- 0.345 ± 0.02	[2, 3]
C_m/C	0.438 ± 0.03	[2]
Bulk Density	5425.03 ± 10	[1]

Table.1: Observational constraints on Mercury's mass, normalized moment of inertia, crust–mantle inertia ratio, and bulk density from MESSENGER tracking and gravity data.



→ Mass, C/MR², C_m/C, and ρ_{bulk} matched within uncertainties.

Fig.3: Distributions of Mercury's geodetic parameters obtained from RJMCMC sampling. The corner plot shows one- and two-dimensional marginals for total mass M, normalized moment of inertia C/MR^2, crust–mantle inertia ratio C_m/C, and bulk density. Red lines mark median values; shaded contours indicate 1 σ, 2σ and 3σ credible regions.

Tidal Love numbers k_2 and h_2

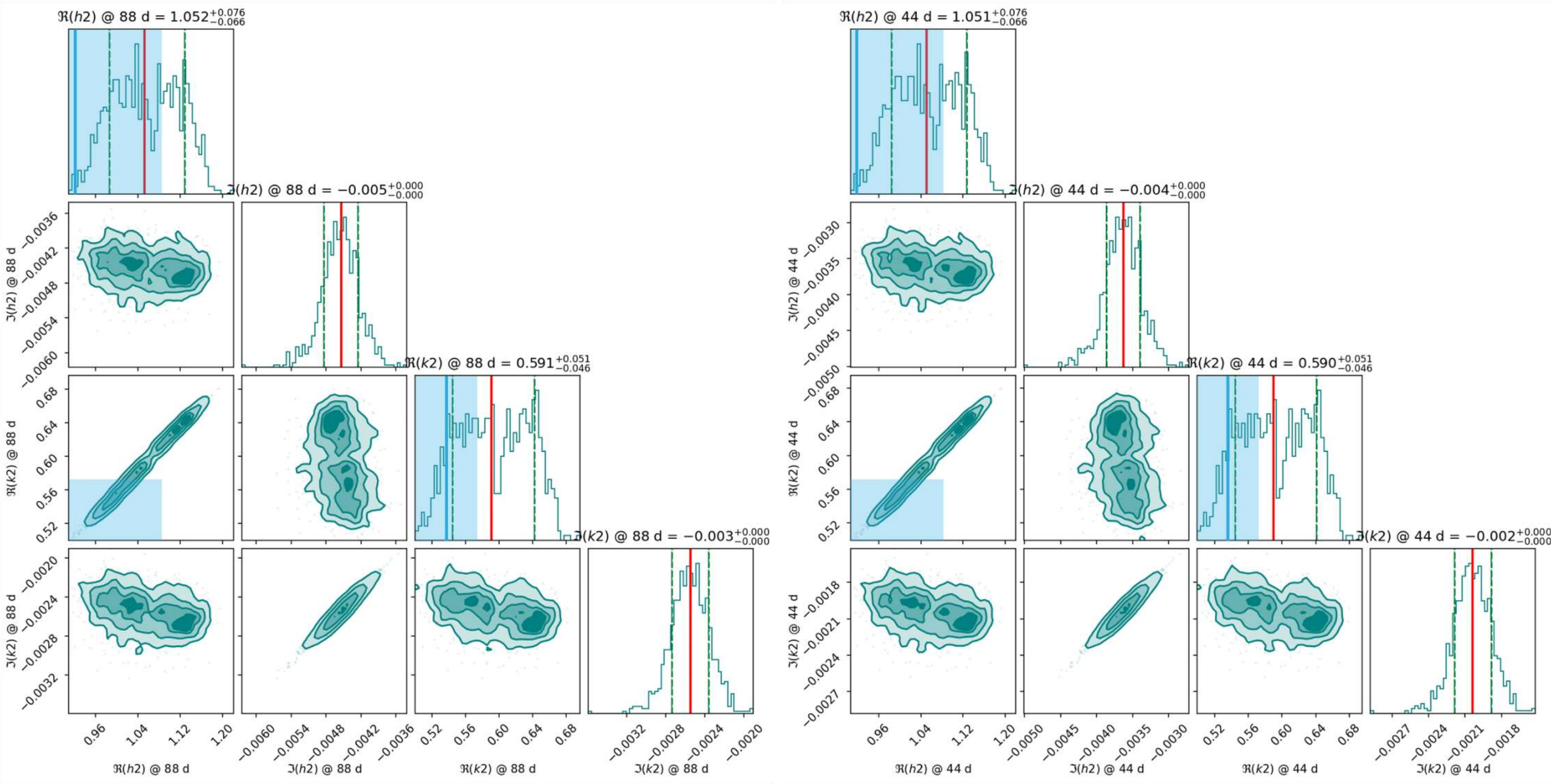


