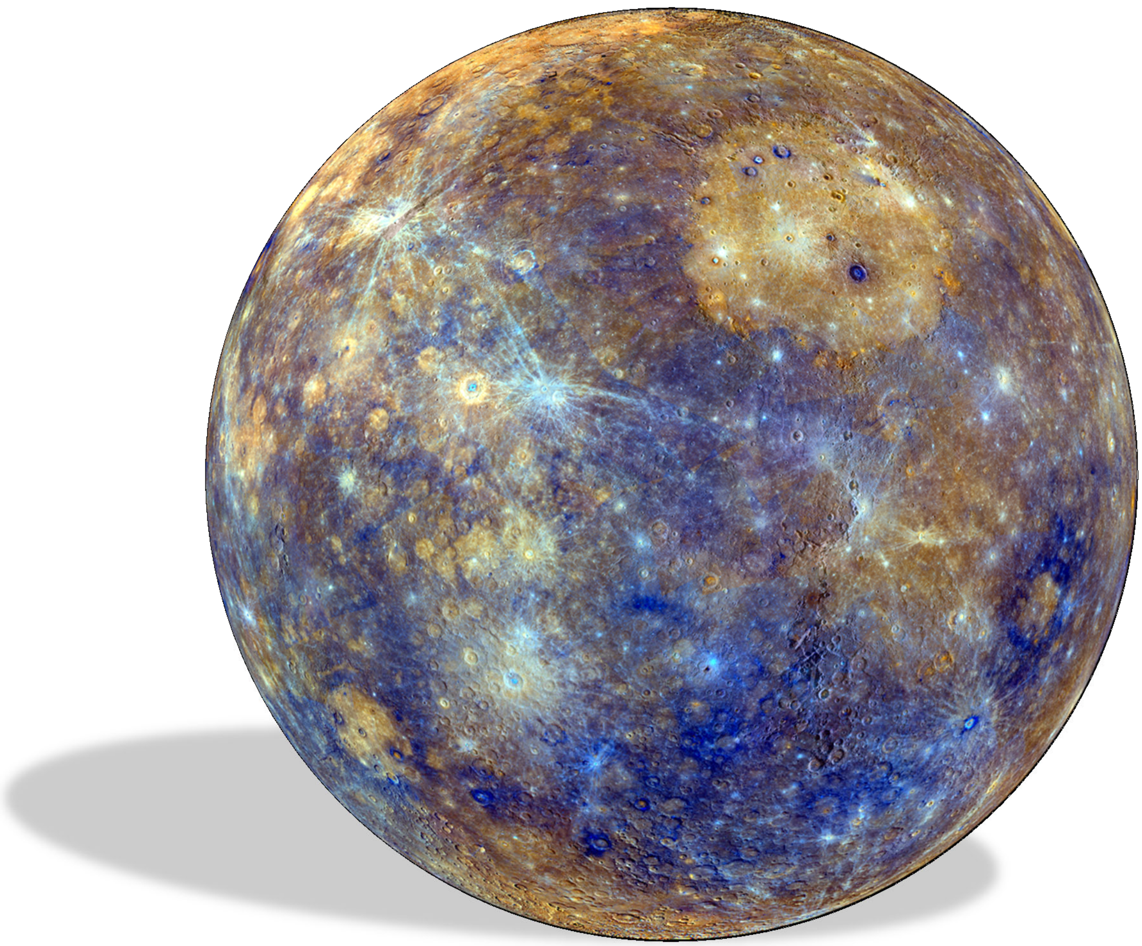
White Paper

on the case for

Landed Mercury Exploration

within the Voyage 2050 long-term plan in the ESA Science Program



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Executive Summary

Thanks to the NASA MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission, our understanding of the planet Mercury has advanced tremendously over the last years. The dual-spacecraft ESA–JAXA BepiColombo mission – currently in cruise phase and reaching Mercury orbit in Dec. 2025 — will greatly advance the orbital exploration of the innermost planet and promises further breakthroughs in Mercury science

Here, we present outstanding questions related to several aspects of Mercury's character and evolution that can be addressed either more fully, or uniquely, by a landed mission. We discuss major outstanding questions of Mercury science that encompass five categories, and suggest how they might be addressed. Those categories include:

- the planet's geochemical makeup;
- its interior structure;
- the geological evolution of Mercury;
- present-day processes at work there; and
- the planet's polar volatile inventory.

A ***Mercury Lander*** was initially conceived for the BepiColombo mission, but was not realized as a mission element due to the costs and complexity of combining an orbiter and a lander system. Again. we recommend exploration of Mercury through a ***Lander***, which will now greatly benefit from the heritage of the MESSENGER and the BepiColombo orbiter missions. This should be the next step in a systematic exploration of Mercury from orbit and will deepen our knowledge of our Solar System, the formation of the planets and about planet Mercury in particular.

