Mercury's interior structure constrained from its thermal state and geodesy data

A.Rivoldini[1][attilio.rivoldini@oma.be], N. Tosi[2], M. Lécaille[3], T. Van Hoolst[1,4], A. Trinh[1], M. Yseboodt[1], R.-M. Baland[1], H. Xiao[5]

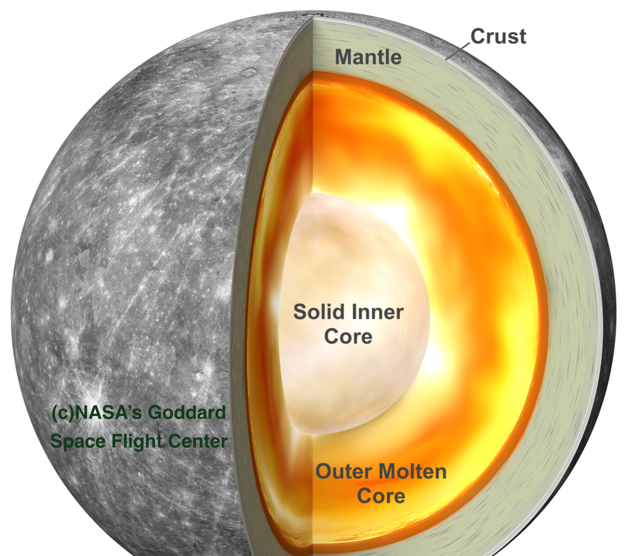
[1]Royal Observatory of Belgium; [2]German Aerospace Center (DLR), Berlin, Germany; [3]Liège University, Belgium, [4]KU Leuven, Belgium; [5]Instituto de Astrofisica de Andalucia, Granada, Spain

Interior structure inference from Geodesy data

Scope

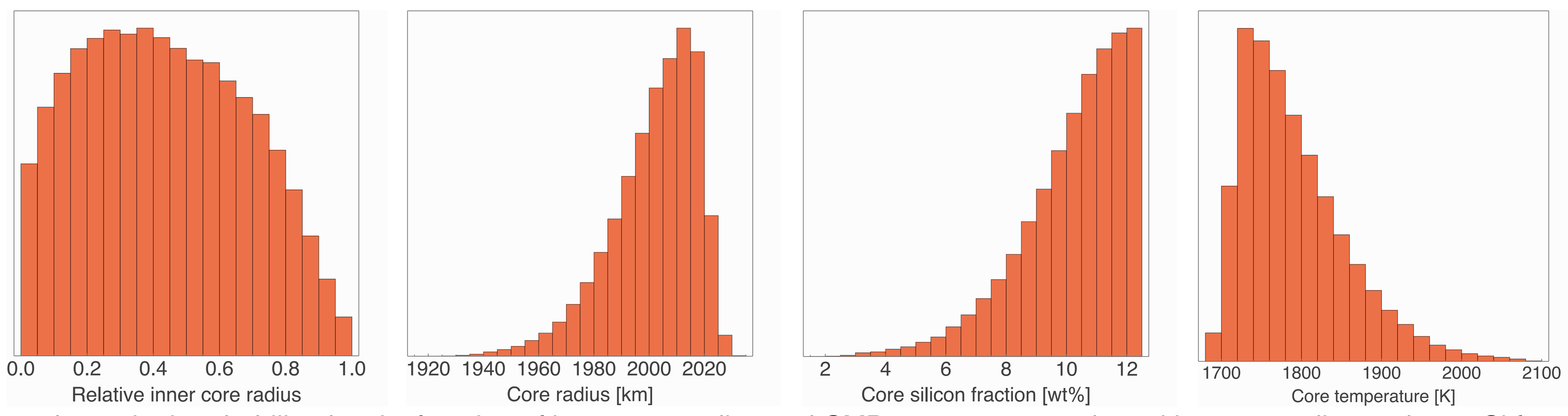
- Geodesy data supplemented with geochemical insights and formation assumptions inform about Mercury's deep interior
  - liquid core state, core radius ~2005±40 km (e.g. Rivoldini+2013, Goossens+2022)
  - inner core?: expected (past and present-day dynamo, radial contraction), but no conclusive evidence
- State-of-the art structure inference based on recent geodesy data (moment of inertia, annual libration amplitude, tidal Love number k_2) using up-to-date equations of state for depth-dependent material properties

