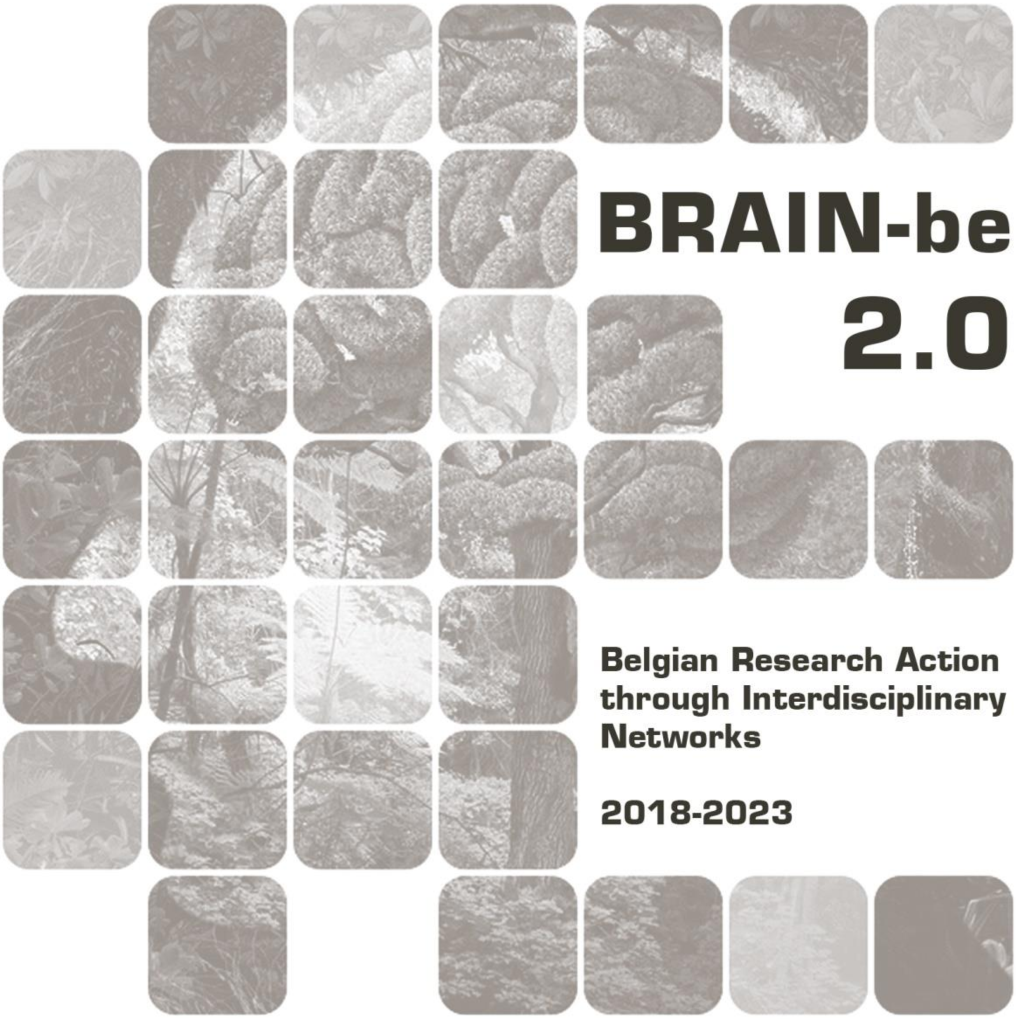

STEM

The STructure and Evolution of Mercury's core

Tim Van Hoolst (Royal Observatory of Belgium)