1. Current and Planned Mercury Exploration

The arrival at Mercury in 2011 of NASA's MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) mission heralded a new age of exploration for this enigmatic planet (Fig. 1). The MESSENGER spacecraft *(Solomon et al., 2008)* was in operation at Mercury for a little more than four years, acquiring global observations of the planet's surface and measurements of the interior, exosphere, and magnetosphere. Thanks to MESSENGER, we now know Mercury to be a world that was once extraordinarily geologically active but with some surface processes that persist even today. It is also a planet with a composition and interior structure unlike that of the other terrestrial bodies in the Solar System, and which hosts complex interactions between an intrinsic magnetic field and a dynamic heliospheric environment. Our understanding of Mercury will be enhanced further by the arrival in 2025 of the joint ESA–JAXA BepiColombo mission *(Benkhoff et al., 2010)* that was launched in Oct. 2018; consisting of two individual spacecraft, BepiColombo will characterize in greater detail the planet's surface, its interior, and the interaction between its magnetosphere and the interplanetary solar wind.

Yet there is a limit to the scientific return of an orbiter mission: an orbiter cannot directly sample surface materials, for example, nor is it able to delve into the interior in the way that a landed mission can. Indeed, the planetary science community has long adopted a stepwise strategy of exploration that starts with flybys before moving to orbiters, and then to landers, rovers, and, ultimately, sample return *(NRC, 2011)*. Mercury was visited first by the NASA Mariner 10 spacecraft, which performed three flybys of the planet in the 1970s. With the successful completion of the MESSENGER mission, and the arrival in the next decade of BepiColombo, our exploration of Mercury stands to have accomplished the first two phases of this stepwise strategy. It stands to reason, then, that we should begin to consider the benefits of a landed mission at Mercury.

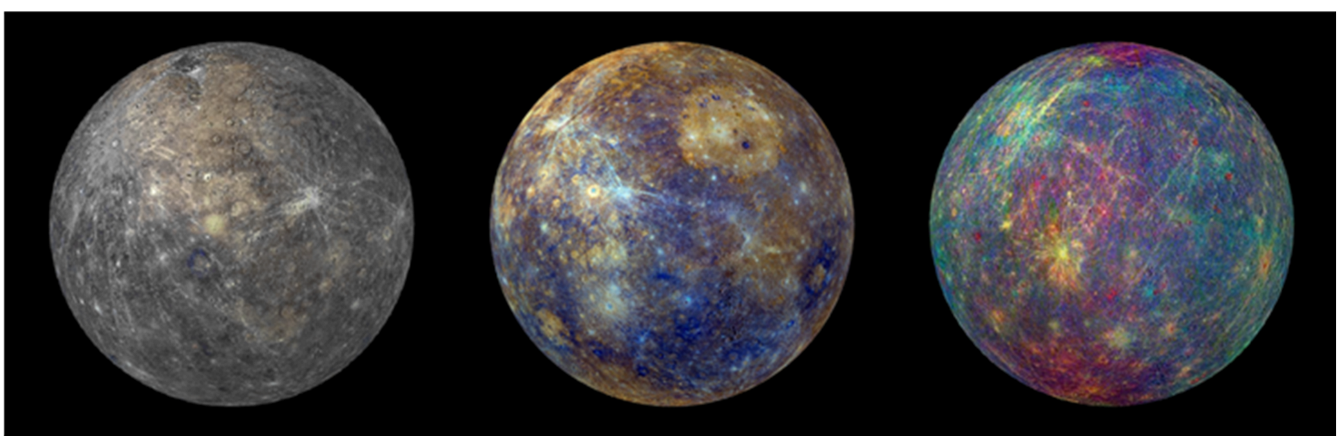

Fig. 1. The MESSENGER spacecraft returned unprecedented, global views of Mercury including, from left to right, color (1000, 750, and 430 nm in red, green, and blue), enhanced color, and compositional data. The BepiColombo mission is poised to build on that knowledge of the innermost plane. Image Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.

In this White Paper, we identify several key aspects of Mercury science that can be best addressed by such a mission. **Our goal here is not to advocate solely for a Mercury lander, but to demonstrate why such a mission architecture would represent a natural next step in the exploration of this planet.** Detailed determination of Mercury's composition, evolution, and interaction with its space environment are crucial for addressing the planetary science community's priorities to understand the beginnings of solar systems and how planets evolve through time *(NRC, 2011)*. To leverage the growth of knowledge—and its increasing depth—of the other bodies of the inner Solar System, it is necessary to develop a comparable understanding of Mercury.

We must therefore prepare for a steady stream of missions to the innermost planet over the coming decades, in which each builds upon its predecessor. With the potentially long cruise time from Earth, comparable to destinations in the outer Solar System, with BepiColombo on target approach, **the time to consider landed exploration of Mercury is now**.