Interior structure model



- Model parameters:
  - inner core radius, core temperature at core mantle boundary (CMB), core flattening
  - mantle composition (mechanical forsterite-enstatite-diopside aggregate)
  - crust thickness and density
- Prior assumptions:
  - iron-silicon core alloy (Si is main light element owing to reducing formation conditions)
  - Si≤1st. eutectic (12.5 wt%) in Fe-FeSi (Edmund+2022)
  - CMB temperature allows for liquid core (Edmund+2022) and is below mantle solidus (Namur+2016)
  - conductive mantle heat transport
  - correlated crust thickness-density via crust mantle density contrast deduced from gravity and topography constraints (Broquet 2026)
- Equations of state for core alloy (Edmund+2022, Terasaki+2019, Dorogokupets+2017) and mantle (Stixrude+2024)
- Core liquidus parameterisation (Edmund+2022)
- Composition-dependent (forsterite, enstatite) mantle rheology (Qu+2021)
- Account for effect of mantle-core coupling on libration amplitude (Dumberry+2013)
- Data: mass, moment of inertia and libration amplitude (Bertone+ 2021), tidal Love number k_2 (Konopliv+ 2020)

Results

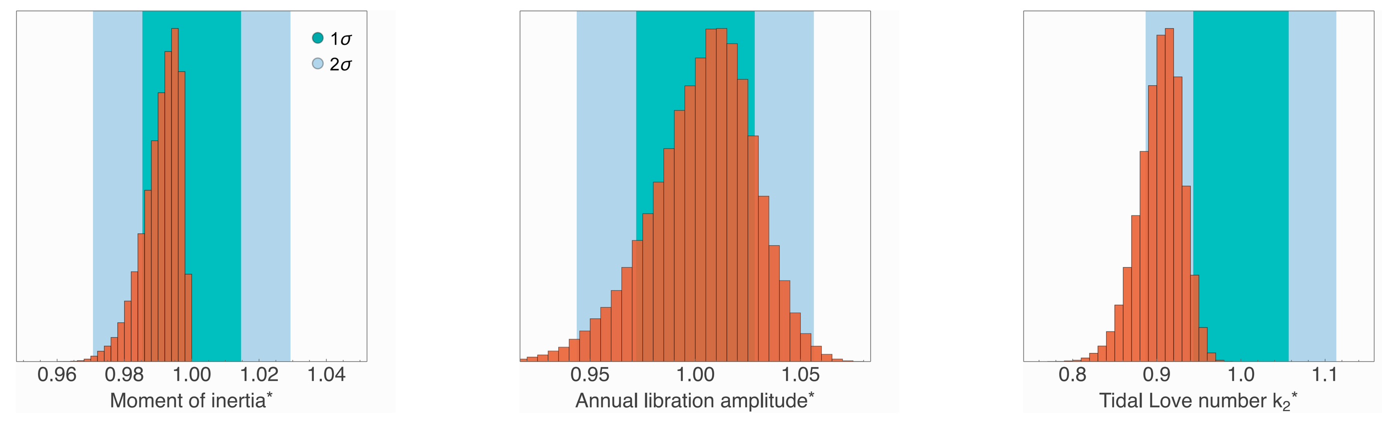


Inferred marginal probability density function of inner core radius and CMB temperature and resulting core radius and core Si fraction

- constrained: core radius (2005± 20km), mantle density (~3200 kg/m³), 8-12 wt%Si, CMB temperature (1790±70 K)
- weakly constrained: inner core radius (870±490 km), mantle composition (forsterite slightly favoured over enstatite), grain size (< 1 mm !!)
- not constrained: (~prior): crust thickness and density, core flattening

Data compatibility

Recomputed marginal probability density function of moment of inertia, annual libration amplitude, and tidal Love number k_2



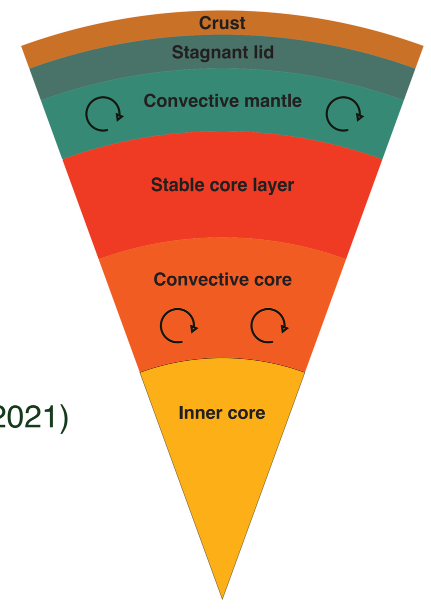
- best-fitting models agree well with MOI and libration amplitude
- predicted k_2 values are only marginally compatible with observations
  - k_2 estimate unreliable? (k_2~0.45-0.56, e.g. Mazarico+2014, Genova+2019, Konopliv+2020)
  - enstatite-rich mantle rheology is too stiff and not representative for Mercury's mantle →~25% reduction in rigidity is required to match measured k_2 (can be achieved by including mantle-softening sulphides, see below)