Pillar 1: Challenges and knowledge of the living and non-living world

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NETWORK PROJECT

STEM

The STructure and Evolution of Mercury's core

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FINAL REPORT

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TABLE OF CONTENTS

ABSTRACT

Mercury is the only terrestrial planet of the Solar System, other than the Earth, to have a magnetic field generated by dynamo action in its core. Spacecraft data also indicated that the core contributes a much larger fraction to the total mass of the planet than do cores of the other terrestrial planets and also gave clues about the composition of the core. Many other, often even basic, characteristics of the core are not yet known. For example, firm evidence of the existence of a solid inner part of the otherwise liquid core is still lacking but also the general thermal and chemical evolution of the core and the working of the dynamo mechanism remain shrouded in mystery. With STEM, we aimed at reaching a better insight into the core of Mercury by improving modelling approaches used for the interpretation of geodesy data. Planetary geodesy, the field of study of the rotation, gravity field and shape of a planet, currently gives the clearest view on Mercury's core, but requires theoretical models to link the observational data to the interior. We reached new and significant results on the evolution of the core of Mercury and of the whole planet, and on the interaction between rotation variations of the mantle and flow and magnetic field generation in the core. This report describes the activities performed and results obtained within the project STEM.

Keywords

Planet – Mercury – Interior structure – Evolution – planetary geodesy

1. INTRODUCTION

This project focused on Mercury, the smallest and innermost planet in the Solar System, which has several unique characteristics that can help improving our understanding of planetary formation, structure, evolution, and habitability. In order to improve the interpretation of data obtained by the NASA mission MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging), the first spacecraft to orbit the planet (2011-2015), and to prepare for ESA's BepiColombo mission, scheduled to arrive at Mercury in December 2025, theoretical models about Mercury's interior, evolution and dynamics have been developed. This has been made possible by joining different but complementary competences in planetary sciences in one institute, the Royal Observatory of Belgium.

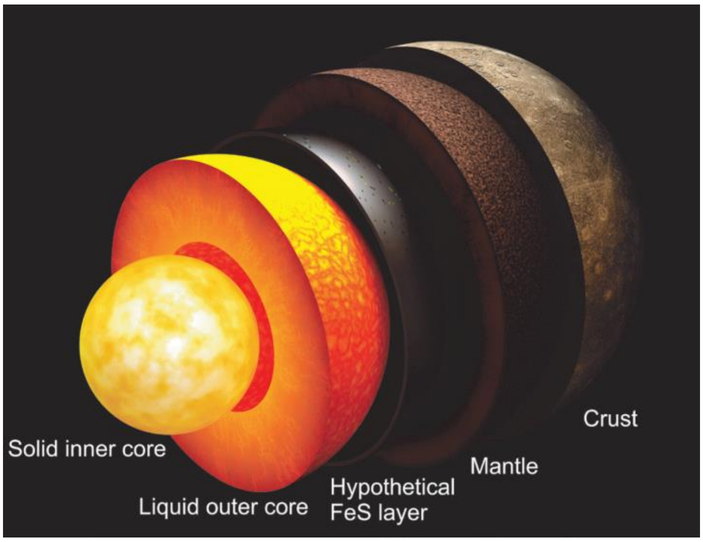

Figure 1: The interior structure of Mercury. The relatively thick crust (~40 km) overlies the comparatively thin mantle (~400 km). The liquid outer core has a radius of ~2,000 km and the central part of Mercury is probably a solid core having a radius of ~1,000 km (from Charlier and Namur 2019).

2. STATE OF THE ART AND OBJECTIVES

Mercury, the smallest and innermost planet in the Solar System, has several unique characteristics that can help to improve our understanding of planetary formation, structure, evolution, and habitability. The first mission ever to fly by Mercury, Mariner 10 in 1974, showed that Mercury is much more massive than its size suggests compared to the other terrestrial planets. This indicates an unusually high metal to silicate ratio and an iron core that is relatively to the size of the planet much larger than that of the Earth, Mars and Venus. Mercury has by far the most elliptical orbit around the Sun of any other Solar System planet and is the only Solar System body in a 3:2 spin-orbit resonance -- meaning that Mercury spins on average exactly three times during the time it needs to complete two full orbits around the Sun. This unique property leads to small periodic variations in Mercury's rotation rate that can be used to probe the deep interior, the central topic of this research project. Observations of these librations, by Earth-based radar (Margot et al. 2007) and by radio tracking and laser altimeter measurements (Mazarico et al. 2014, Stark et al. 2015, Genova et al. 2019) of the NASA MESSENGER spacecraft, revealed that the core is mechanically detached from the solid mantle and therefore must be liquid close to the core-mantle interface. Mercury also features a relatively weak, global magnetic field generated most likely by fluid flows in its molten and electrically conducting core, not unlike Earth's geomagnetic field (Johnson et al. 2018). Mercury is the only other example of a terrestrial planet with a self-sustained magnetic field, apart from Earth, which makes it invaluable in order to test and develop planetary magnetism theories.