2. The Case for Landed Mercury Science

In this section, we discuss several major aspects of Mercury's character and evolution where substantial knowledge gaps exist, but where our current understanding could be dramatically improved with data acquired from the planet's surface. We do not offer specific recommendations for any particular landed mission architecture, but we note where appropriate potential types of instrumentation that could aid in addressing these gaps. We emphasize that this discussion, though illustrative, is by no means exhaustive.

2.1. Geochemistry: Placing Mercury in Geochemical Context with Other Terrestrial Worlds

Geochemical observations obtained by the X-Ray Spectrometer (XRS) and Gamma-Ray and Neutron Spectrometer (GRNS) onboard the MESSENGER spacecraft revealed Mercury as a geochemical end-member among the terrestrial planets *(e.g., Nittler et al., 2011; Peplowski et al., 2011).* The high abundances of sulfur (>3 wt%) and low abundance of iron (<3 wt%) on the surface of Mercury indicate extremely low oxygen fugacity, such that Mercury is the most chemically reduced of the terrestrial planets *(e.g., Nittler et al., 2011; Zolotov et al., 2011; McCubbin et al., 2017).* In oxygen-starved systems, elements will deviate from the geochemical behavior that they exhibit at higher oxygen fugacities. In situ geochemical analyses would give new insight into these behaviors, allow for better interpretations regarding the thermochemical evolution of the planet, and provide substantial advances toward our understanding of planet formation.

Mercury is extremely diverse in terms of surface compositions *(e.g., Peplowski et al., 2015a; Weider et al., 2015; Vander Kaaden et al., 2017)* (Fig. 2) and is also volatile-rich *(e.g., Peplowski et al., 2011)*, an unexpected finding given the planet's heliocentric distance *(e.g., Albarède, 2009; Peplowski et al., 2011; Peplowski et al., 2014; Peplowski et al., 2015b).* Yet despite the insights provided by MESSENGER and those sure to come from BepiColombo, several outstanding compositional questions remain, including:

- the nature, origin, and abundance of Mercury's low-reflectance material;
- the mineralogy of the planet's varied surface materials; and
- the composition of diffuse deposits interpreted to be pyroclastic in nature.

Placing tighter constraints on the geochemical, mineralogical, and isotopic properties of the surface **can be accomplished through in situ compositional and petrological measurements** obtained from a lander mission equipped with geochemical and imaging instruments. Given Mercury's geochemical end-member characteristics, the results obtained from landed science would give us

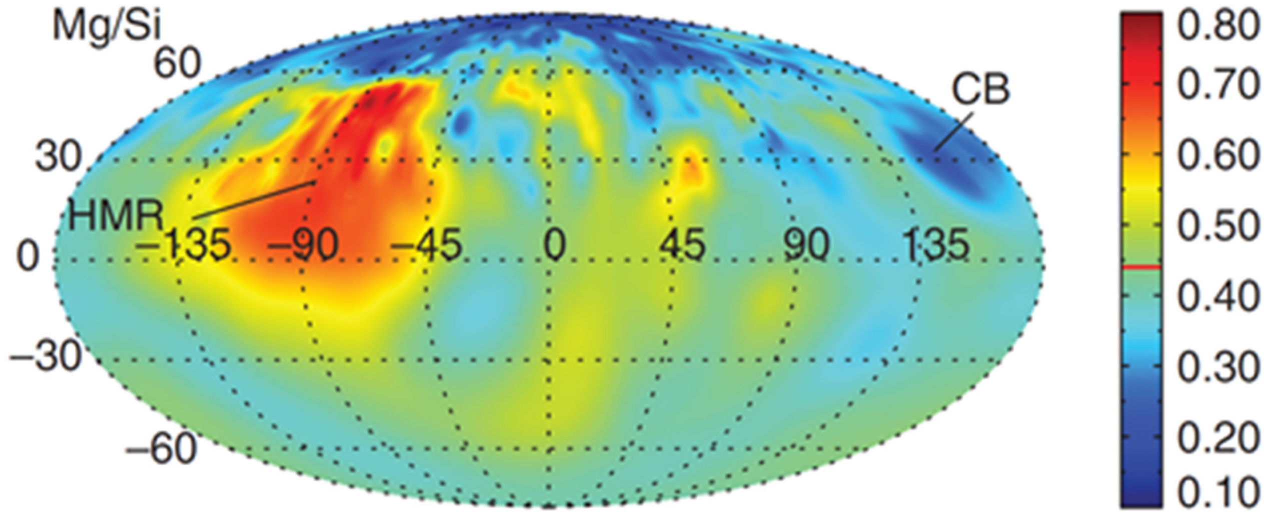

Fig. 2. Mg abundance on Mercury. Map is in Molleweide projection, centered at 0°N, °E. Red line in color scale is area-weighted global average of mapped data. HMR: high-Mg region; CB: Caloris basin. After *Nittler et al. (2018)*.

unprecedented information on planetary differentiation and formation processes in our Solar System—information that could also be used as a local analog for understanding extrasolar planets, and particularly those close to their host star. A fuller understanding of Mercury's geochemistry would also inform subsequent exploration efforts, especially the aspirational goal of sample return from the innermost planet, and could even help to identify samples from Mercury proposed to exist in the worldwide meteorite collection *(e.g., Gladman and Coffey, 2009)*.