Interior structure inference from thermal constraints and long-period libration

Scope

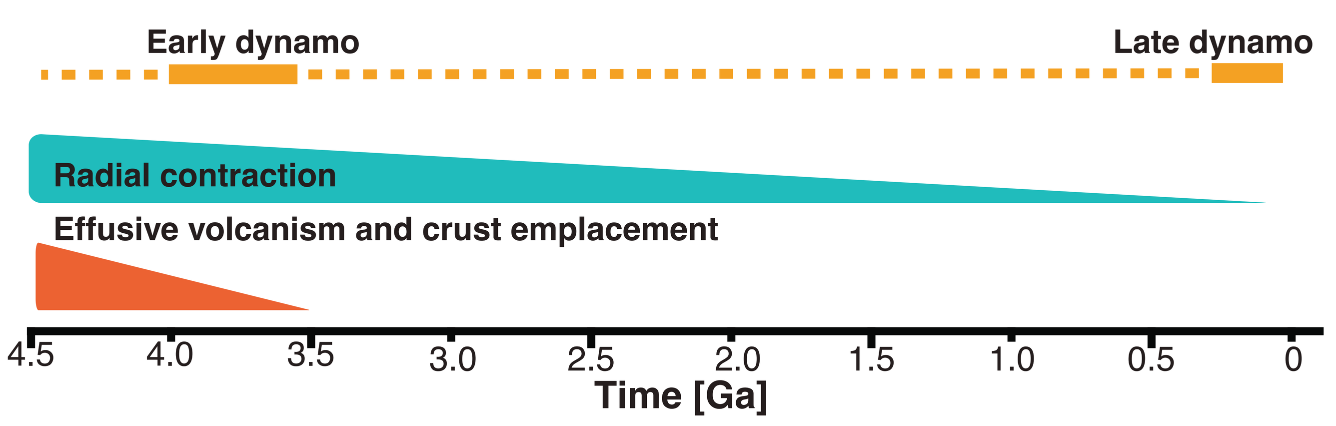
- Whole planet thermal evolution studies (e.g. Davies+2024, Knibbe+2025, Lécaille+2026) as well as numerical dynamo simulations (e.g. Kolhey+2025) that agree with thermal evolution constraints and magnetic field features require an inner core
- The measured long-period forced libration time series (Xiao+2025) can be explained if Mercury has a large inner core (>1300km) (Rivoldini+2025)
- Assess how results from whole planet thermal evolution studies and self-consistent structure modelling can further improve our knowledge about Mercury's interior and determine whether those models agree with geodesy data and long-period libration