The aim of this project was to improve and refine our understanding of the formation and evolution of Mercury's interior from current and future rotation data, complemented by other geophysical data, by developing two separate but closely related pathways, building upon the expertise within the planetary research group at the Royal Observatory of Belgium. We planned to extend libration theory to include flow in the outer liquid core and developed a new thermal modelling of Mercury's core to aid and improve the interpretation of geodesy data in terms of interior properties. Planetary geodesy - the study of the rotation, gravity field and shape of a planet – currently constitutes the main source of information on Mercury's interior.

Because of its 3:2 spin-orbit resonance, Mercury experiences periodically reversing gravitational torques exerted by the Sun, resulting in a libration with a period equal to the orbital period of about 88 days. Basic libration theory shows that the amplitude of libration is inversely proportional to the polar moment of inertia of the layers taking part in the libration motion. If Mercury were to be entirely solid, the whole planet would participate in the libration as a solid body and the amplitude of libration would be inversely proportional to the polar moment of inertia of Mercury. Earth-based radar measurements showed a libration amplitude more than twice that expected for an entirely solid planet indicating that only a fraction of the planet participates in the motion. This led Margot et al. (2007) to suggest the existence of a liquid core in Mercury.

Peale et al. (2002) showed that pressure forces on irregularities at the core-mantle boundary and magnetic coupling between the conducting liquid core and a conducting layer in the bottom mantle cannot modify the libration amplitude based on the moment of inertia of the mantle to a level above current and future expected uncertainties. An inner core can decrease the amplitude of libration through coupling with the mantle (Van Hoolst et al. 2012, Dumberry et al. 2013). These studies assume that flow in the liquid outer core with respect to the mantle is either absent or given by an essentially rigid body rotation around an equatorial axis. Nevertheless, rotational variations, such as librations caused by gravitational torques acting on Mercury, can induce substantial internal flows (e.g. Le Bars et al. 2015). In particular, resonances with internal modes of the fluid core may amplify the librational motion. Here we planned to study the effect of inertial oscillations of the fluid core on Mercury's librations. The inertial oscillations owe their existence to the presence of Coriolis forces within the fluid (Greenspan, 1968). Although a relatively large amount of literature exists on inertial oscillations (waves and modes), they still remain puzzling (see e.g. Rieutord and Valdettaro 2018). Triana et al. (2019a) demonstrated how inertial modes in a two-layer planet can exert torques on the mantle (and vice versa) leading to changes in both frequency and damping of the inertial modes and also to changes in the mantle's spin direction. To infer Mercury's internal structure based on current and future measurements of its rotation, an accurate fluid dynamical model is needed that takes into account the coupling between inertial eigenmodes of the fluid core and the rotational dynamics of the mantle (and solid inner core). The development of such a model constituted one of the main objectives of this project.

To interpret geodesy data in terms of the interior of Mercury, interior structure models are required that connect the interior to the quantities that can be derived from the observational data. Libration gives mainly information about the polar moment of inertia of the mantle, depends to a much lesser effect on the moments of inertia of the inner and outer core, and may also be affected by flow in the outer core (as explained above). Other geodesy data that directly inform on the deep interior are the orientation of Mercury in space and tides, which are described by Love numbers. The geodesy data therefore give information on the mass distribution (through the moments of inertia), deformation, and potentially fluid flow. They therefore are related to the internal density and (visco-)elastic properties of the planetary materials. In interpreting the data, it is essential to consider only models that are physically consistent and do not contradict other knowledge about Mercury. This implies for example that the models must take into account data about Mercury's composition, are based on material properties of constituent materials, and that only core structures should be studied that can be expected to be realistic. In particular, models of Mercury's interior must be consistent with the existence of a current and ancient magnetic field, and a likely inner core must be compatible with melting data relevant for the considered core composition. It is therefore important to construct a good model of the temperature inside the core of Mercury that is in agreement with constraints on its past and present thermal state. The second major objective of this project was to develop a model describing the evolution of the core temperature.