2.2. Interior Structure: Understanding Planetary Formation in the Solar System

With its high bulk density *(Ash et al., 1971)* and super-size metallic core *(Smith et al., 2012)* (Fig. 3), Mercury occupies a unique place among terrestrial planets and is key to understanding planetary formation and evolution. The origin of Mercury is indeed still unclear, particularly its high metal-to-silicate ratio. Refined geophysical constraints in addition to new in situ geochemical data are needed to refine or discard the "chaotic" and "orderly" formation models *(Ebel and Stewart, 2018)*.

Crucial geophysical data could be effectively acquired by a landed mission. For example, a lander equipped with a seismometer would provide:

- a determination of the interior structure with high fidelity;
- important constraints on density, temperature, and composition at depth; and
- the present-day level of seismicity at Mercury.

The degree of seismic activity on Mercury is unknown – however, should be significantly larger than is currently observed by InSight on Mars. The planet undergoes thermal cycling *(Williams et al., 2011)*,

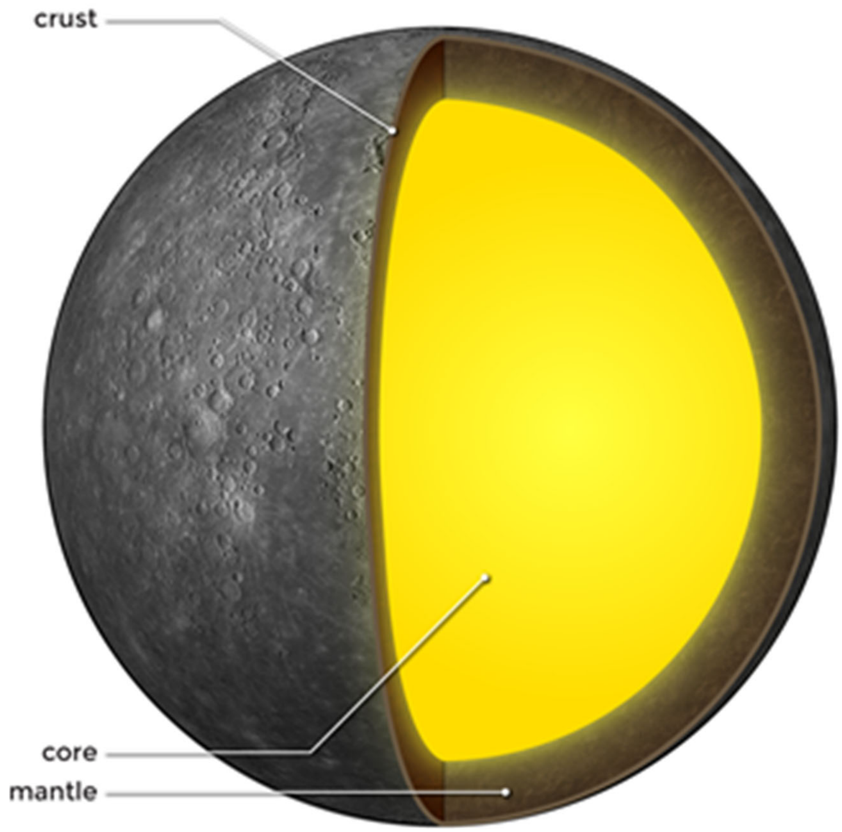

Fig. 3. Schematic of the interior of Mercury. The core is more than 80% the radius of the entire planet *(e.g., Margot et al., 2018)*.

flexing from solar tides *(e.g., Padovan et al., 2014; Steinbrügge et al., 2018)*, and may even still be contracting *(Banks et al., 2015)*. All these crustal processes could be assessed with a seismic investigation. The prevalence of tidally-induced quakes has been demonstrated by the Apollo Seismic Network for the Moon (*Lammlein et al., 1977; Nakamura 2005*). The present-day impact flux at Mercury could also be characterized, as the lunar seismometers have shown (*Dorman et al., 1978; Oberst and Nakamura, 1991)* placing vital bounds on the impact history of the inner Solar System *(e.g., Le Feuvre and Wieczorek, 2011)*. Although multiple stations would be preferable, the NASA Discovery-class InSight mission *(Banerdt et al., 2012)*, which arrived at Mars in November 2018, has demonstrated the capability of single-seismometer experiments for studies of the seismic environment. And a single seismic station might perform better on a world with such a shallow core.