Thermal evolution model



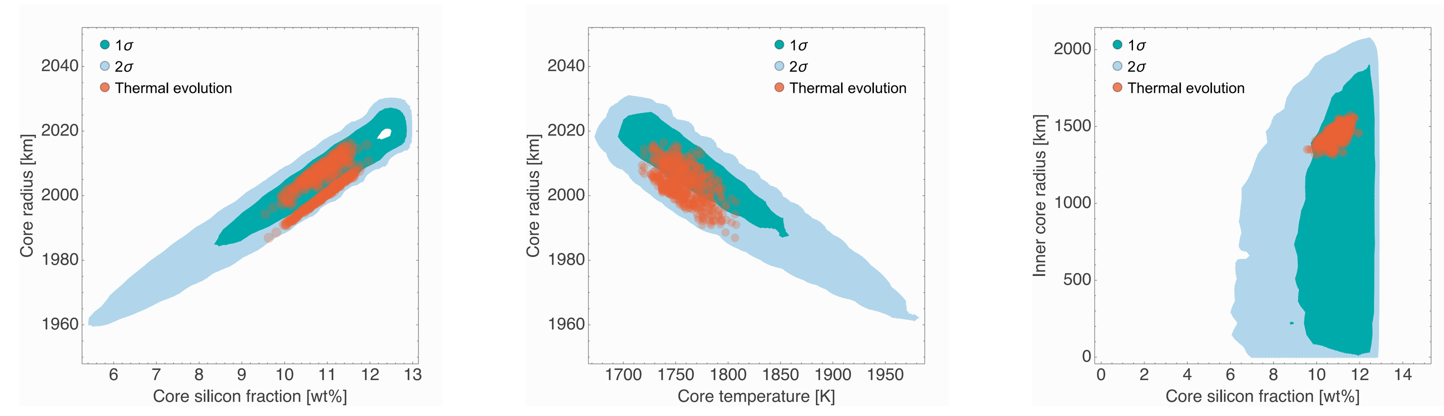
- Initial models are self-consistent (agree with mass), depend on mantle and core composition, and assumed starting thermal state
- Based on the same equations of state for mantle and core as in part one (mantle and core composition-dependent transport properties and melting parameterisation)
- Simulate thermal evolution using **TEMPURA** code (Baumeister+2023) for the mantle and **Thermal History** code for the core (Greenwood+2021)
- MC parameter space exploration: core radius, mantle viscosity, mantle composition, HPE enrichment factor, mantle temperature, CMB temperature

Thermal evolution constraints



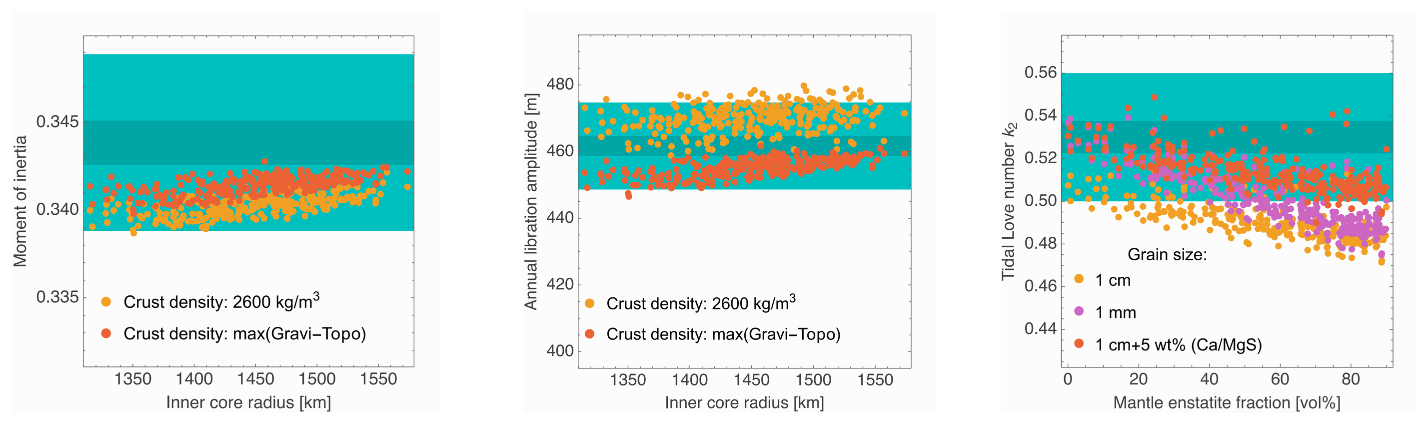
- Crust formation timing (90% before 1 Gyr) and thickness (15-60 km) (e.g. Padovan+2015, Byrne+2016, Sori+2018)
- Radial contraction (50% contraction by 1Gyr) (e.g. Di Achille+2012, Byrne+2014, Crane+2017, Watters+2021, Broquet+2026)
- Present-day upper core thermal boundary layer and inner core (e.g. Kolhey+2025)
- Past (0.5-1 Gyr) and present-day dynamo (e.g. Johnson+2015+2026, Narrett+2026)
- Parameter space: 50000 models → only 0.8% models satisfy constraints!