Upon obtaining results from both models, core evolution theory and core fluid dynamics, we planned to re-interpret the current geodesy data to determine improved constraints on the deep interior of Mercury. The models also build upon the results obtained in the previous, international and interdisciplinary BRAIN-be project COME-IN (Constraining Mercury's Interior, 2014-2019), in which several complementary lines of investigation were integrated, related to the crust, mantle and core of Mercury, including performing novel high-pressure experiments and developing advanced theoretical modelling. What is truly unique in this project is that we planned to couple sophisticated rotation modelling with state-of-the-art fluid mechanics of the core and innovative modelling of the evolution of Mercury's core. Those topics are normally considered in separate lines of research, but are all essential in reaching our goal, which was to construct a theoretical model that allows for the best interpretation of Mercury's existing geodesy data. The project will also contribute significantly to the science preparation and exploitation of the ESA/JAXA BepiColombo mission, launched to Mercury in 2018 with arrival foreseen in 2025, in which the Royal Observatory of Belgium is a central partner.

3. METHODOLOGY, SCIENTIFIC RESULTS AND RECOMMENDATIONS

The project consists of three Work Packages (WP). The objective of the first WP is to develop new models of the thermal evolution of the core of Mercury. The second WP aims at investigating possible effects of fluid flow in the core on the rotation of Mercury. The results of the two work packages are used in WP3 to derive the best constraints on Mercury's interior and to assess differences with current theories neglecting the response of the fluid core flow on libration.

Work Package 1

In the first WP, we advanced our understanding of the evolution of Mercury's core. We had previously shown that the observed libration (small periodic variations around the mean rotation rate) together with the observed obliquity (the orientation of Mercury) strongly constrain the core size and density of Mercury but provide little information on a solid inner core. Additional constraints can be obtained from the thermal evolution of Mercury, in particular on the solid inner core and the stratification of the liquid outer core. An important feature of Mercury's core is that it highly likely has an upper layer that is stable to convection. When the heat flux through the core-mantle boundary becomes smaller than the heat conducted along the adiabat in the core, a stable layer develops at its top. In this thermally stratified layer, heat is transported by conduction and not by convection. In our model, and in contrast to previous studies in which the temperature profile is considered to be adiabatic throughout the core, the temperature profile in the convective layer is taken to be the adiabatic temperature and the temperature in the stable upper part of the core and in the solid inner core is determined from the conductive heat equation. The position of the interface between both layers varies in time and is determined by requiring continuity of temperature and heat flux. Three different thermal evolution models for the core that take into account the possible presence of this stably stratified layer were studied in the project. One method is a fully numerical solution method. In principle, such a numerical solution of the exact set of equations and boundary conditions provides the most accurate description of the thermal evolution of the core. Numerical difficulties associated with spatial convergence, stiffness of the diffusion equation, and an evolving interface between the convective and conductive layers make this approach challenging. Despite many efforts, including an implementation of a method proposed for the Earth by Labrosse et al. (1995), it was decided to focus further attention on methods involving some additional approximations or iterations to reach a solution.

The first method, a piece-wise steady-flux numerical scheme was developed to study the evolution of Mercury's core with a stable layer on top. The scheme is an extension of the method of Knibbe and van Westrenen (2018) and adopts a steady-flux solution of the conduction equation in each interval of a chosen discretization of the core in the radial direction. It imposes continuity of temperature at each grid point, which also guarantees energy conservation of the numerical scheme. We showed that discretization of the conductive region of a planetary core is only needed if heat fluxes vary rapidly with time, such as during a few hundred million years after the onset of stratification. We demonstrated that thermal stratification significantly influences the thermal evolution of Mercury's core and the heat flux from the core into the mantle. We also elucidated differences in the evolution of a stratified layer between the Earth and Mercury.