A landed mission would also offer an opportunity for high-accuracy geodesy, as direct-to-Earth radio tracking would help improve the orientation dynamics, particularly the longitudinal librations (*Stark et al., 2015*) and the nutation of the spin axis (especially for a landing site at low latitudes), which are sensitive to the size and shape of the core *(Dehant et al., 2011)*. In addition to the seismometer and radio transponder, other experiments could be advantageously included to make the lander a geophysical station. For example, a heat probe (as for the InSight mission) would provide crucial heat

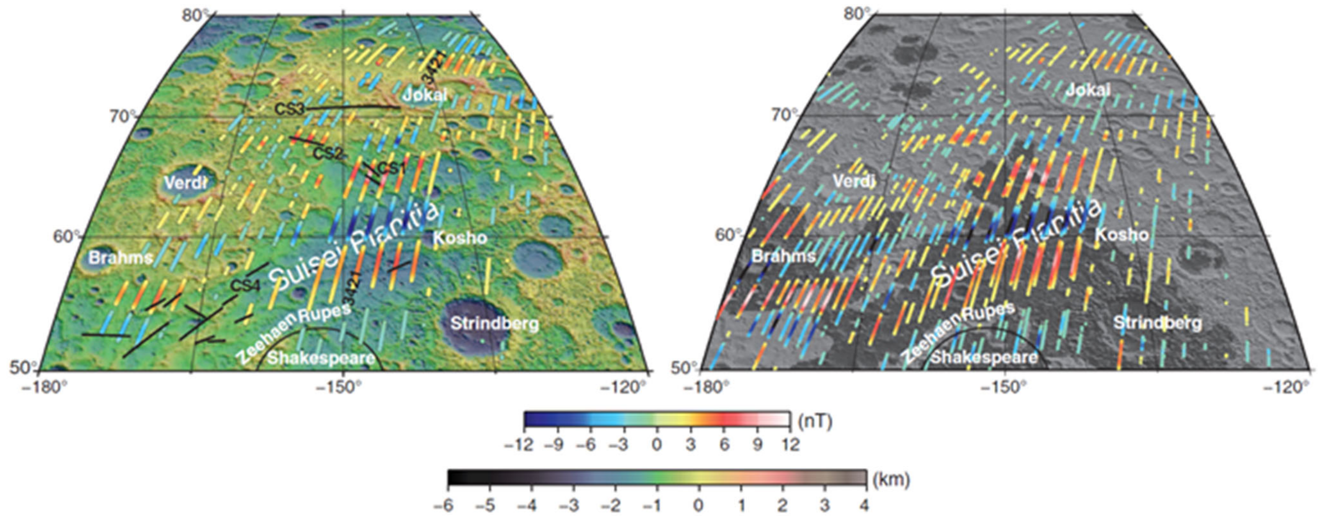

Fig. 4. Remanent magnetic field detected in Mercury's crust. Signatures detected by MESSENGER over Suisei Planitia are shown. Crustal magnetization was detected both at altitudes of 25–60 km (left) as well as at lower altitudes of 14–40 km (right). After *Johnson et al. (2015)*.

flux observations directly relevant to the core dynamo *(Stanley et al., 2005)* as well as to topography compensation mechanisms *(James et al., 2015)*. A magnetometer would help characterize the electrical and conductivity structure of the crust and mantle *(Johnson et al., 2016*; *Zhang and Pommier, 2017)*. A zenith camera, tracking stars in the celestial sphere, would provide accurate measurement of the Mercury's complex rotation and tidal deformation (*Noda et al., 2008*). And the science return of a geophysical lander at Mercury would be further enhanced if paired with companion GRAIL-like orbiters *(Zuber et al., 2013)* or a GOCE-like gravity gradiometer *(Drinkwater et al., 2003*; *Griggs et al., 2015)*; an orbiting laser ranging system for use with a laser retroreflector on the lander would yield even more accurate geodetic data.

2.3. Geological History: Exploring Mercury's Evolution since Formation

Data returned by the MESSENGER mission have provided a global characterization of the history of the planet as recorded by its surface features *(e.g., Denevi et al., 2013; Marchi et al., 2013; Byrne et al., 2014)*. Mercury was an active planet early in its history, as evinced by its modest density of large impact basins *(Marchi et al., 2013)* followed by a rapid waning of volcanic activity *(Byrne et al., 2016)*, all of which are overprinted by tectonism associated with global contraction *(Byrne et al., 2014*; *Watters et al., 2015)*.

However, as is the case for all bodies beyond the Earth–Moon system, we lack sufficient precision in our understanding of the absolute ages of events, landforms, and deposits on the surface. **In situ geochronological measurements of surface materials would place vital constraints on the absolute timing of events in Mercury's evolution**, as well as critical chronological and impact flux models for the entire Solar System.