Fig.4: Corner plots of Mercury's degree-2 Love numbers. Real and imaginary parts of h_2 and k_2 at 44 d and 88 d periods. Blue shaded areas correspond to the observables from [1] and [8].

- 44-day and 88-day periods give similar Love numbers: $\Re(h_2) \approx 1.05$, $\Re(k_2) \approx 0.59$.
- Both values are higher than earlier estimates ($\Re(h_2) \approx 0.92$, $\Re(k_2) \approx 0.53$).
- Imaginary parts very small (<0.003) → weak tidal dissipation (high Q ≈ 200).

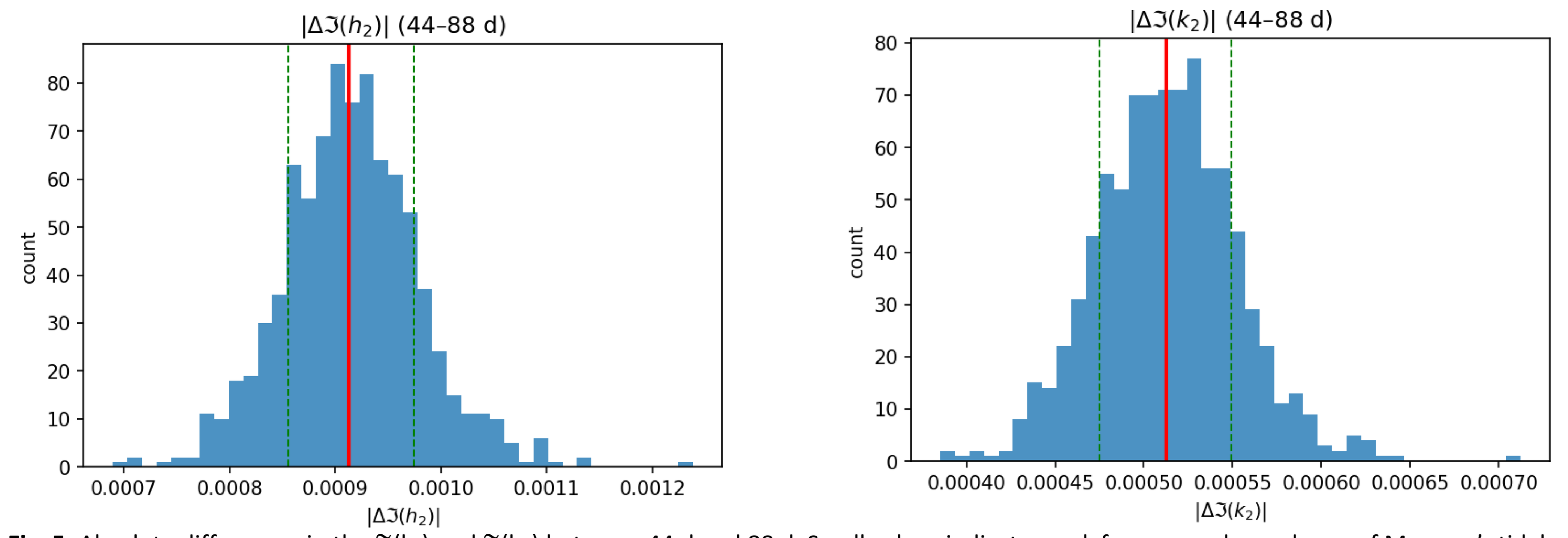


Fig. 5: Absolute differences in the $\Im(k_2)$ and $\Im(h_2)$ between 44 d and 88 d. Small values indicate weak frequency dependence of Mercury's tidal dissipation, a key target for BepiColombo.