In the second method, we adopted an iterative solution scheme developed by Greenwood et al. (2020) for the Earth. We showed that this method and the previous method show excellent agreement. We performed an extensive set of calculations of the evolution of Mercury in this method. We first considered a constant heat flux out of the core to be able to focus on the physical mechanisms acting in the core. This approach has allowed us to understand that the cooling history of the convective core beneath the stable layer is almost insensitive to the core-mantle boundary heat flux because of conservation of energy flux at the interface. The smaller that heat flux is, the larger the stably stratified layer and the smaller the convective core. The time of onset of inner core nucleation is independent of the heat flux through the CMB when a stable top layer exist, but is strongly different from cases without stable layer. We also showed that Mercury cannot have a dynamo when a stable layer is present, except when an inner core is growing. The presence of a solid inner core growing in the center of the core generates buoyancy forces (latent heat and gravitational energy) acting against the stratification. Therefore when the inner core forms in a partly stratified core, the stratified layer shrinks due to the buoyancy forces supplied by the growing inner core. The larger the inner core, the more powerful the buoyancy forces and the lower the impact of stratification on the core evolution.

The heat flow out of the core depends on the evolution of the mantle. We therefore coupled the evolution of the core to that of the mantle. An important conclusion from these studies is that there is significant feedback between the evolution of the core and that of the mantle, in contrast to for example the evolution of the Earth. A complication was that convective energy transport may not be the dominant heat transport mechanism during Mercury's entire history because Mercury's mantle is thin. The transition from a convective to a conductive state is not captured well in existing parametrized evolution models of Mercury. As a result we also developed a new parameterized model of the evolution of the mantle that smoothly transitions from convection to conduction.

The interior structure and evolution results depend sensitively on thermodynamic and transport properties of Mercury's core, which in turn depend on the core's unknown composition. We implemented different composition models based on the most recent data about iron alloys and also participated in laboratory measurements of those data. We considered models consisting of Fe and S, of Fe and Si, and of Fe and both light elements S and Si. We also considered different sizes of the core. Our self-consistent model of the coupled evolution of the core and the mantle allows to put realistic constraints on Mercury's interior. We showed that a stable layer in the core delays cessation of mantle convection and allows for a past and present-day dynamo, in accordance with observations. We demonstrated that Mercury's core must likely have other light elements than silicon otherwise Mercury could not have a dynamo operating at present time. Models with a small fraction of S have a present-day inner core of ~1000km, a ~600km thermal boundary layer, and generate sufficient ohmic dissipation to drive a past and present-day dynamo. Our results also show that the cessation of mantle convection decreases the thickness of the thermally stratified layer and increases ohmic dissipation.

WP3 has been mostly integrated into WP1 as we demonstrated in WP2 (See below) that flow in the core will not affect the interpretation of observed libration because of its small effect.

Several articles have been published or are in preparation about these results (see Sect. 5). We also presented our results at various international scientific conferences, including four invited talks and one keynote lecture (Sect. 4).

Work Package 2

To goal of WP2 was to develop a model that couples the rotation of Mercury to flow and waves in its liquid outer core. To calculate the flow in the liquid core of Mercury, we considered a homogeneous fluid in a spherical shell, bounded by the mean inner and outer core radie of Mercury, and adopted the Boussinesq approximation. We described the libration forcing of the mantle by a superposition of three motions of the core-mantle boundary: an oscillation in the longitudinal direction and two oscillations of the radial coordinate of the core-mantle boundary resulting from the triaxial shape of the boundary. We determined the response of the core fluid to the forcing by solving the MHD equations in a reference frame rotating with the mean angular rotation velocity. The values of the dimensional parameters that control the motion, the Ekman number, the magnetic Ekman number, the Lehnert number and the Prandtl number, are chosen in a range of values that is as close to the expected values in Mercury's core as is numerically possible. We use an optimized spectral decomposition of the variables in the radial direction and solved the resulting equations with the KORE code (https://github.com/repepo/kore).