As MESSENGER orbited closer to the surface near the end of the mission, crustal remanent magnetization was discovered *(Johnson et al., 2015; Hood et al., 2016)* (Fig. 4). However, magnetization signals detected at orbital altitudes require magnetizations over considerable depth, and so an orbiter cannot provide the necessary insight into where such signals arise in the crust. Investigating remanent magnetization with a surface magnetometer on a landed mission would establish important links between:

- surface geological processes and evolution;
- integrated igneous activity and depth; and
- the history of interior melt production and dynamo generation.

Determining the carriers of the magnetization *(Strauss et al., 2016)*, through geochemical and mineralogical assessment of surface materials (Section 2.1), is crucial for understanding crustal magnetization and its history. Such assessment, in concert with investigation of crustal structure with a seismic experiment (Section 2.2), would yield meaningful limits on estimates of the thickness of magnetization on Mercury—particularly when paired with local magnetic field measurements. These local measurements would also aid complementary studies of electromagnetic fields in the crust and mantle to characterize internal structure *(Anderson et al., 2014; Johnson et al., 2016)* (Section 2.2), as well as interactions between the internal and external magnetic fields (Section 2.4).

2.4. Present-Day Mercury: Investigating Active Planetary Processes

The MESSENGER mission showed us that present-day Mercury experiences a number of active processes that could readily be investigated by instruments on a lander. For example, the surface is subjected to an especially harsh space-weathering environment *(e.g., Domingue et al., 2014)*. As these particle–surface interactions are an important source of the exosphere *(e.g., Martinez et al., 2017; Merkel et al., 2018)*, and may contribute to macroscopic landscape modification in the formation of hollows *(e.g., Blewett et al., 2016)*, it is critical that we better understand the effects of solar-wind and magnetospheric charged particles (ions and electrons) and interplanetary dust particles (IDPs) on Mercury's surface materials. Although information on the charged particle environment surrounding the planet was obtained by MESSENGER, and will be substantially augmented by BepiColombo's dual-spacecraft measurements, **in situ measurements at the surface enable the direct study of particle–surface interactions**.

Measurements that are needed include, but are by no means limited to:

- the incoming IDP flux at the surface;

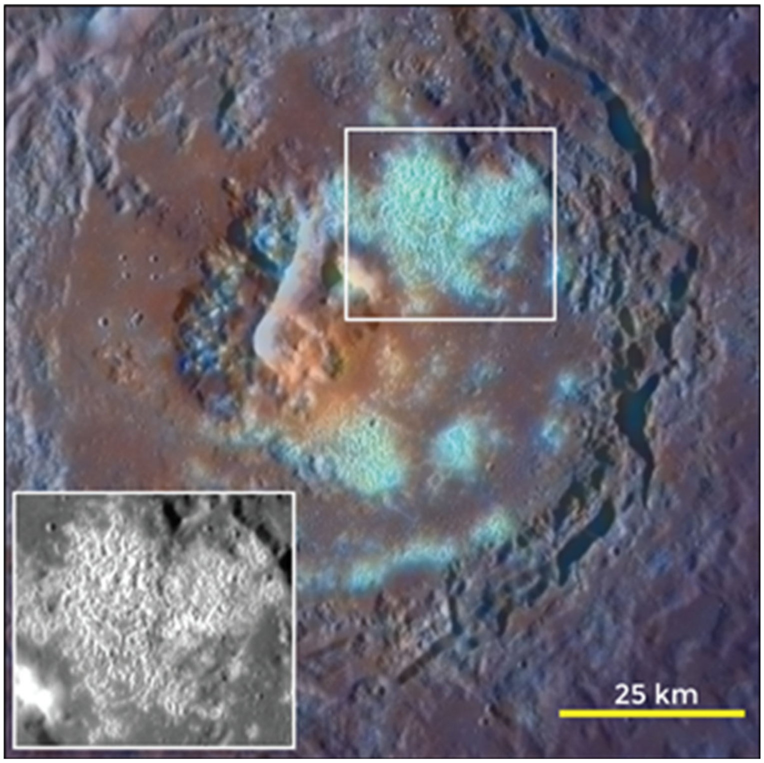

Fig. 5. Enhanced-color view of hollows (blue) inside Tyagaraja crater on Mercury; the inset shows these hollows in monochrome. After *Blewett et al. (2011)*.

- the flux of charged particles, both from the magnetosphere and solar wind as well as that released from the surface during sputtering and meteoroid impact vaporization events; and
- the neutral atoms and molecules present.