- Tiny differences between 44 d & 88 d ($\lesssim 10^{-3}$) suggest possible frequency dependence.
- Narrow posterior spreads → robust constraints.

→ Future BepiColombo data at multiple frequencies can directly test these predictions.

Interior structure

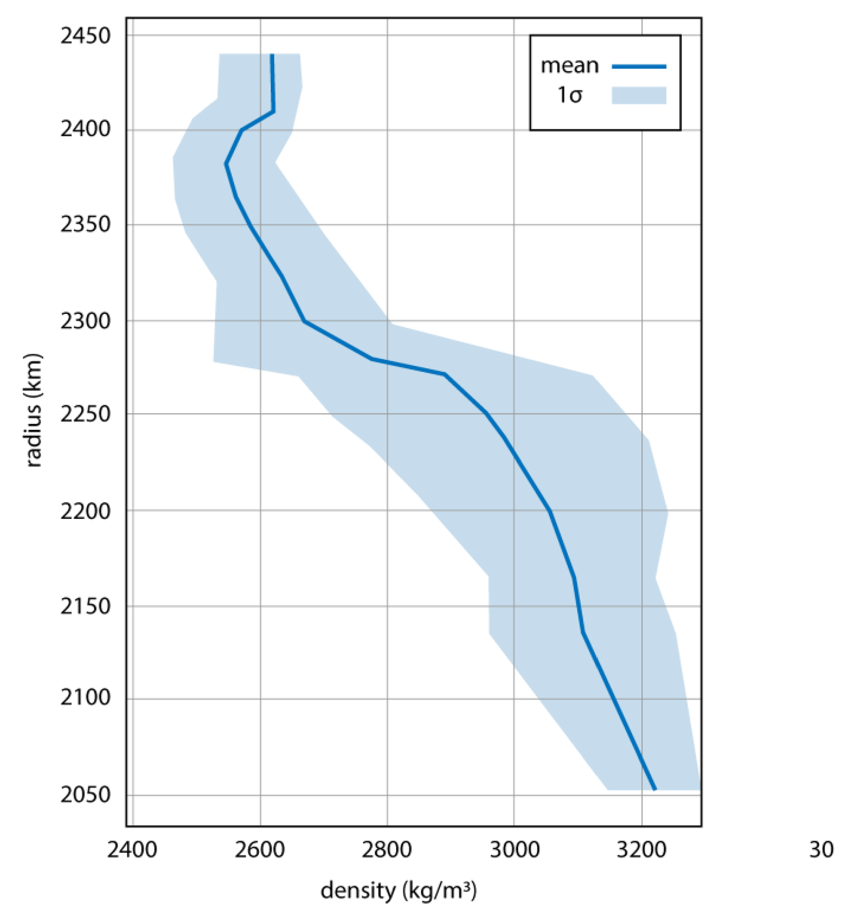


Fig.6: Radial profiles of Mercury's mantle density from RJMCMC models. The blue line shows the posterior mean and the shaded area the 1σ confidence interval.