Torques at the core-mantle boundary are the main mechanism of transferring angular momentum between the mantle and the core. We neglected torques at the inner core boundary because the libration of the solid inner core is expected to be an order of magnitude smaller than that of the mantle. We considered two types of torques: a viscous torque and an electromagnetic torque. The viscous torque is related to tangential stresses at the core-mantle boundary, and the electromagnetic torque results from the action of Lorentz forces in a conductive layer at the bottom of the mantle. We showed that the viscous torque is about 4 orders of magnitude smaller than the total torque needed to drive Mercury's mantle libration for realistic values of the Ekman number. We can therefore conclude that the viscous torque can be neglected in studies that interpret the observed amplitude of the 88 day libration of Mercury in terms of the interior structure of the planet since the amplitude is only known to within a few percent. By considering a thin, electrically conductive layer at the bottom of the mantle, and assuming a background dipolar magnetic field permeating the planet, we were able to compute the associated electromagnetic torque. This torque turns out to be even smaller in magnitude compared to the viscous torque, so it is negligible as well.

Since Mercury is expected to have a stably stratified layer at the top of the core, we specifically considered how such a layer can affect the core flow. The viscous torque was shown to slightly increase by top layer stratification. No such effect was observed for the electromagnetic torque, that seems unaffected by the presence of stratification near the core-mantle boundary. When the top part of the core is stably stratified, the waves that can propagate in it are gravito-inertial waves. For frequencies significantly smaller than the Brunt-Väisälä frequency, as is expected to be the case for libration forcing, both the particle motion and the energy propagation of the waves is dominantly in the horizontal direction in the stable layer. Gravito-inertial modes then have a much smaller kinetic energy density in the stable layer than in convective region below because radial motion is suppressed in the stable layer. Flow in response to libration forcing has a spatial structure similar to that of the inertial mode closest in frequency to the libration frequency. For top stratification, the flow in the core will therefore be restricted to the layer close to the CMB. It will be larger than in the absence of stable stratification, leading to a larger torque (see Fig. 2).

An important effect of a stably stratified outer layer is that radial forcing generates a strong tangential flow near the CMB. This pumping mechanism is stronger with decreasing viscosity. The flow induces a non-axisymmetric magnetic field that might explain features in the observed magnetic field of Mercury.

Those results have been presented at two major scientific conferences on planetary sciences and an article describing the methods and results is submitted for publication in a scientific journal.

The project constituted an important step towards a more profound understanding of the structure, fluid dynamics and evolution of Mercury. Such studies are essential to interpret data about Mercury’s interior and to assess the reliability of the constraints the observations put on the interior. The results will contribute largely to a better interpretation of measurements to be made by the upcoming BepiColombo mission to Mercury. The project opens many future lines of research. The results and methods developed will, for example, help unraveling how Mercury could have had a global magnetic field in its early history and also at present, and help understanding the observed characteristics of the magnetic field.

The project also strengthened the position of Belgium within international research initiatives like BepiColombo. It provided scientific support to the Belgian science policy makers and has stimulated research in planetary sciences in Belgium in general and at the Royal Observatory of Belgium, where planetology belongs to the strategic scientific priorities.

In addition to improving our understanding of Mercury, the project results are also useful for comparative planetology. For example, our level of knowledge on Mercury’s interior is becoming comparable to that of Mars, necessary for a detailed comparison of both planets. Our results have provided deeper insight into the diversity of the terrestrial planets and helps better appreciating the different evolution tracks a terrestrial planet can follow. It therefore also has implications for the study of terrestrial-like exoplanets, a topic of intense international investigations.