The acquisition of these data could be accomplished with a combined ion and neutral mass spectrometer and a dust experiment. Together with in situ analysis of mineralogy and geochemistry (Section 2.1), these charged particle and IDP measurements would greatly further our understanding of the source and loss mechanisms behind the complex surface–exosphere–magnetosphere system, and of the processes involved in the initiation and growth of Mercury's distinctive hollows (Fig. 5).

Mass spectrometers would also allow detection at the surface (and during descent) of exospheric density, a measurement crucial for determining both the high-mass-atoms composition of the exosphere and the release processes at work at the surface, and could also help characterize the absorption spectra of surface materials at Mercury conditions *(Helbert et al., 2013; Ferrari et al., 2014)*. And in situ imaging of the surface could return useful information regarding the physical properties of the regolith, including grain size, shape, and mechanical strength.

Moreover, large-scale investigations of the morphological structure and temporal dynamics of the exosphere and magnetosphere could be conducted from the surface. These measurements could be

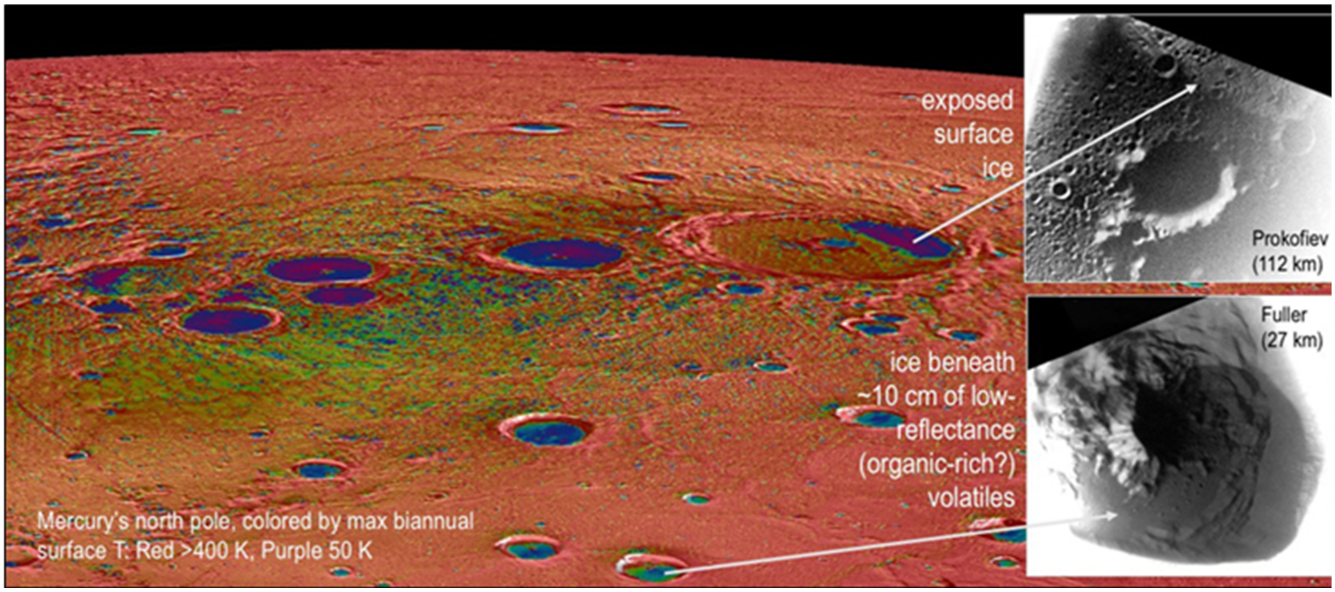

Fig. 6. Mercury's polar deposits feature large expanses of exposed water ice (e.g., Prokofiev crater, top right) as well as other volatiles (e.g., Fuller crater, bottom right).

obtained using either an imaging spectrometer system to provide both spectral and spatial information, or by the use of an all-sky camera with narrowband filters. Such methods are routinely used to study the Earth's airglow, and could be similarly employed at Mercury. The siting of these instruments near the midnight equator would allow intense study of the tail structure, whereas a location near the poles would enable a study of the day–night transport. A fixed-surface location is desired because completely disentangling the spatial and temporal aspects from a rapidly moving spacecraft is difficult—another example of how a Mercury lander could build upon the science return of previous and planned orbiter missions.

2.5. Polar Volatiles: Understanding the Inventory and Origin of Volatiles in the Inner Solar System

Earth-based radio telescopes provided the first tantalizing evidence for the presence of water ice at Mercury's polar regions *(e.g., Slade et al., 1992; Harmon and Slade, 1992; Butler et al., 1993; Harmon et al., 2011)*. Subsequently, multiple MESSENGER datasets provided strong evidence that Mercury's radar-bright materials are composed of water ice: the deposits are located in permanently shadowed regions *(e.g., Deutsch et al., 2016; Chabot et al., 2018)* with temperatures cold enough to sustain water ice *(Paige et al., 2013)*; neutron spectrometer results show elevated levels of H in Mercury's north polar region *(Lawrence et al., 2013)*; and reflectance measurements and images have revealed the surfaces of the polar deposits to have albedo properties distinct from Mercury's regolith *(e.g., Neumann et al., 2013; Chabot et al., 2016)*. Together, these data point to extensive deposits of water ice and other volatile compounds in Mercury's polar regions (Fig. 6).