Thermal evolution versus geodesy-constrained models

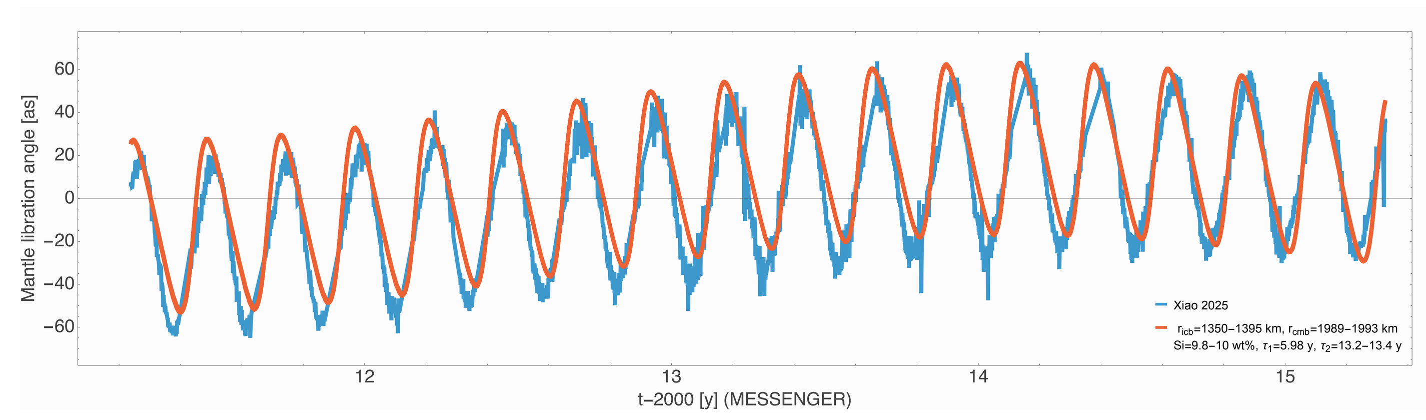


Confidence regions (1&2σ) of geodesy data-constrained interior structure models and models in agreement with thermal evolution constraints

Predicted geodesy observables



Moment of inertia, annual libration amplitude as a function of inner core radius and k_2 as a function of mantle enstatite fraction for different grain sizes and 5wt% sulphides. Results are shown for a low and maximal crust density.



Libration time series over MESSENGER era (Xiao+2025) and prediction of best-fitting thermal evolution models.

Conclusion

- Significant parameter space reduction and information about core structure can be achieved if geodesy data and results from thermal evolution simulations are combined (Inner core radius 380-1360 $km_{1\sigma}$ → 1315-1574 km)
- Thermally-constrained interior structure models with an inner core of 1350-1400 km and a libration normal mode period close to 5.93 (Jupiter orbit perturbation) agree best with the libration time series (core flattening ~50% of surface flattening)
- More precise observations (geodesy and thermal) expected from BepiColombo will further improve the above inferences

Rivoldini+2013, 10.1016/j.epsl.2013.07.021
Goossens+2022, 10.3847/PSJ/ac4bb8
Edmund+2022, 10.1038/s41467-022-27991-9
Namur+2016, 10.1016/j.epsl.2016.01.030
Terasaki+2019, 10.1029/2019JE005936
Dorogokupets+2017, 10.1038/srep41863
Stixrude+2024, 10.1093/gji/ggae126
Qu+2021, 10.1029/2021JB022504
Dumberry+2013, 10.1016/j.icarus.2013.03.001
Bertone+ 2021, 10.1029/2020JE006683
Konopliv+ 2020, 10.1016/j.icarus.2019.07.020
Davies+2024, 10.1016/j.epsl.2024.118812
Knibbe+2025, 10.1016/j.pepi.2025.107348
Kolhey+2025, 10.1029/2024JE008660
Xiao+2025, 10.5194/epsc-dps2025-325
Rivoldini+2025,10.5194/epsc-dps2025-1543
Lécaille+2026, 10.5194/epsc2026-648
Baumeister+2023, 10.1051/0004-6361/202245791
Greenwood+2021, 10.1016/j.pepi.2021.106763
Padovan+2015, 10.1002/2014GL062487
Byrne+2016, 10.1002/2016GL069412
Sori+2018, 10.1016/j.epsl.2018.02.033
Di Achille+2012, 10.1016/j.icarus.2012.07.005
Byrne+2014, 10.1038/ngeo2097
Crane+2017, 10.1002/2017GL072711
Watters+2021, 10.1038/s43247-020-00076-5
Broquet+2026, 10.1029/2025JE009584
Johnson+2015, 10.1126/science.aaa8720
Johnson+2026, 10.1073/pnas.2535723123
Narrett+2026, 10.1073/pnas.2608701123

This work was financially supported by the Belgian PRODEX program managed by the European Space Agency in collaboration with the Belgian Federal Science Policy Office