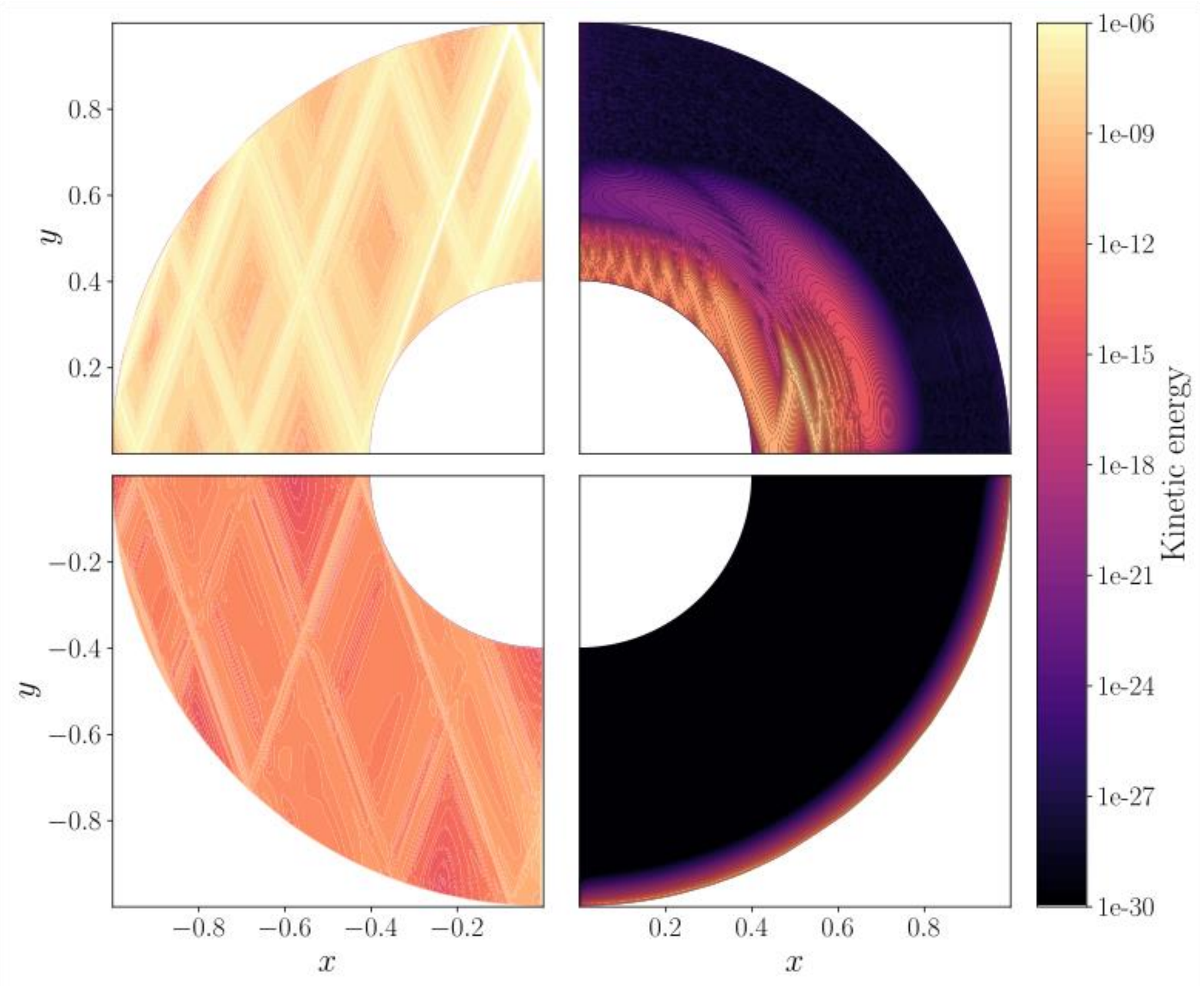

Figure 2: Meridonial cuts of the kinetic energy density in a simple model of Mercury's fluid outer core. Top row: eigenmode closest to the libration frequency. Bottom row: core flow in response to a libration forcing at the core-mantle boundary. Left column: without stratification. Right column: neutrally stratified core smoothly transitioning into a stably stratified layer at the top of the core with Brunt-Väisälä frequency equal to 100 times the orbital frequency at the CMB.