Additionally, MESSENGER imaging confirmed that these **large deposits of volatiles are exposed directly on the surface**, providing a unique opportunity for landed science. In situ measurements are ideally suited to address the major open science questions about Mercury's polar deposits, including the origin of Mercury's polar volatiles, and whether the deposits represent an ancient, recent, or ongoing formation process; the nature of the volatiles trapped at Mercury's poles, and whether they include organic-rich materials delivered to the inner planets; and the processes that act in permanently shadowed regions, and whether these processes produce or destroy water ice.

Addressing these questions has implications not only for Mercury but also for understanding the inventory of inner Solar System volatiles, including those on the Moon and the potential delivery of volatile species to early Earth and Mars. Landed measurements would provide fundamental new data not otherwise available to us, such as direct measurements of:

- the origin and composition of the volatile compounds within Mercury's polar deposits;
- the purity of the ice; and
- the physical and mechanical properties of the volatiles, including volume, grain size, strength, thickness, and evidence for layering.

Such measurements would address crucial, open science questions about Mercury's polar volatiles, which in turn would provide new insight into the volatile inventory and evolution of the inner Solar System worlds.

3. The Logical Next Steps in Mercury Exploration: Mercury Lander

The idea of sending a lander to Mercury's surface is not new. Already in the initial planning of the BepiColombo mission, a Mercury Surface Element (MSE) lander module was considered (*ESA, 2000*). In fact, it was proposed to "perform *in situ* ground-truth physical, optical, chemical and mineralogical observations" (*ESA, 2000, p. 14*), which also reflects our proposed scientific questions listed above. To address these questions an instrument for sub-surface heat flow measurement, a seismometer, a magnetometer, cameras and a spectrometer were considered. Unfortunately, the lander could not be implemented within the BepiColombo mission due to cost limitations. However, many of the proposed instrument designs have been used on NASA's InSight Mars lander (*Banerdt et al., 2012*), e.g. HP3, SEIS. With the experience obtained from InSight and small landers such as Philae on Rosetta (*Boehnhardt et al., 2017*) landers and Mascot on Hayabusa-2 (*Ho et al., 2017*) the technological development of such instruments does not need to start from scratch. More recently, a rapid mission-architecture study into the feasibility of a Mercury landed mission was conducted in support of NASA's Planetary Science Decadal Survey 2013–2022 (*NRC, 2011*). This early study found that any such mission would face challenges in the enormous launch energy and relative velocity involved in bringing a spacecraft/lander to Mercury's surface (*Hauck et al., 2010; NRC 2011*). Hence, the Mercury Lander would be an L-Class mission. A new study should consider a variety of architectures, e.g., chemical and solar-electric propulsion, proven as well as planned launch vehicles (e.g., SpaceX's Falcon Heavy, NASA's Space Launch System, ESA's Ariane 6, etc.), and prospective landing sites and commensurate limits on the duration of surface operations (*McNutt et al., 2018*). Within the open forum at the "Mercury: Current and Future Science of the Innermost Planet" meeting, held in May 2018 and planned for May 2020, the idea to perform *in situ* observations on the surface of Mercury was enthusiastically supported by the scientific community.

Our improved knowledge of Mercury now and after BepiColombo enables us to better understand the evolution of terrestrial planets in general, potentially including those in orbit about other stars. For example, Mercury with its large iron core is an important model for extrasolar planets with high iron mass fractions *(e.g., Santerne et al., 2018)*. It is also a useful analog for studying exoplanets within carbon-rich stellar systems. Such planets are expected to have low oxygen fugacities, and may therefore feature sulfur-rich crusts and, if present, atmospheres.

Finally, the development and ultimate dispatch to Mercury of a lander should not signify the end of exploration efforts for the planet. Indeed, following the decades-long established protocol of flyby, orbiter, and lander approach, it follows that an aspirational goal should be the collection from the surface and the delivery to Earth of a sample of Mercury (*McNutt et al., 2018*). Such a sample would enable transformative planetary science that would not only place vital constraints on the thermochemical evolution of Mercury but also provide critical insight into the building blocks that formed the terrestrial worlds in this and other star systems. We believe that the continued exploration of

Mercury should be conceived as a multi-mission, multi-generational effort, guided by the crucial input provided by the Mercury science community.

Therefore we recommend that a Mercury lander shall be considered within the ESA Voyage 2050 long-term planning.

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