EPSC Abstracts
Vol. 7 EPSC2012-517-1 2012
European Planetary Science Congress 2012

Seismological Observables Inferred from Structural Models of Mercury's Interior

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Abstract

The MESSENGER mission conducted measurements of the mass, moment of inertia factor, and mantle moment of inertia of Mercury. The corresponding measurement uncertainties translate into an imprecise knowledge of Mercury's interior structure beyond that owing to the inherent non-uniqueness of the inversion problem. Exploring the resulting model space, we construct a suite of a few hundred spherically symmetric structural models with varying crustal thicknesses, core radii and sulfur contents. These are evaluated for seismic travel times and ray paths in order to identify discriminants suitable for future seismic experiments aimed at the determination of key parameters of Mercury's interior.

1. Observational Constraints

From radio tracking of the MESSENGER spacecraft, Smith et al. [1] derived a spherical harmonics expansion of Mercury's gravity field, which yields estimates for the mass and moment of inertia factor of the entire planet. Using earth-based radar observations of the planet's rotation state, Smith et al. could also estimate separately the moment of inertia of the planet's rigid outer shell (usually identified with the silicate mantle), based on the theory of Peale [2]. The possibility to distinguish a rigid outer and a liquid inner shell imposes most reliable constraints on Mercury's core size in terms of the core-mantle-boundary radius.

Mercury's radius is taken as R=2439.1 *km*. From the planeto-centric constant of gravitation, we derive Mercury's mass as $M = (3.3012 \pm 0.0004) \times 10^{23}\,kg$, using the CODATA 2010 recommended value for Newton's gravitational constant, $G = (6.67384 \pm 0.0008) \times 10^{-11} m^3 kg^{-1} s^{-2}$ [3]. The uncertainty in mass mainly results from the uncertainty in Newton's gravitational constant. The moment-of-inertia factor used in the present study is $C/MR^2 = 0.353 \pm 0.017$, the moment of inertia of the solid shell, normalized to the moment of inertia of the whole planet, is given by [1] as $C_M/C = 0.452 \pm 0.035$.

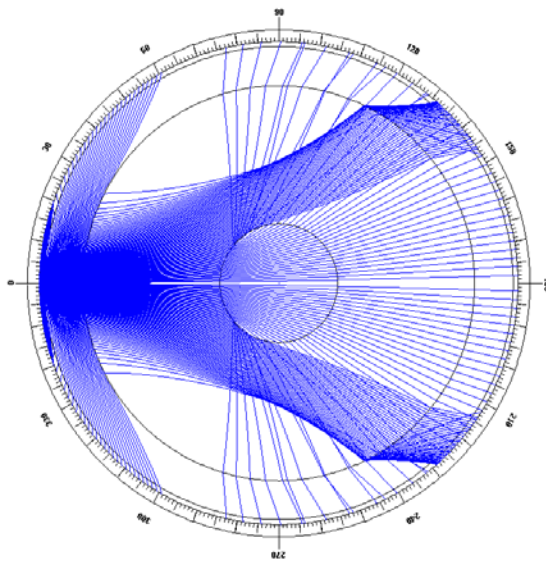

Fig. 1: P, PKP, and PKIKP ray paths from a surface source on the left side of the planet, computed for a Mercury model with a 50 *km* thick crust, a core radius of 1996 *km*, and a solid inner core of 600 *km* in radius.

2. Interior Structure Modeling

We construct radially symmetric ("1D") spherical models that all have the same four layer type structure consisting of

1. a crust layer predominantly composed of plagioclase;
2. a peridotitic mantle composed of olivine;
3. an iron-rich Fe-FeS liquid outer core;
4. a pure iron solid inner core

Hydrostatic equilibrium is assumed with pressure is integrated alongside an adiabatic temperature profile, and the relative fractions of the mantle constituents as well as the sulfur content of the outer core are adjusted according to the respective equations of state and Voigt-Reuss-Hill averaging as to fit the observational constraints.

Free parameters of the model construction are the radius of the inner core and the thickness of the crust. Variation of the inner core radius strongly affects the sulfur content that is admissible for the outer core, as the density distribution of the core is required to match the observed moment-of-inertia factor. The outer core radius is comparatively well constrained. Please note that our compositional models of the core are restricted to the iron-rich side of the eutectic.

5. Seismic Travel Times and Ray Paths

Once composition and radial density distributions are defined, the propagation velocities of seismic P and S waves can be derived from Voigt-Reuss-Hill averages of the elastic properties of the constituents in each layer. It is then straightforward to compute seismic travel time curves and ray paths [4 and references therein].

A key question is: What kind of seismological observations would be best suited to further reduce the ambiguity of interior structure modeling? Provided a sufficient amount of seismic data were available, travel time inversion could result in a detailed and unique interior structure model. However, the acquisition of an extensive data set under harsh environmental conditions at Mercury's surface is challenging, so that it would be favorable to reduce the necessary amount of data as much as possible by identification of the most crucial observations.

To this end, we compare travel time curves for the most important seismic phases and derive relations between possible ranges of observational and key interior structure parameters. The distances and travel times at which legs of travel time curves begin and end, like the beginning of the core shadow, the closest distance at which core phases are observable, or the relative arrival times of core reflected phases, among others, are studied to infer in a parametric way how travel time curves depend on the planet's interior structure.

6. Results

Preliminary models indicate that all constraints can be satisfied within their respective uncertainties by core radii around 2000 km. The entire olivine continuum from pure forsterite to pure fayalite is admissible for the composition of the mantle. Those models that best reproduce both the mean moment-of-inertia factor of the whole planet and the mean normalized moment of inertia of the solid shell have mantles consisting of an about 50/50 mixture of forsterite and fayalite, or mantles rich in periclase.

Computations of P wave paths suggest that an antipodal focusing of elastic waves from impact sources does not occur. The reasons are twofold: first, the "focal length" of the liquid core does not fit and second, a solid inner core acts as a dispersing lens.

Acknowledgements

This research has been supported by the Helmholtz Association through the research alliance ''Planetary Evolution and Life''.

References

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