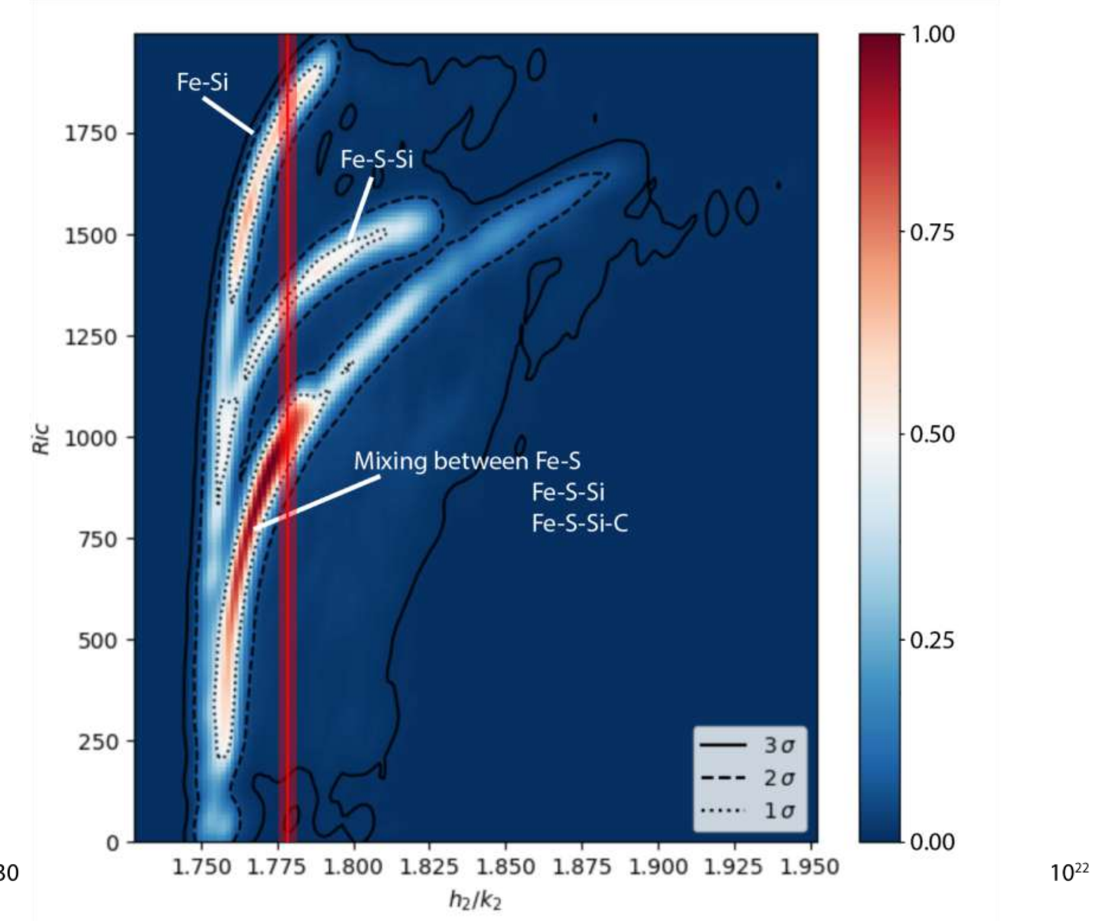


Fig.7: Probability density distribution of Mercury's interior models in the space of inner core radius R_{ic} versus the ratio h_2/k_2. The color scale indicates normalized probability density. Contours show the 1σ, 2σ, and 3σ confidence intervals. Different compositional domains are annotated: Fe–Si, Fe–S–Si, and regions of mixing between Fe–S, Fe–S–Si, and Fe–S–Si–C.

- Density jump Δρ ≈ 200 kg/m³ at crust–mantle boundary.
- Jump in density due to mixing with MgS-CaS (12 ± 4%) in the upper part of the mantle.

- Fe–Si–S(–C) mixtures favoured.
- Inner core radius > ~900 km.
- Clusters show compositional domains
- Giving the mantle structure consisting of a mixing with sulfide elements:

$$\Re(h_2/k_2) = 1.78 \pm 0.27$$

Key Insights

- RJMCMC constrains mantle layering.
- The inner core is composed of a mixing with light elements and a size of > ~900 km in radius.
- $\Re(k_2) \approx 0.59$, $\Re(h_2) \approx 1.05$ (higher than expected).
- Minimal differences between 44 d & 88 d.
- **Weak tidal dissipation (high Q ≈ 200).**

Outlook

- BepiColombo may test predicted frequency-dependence.
- Method transferable to other terrestrial bodies.
- Future: refine mantle mineralogy & rheology constraints.

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