4. DISSEMINATION AND VALORISATION

Contributions at scientific conferences:

1. Knibbe J., Rivoldini A., Luginbuhl S., Namur O., Charlier B., Mezouar M., Sifre D., Berndt J., Kono Y., Neuville D., van Westrenen W., and Van Hoolst T., 2021, "Mercury's Interior Structure constrained by Density and P-wave Velocity Measurements of Liquid Fe-Si-C Alloys.", EPSC 2021, abstract EPSC2021-756, in TP1 – Planetary Dynamics: Shape, Gravity, Orbit, Tides, and Rotation from Observations and Models, EuroPlaNet Science Congress 2021, virtual meeting, EPSC2021-756, 13-24 September 2021.
2. Knibbe J., Rivoldini A., M.Luginbuhl S., Namur O., Charlier B., Mezouar M., Sifre D., Berndt J., Kono Y., Neuville D., Van Westrenen W., and Van Hoolst T., 2021, "Constraining Mercury's Interior Structure by Density and P-Wave Velocity Measurements of Liquid Fe-Si-C Alloys.", MR22A-06, AGU Fall Meeting, New Orleans and online, 13-17 December 2021 (invited)
3. Knibbe J., Rivoldini A., Luginbuhl S., Namur O., Charlier B., Mezouar M., Sifre D., Berndt J., Kono Y., Neuville D., van Westrenen W., and Van Hoolst T., 2021, "Mercury's Interior Structure Constrained by Density and P-Wave Velocity Measurements of Liquid Fe-Si-C Alloys.", BepiColombo GGWG virtual meeting, 18 June 2021 (invited)
4. Zhao, Y., Deproost, M.H., Knibbe, J., Rivoldini, A., Van Hoolst, T., 2022, Evolution of the thermally stratified layer in the outer core of Mercury, European Geosciences Union General Assembly, Vienna, Austria
5. Seuren, F., Triana, S.A., Rekier, J., Van Hoolst, T., Dehant, V., 2022, The influence of a stratified core on Mercury's librations, European Geosciences Union General Assembly, Vienna, Austria (invited)
6. Van Hoolst, T., Rivoldini A., Zhao Y., Knibbe J., Baland R.M., Beuthe M. 2022, Mercury's deep interior and evolution: A perspective from geodesy and geophysics, 'Mercury 2022: Current and future science of the innermost planet', Orléans, France, 7 -10 June (keynote talk)
7. Charlier, B., Namur, P., Beuthe, M., Genova, A., Van Hoolst, T., 2022, A consistent model for the chemical, mineralogical, and physical characteristics of Mercury's crust, 'Mercury 2022: Current and future science of the innermost planet', Orléans, France, 7 -10 June
8. Rivoldini, A., Deproost, M.H., Zhao, Y., Knibbe, J., Van Hoolst, T., 2022, The effect of a thermally stratified layer in the outer core of Mercury on its internally generated magnetic field, Study of the Earth's Deep Interior (SEDI), Zürich, Switzerland
9. Rivoldini, A., Deproost, M.H., Zhao, Y., Knibbe, J., Van Hoolst, T., 2022, The effect of a thermally stratified layer in the outer core of Mercury on its internally generated magnetic field, European Planetary Sciences Congress, Granada, Spain
10. Knibbe, J.S., Zhao, Y., Rivoldini, A., Van Hoolst T., 2022, Parametrizing the thermal evolution of a convective mantle that becomes conductive, European Planetary Sciences Congress, Granada, Spain
11. Knibbe, J., 2022 Some technical challenges for parametrized one-dimensional thermal evolution models of Mercury, Europlanet Science Congress 2022, Granada, Spain (invited)
12. Seuren, F., Rekier, J., Triana, S. A., and Van Hoolst, T., 2022, The core flow induced by Mercury's libration: density stratification and magnetic fields , European Planetary Science Congress 2022, Granada, Spain

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Evolutionary constraints on Mercury's interior
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6. ACKNOWLEDGEMENTS

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