Subject title: Interior structure of Mercury and Venus from gravity and topography

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Financing: Doctoral contract with or without teaching assignment

Presentation of the subject:

The interior structure of the terrestrial planets is a reflection of how they formed and evolved over geologic time. One manner to investigate the present-day subsurface of a planet is through the analysis of gravity and topography data that can be acquired by orbiting spacecraft. Lateral variations in the gravity field and surface elevation are known to be a result of processes that are occurring in the crust, mantle and core. The longest wavelength signals are generally dominated by density anomalies in the mantle (e.g., Kiefer al., 1986, James et al., 2015), and shorter wavelength signals are usually a result of processes occurring in the crust (Wieczorek, 2015). The analysis of the mantle derived signals can provide key constraints on fundamental properties, such as the mantle viscosity profile and the spatial distribution and amplitude of mantle density and temperature anomalies (Pauer et al., 2006; Maia et al., 2023).

Constraining the interior structures of Mercury and Venus are major objectives of two upcoming European space missions: BepiColombo (with a science phase starting in early 2027) and EnVision (with an expected launch in 2031). Though this thesis project will initially focus on using pre-existing datasets from the MESSENGER and Magellan missions, these upcoming missions will eventually provide improved datasets with global coverage and unprecedented resolution. They will also make precise geodetic measurements of the tidal response and rotational state of the two bodies, which are also sensitive the planet's interior structure. Data from BepiColombo will be made available in the first half of this thesis project, and results from the proposed Venus investigation will be instrumental for interpreting future data from EnVision. Members of this project participate in the science teams of both missions. In particular, Mark Wieczorek is a co-investigator of the BepiColombo laser altimeter that will provide a global shape model of Mercury and he is also a member of the EnVision radio science investigation. The student will have early access to BepiColombo mission-related data and will be included in both mission science teams.

In this thesis project, the Ph.D. candidate will model the dynamic gravity signatures of Mercury and Venus using well-established loading models of mantle viscous deformation (e.g., Hager and Clayton, 1989). The dynamic gravity signal resulting from mantle flow can be expressed as the sum of contributions from mantle density anomalies and from flow-induced displacements at the surface, core–mantle boundary, and internal compositional interfaces. These displacements depend critically on the mantle viscosity structure, which is closely linked to the planet's geodynamic history. In addition to using the quasi-analytical model of Hager and Clayton (1989) to predict the gravitational signature from mantle convection, the Ph.D. candidate will also make use of more realistic numerical mantle convection simulations from the GAIA and StagYY codes in collaboration with Nicola Tosi (DLR, Berlin), Paul Tackley (ETH Zurich), and Julia Maia (ESA/ESAC).

For the planet Mercury, one of the most intriguing geophysical features is the Northern Rise, an approximately 1000 km-diameter swell associated with a large positive gravity anomaly. Its origin is consistent with a deep-seated mantle density anomaly (James et al., 2015), and anomalous magnetic field data in this region further suggest the presence of a deep anomaly located near the core–mantle boundary (Plattner and Johnson, 2021). This project will investigate this hypothesis by performing the first localized spectral admittance inversions of this region using viscous loading models to constrain the depth, size, and density of the anomaly. This will use techniques that we previously developed for Venus (Maia et al. 2023). Results from this analysis will help assess whether mantle density anomalies are plausible sources for these observations, whether they result from compositional or thermal anomalies, and whether there are any significant discontinuities in the mantle viscosity and density profile. In collaboration with Nicola Tosi (researcher at DLR and interdisciplinary scientist of the BepiColombo mission), we will test the plausibility of the existence and long-term stability of such an anomaly in Mercury's mantle using self-consistent 3D models of the thermo-chemical evolution of the mantle and core (e.g., Tosi et al., 2025). When new global models of the Mercury gravity field are made available in late 2027, it will be possible to investigate other regions where the gravity field is dominated by signals coming from the mantle.

For the planet Venus, the structure and dynamics of the mantle remain among the most poorly understood of all the terrestrial planets. The proposed mantle viscosity structures vary widely (e.g., Maia et al., 2023; McGregor et al., 2024), and the geodynamic regime controlling the planet's heat loss is highly debated (Rolf et al., 2022). This second project will focus on computing and analyzing the dynamic gravity and topography signatures predicted from an existing database of thermal evolution models developed by Paul Tackley and his team (ETH Zurich), who have produced state-of-the-art Venus geodynamic models for over a decade. These results will be used to help constrain Venus' geodynamic regime and to assess the relative contributions of thermal and compositional density anomalies in the mantle. From these models, it will be possible to assess the validity of the assumptions used in the quasi-analytical model of Hager and Clayton (1989), such as the effect of lateral variations in viscosity and the use of simple two-dimensional mass sheets to simulate mantle loads.

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