The case for landed Mercury science

Paul K. Byrne 1,2 · David T. Blewett 3 · Nancy L. Chabot 3 · Steven A. Hauck II 4 · Erwan Mazarico 5 · Kathleen E. Vander Kaaden 6 · Ronald J. Vervack 3 · Jürgen Oberst 7 · Hauke Hussmann 7 · Alexander Stark 7

Received: 11 August 2020/Accepted: 20 August 2021/Published online: 15 October 2021
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Abstract
In this White Paper, submitted to ESA in response to the Voyage 2050 Call, we advocate for establishing key scientific priorities for the future of Mercury exploration, including the development of specific science goals for a landed mission. We support the Mercury science community in fostering closer collaboration with ongoing and planned exoplanet investigations. The continued exploration of Mercury should be conceived as a multi-mission, multi-generational effort, and the landed exploration of Mercury should be a high scientific priority in the coming decades.

Keywords Mercury · Lander · Geology · Geophysics · Geochemistry · Space environment

1 Current and planned mercury exploration

The arrival into Mercury orbit in 2011 of NASA’s MESSENGER mission heralded a new age of exploration for this enigmatic planet (Fig. 1). The MESSENGER (MErcury
Surface, Space ENvironment, GEOchemistry, and Ranging) spacecraft [1] operated at Mercury for over four Earth 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 once extraordinarily geologically active but that has 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 2025 arrival of the joint ESA–JAXA BepiColombo mission [2]; with two discrete spacecraft, BepiColombo will characterize in greater detail the planet’s surface, interior, and the magnetosphere–interplanetary solar wind interaction.

Yet there is a limit to the scientific return of an orbital 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 [3]. 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 coming decade of BepiColombo, our exploration of Mercury has 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.

Here, we identify several key aspects of Mercury science that can be best addressed by such a mission. Our goal here is not to advocate for a specific location on Mercury, but to demonstrate why such a lander in general 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 planetary systems and how planets evolve through time [3]. To leverage our growing knowledge—and increasing depth—of the other inner Solar System bodies, it is necessary to develop a comparably deep understanding of Mercury.

We must therefore plan for a steady stream of missions to the innermost planet over the coming decades, with each building upon its predecessor. With the necessarily long cruise time from Earth, comparable to destinations in the outer Solar System, and the

![Fig. 1](image.png)

**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 multispectral data. Image credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington
limited number of spacecraft mission opportunities, 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 rocky 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 rocky planets (e.g., [4, 5]). 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., [4, 6, 7]). 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., [8–10]) (Fig. 2) and is also volatile rich (e.g., [5], an unexpected finding given the planet’s heliocentric distance (e.g., [5, 11–13]). 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.

Fig. 2 Mg abundance on Mercury. Map is in Mollweide projection, centered at 0°N, 0°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. [14]
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 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 planet [15], and could even help to identify samples from Mercury proposed to exist in the worldwide meteorite collection (e.g., [16]).

2.2 Interior structure: understanding planetary formation in the Solar System

With its high bulk density [17] and super-size metallic core [18] (Fig. 3), Mercury occupies a unique place among terrestrial planetary bodies and is key to understanding planet formation and evolution. The origin of Mercury is indeed still unclear, particularly its high metal-to-silicate ratio. Improved geophysical constraints in addition to new in situ geochemical data are needed to refine or discard existing “chaotic” and “orderly” formation models [19].

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.

Fig. 3 Schematic of the interior of Mercury. The core is more than 80% the radius of the entire planet (e.g., [20])
The degree of seismic activity on Mercury is unknown; however, the planet undergoes thermal cycling [21], flexing from solar tides (e.g., [22, 23]), and may even still be contracting [24]—and 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 [25, 26]. The present impact flux at Mercury could also be characterized, as the lunar seismometers have shown [27, 28], placing vital bounds on the impact history of the inner Solar System (e.g., [29]). Although multiple stations would be preferable, the NASA Discovery-class InSight mission [30], operating on Mars since November 2018, has demonstrated the capability of single-seismometer experiments for interior studies. And a single seismic station might perform better on a world with as shallow a core as Mercury.

A landed mission would also offer an opportunity for high-accuracy geodesy, as direct-to-Earth radio tracking would help improve the orientation dynamics—in particular, the longitudinal librations [31] 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 [32]. In addition to a seismometer and radio transponder, which could place further bounds on the size of the inner core [33], 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 flux observations directly relevant to the core dynamo [34] as well as to topography compensation mechanisms [35]. A magnetometer would help characterize the electrical and conductivity structure of the crust and mantle [36, 37]. A zenith camera, tracking stars in the celestial sphere, would provide accurate measurement of Mercury’s complex rotation and tidal deformation [38]. And the science return of a Mercury geophysical lander would be further enhanced if paired with GRAIL-like orbiters [39] or a GOCE-like gravity gradiometer [40, 41] to finely map density and thickness variations in the lithosphere and crust. Indeed, 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., [42–44]). Mercury was an active planet early in its history, as evinced by its modest spatial density of large impact basins [43] followed by a rapid waning of volcanic activity [45], all of which are overprinted by tectonism associated with global contraction [44, 46].

However, as for all bodies beyond the Earth–Moon system, we still lack a complete understanding of the absolute ages of events, landforms, and deposits on the surface. In situ geochronological measurements of surface materials with sufficient precision could place vital constraints on the absolute timing of events in Mercury’s evolution, as well as chronological and impact flux models for the entire Solar System.

As MESSENGER orbited closer to the surface near the end of its mission, crustal remanent magnetization was discovered [47, 48] (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 magnetization [49] through geochemical and mineralogical assessment of surface materials (§ 2.1) is key to understanding crustal magnetization and its history. Such assessment, in concert with investigation of crustal structure with a seismic experiment (§ 2.2), would yield meaningful limits on estimates of the thickness of magnetization on Mercury—especially 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 [36, 50] (§ 2.2), and interactions between the internal and external magnetic field (§ 2.4).

2.4 Mercury today: investigating active planetary processes

The MESSENGER mission showed us that 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., [51]). As these particle–surface interactions are an important source of the exosphere (e.g., [52, 53]), and may contribute to macroscopic landscape modification in the formation of hollows (e.g., [54]), 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;
- 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.

![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. [47]](image-url)
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 (§ 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 [56, 57]. And in situ imaging of the surface could determine 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 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 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 inner solar system volatile inventories and origin

Earth-based radio telescopes provided the first tantalizing evidence for the presence of water ice at Mercury’s polar regions (e.g., [58–61]). Subsequently, multiple MESSENGER datasets provided strong evidence that Mercury’s radar-bright materials are

Fig. 5 Enhanced-color view of hollows (blue) inside the 97-km-diameter Tyagaraja crater. Inset: hollows in monochrome. After Blewett et al. [55]
composed of water ice: the deposits are located in permanently shadowed regions (e.g., [62, 63]) with temperatures cold enough to sustain water ice [64]; neutron spectrometer results show elevated levels of H in Mercury’s north polar region [65]; and reflectance measurements and images have revealed the surfaces of the polar deposits to have albedo properties distinct from Mercury’s regolith (e.g., [66, 67]). Together, these data point to extensive deposits of water ice and other volatile compounds in Mercury’s polar regions [68] (Fig. 6).

MESSENGER data 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 if 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:

![Fig. 6](image-url)  
**Fig. 6** Mercury’s polar deposits feature large expanses of exposed water ice, as well as other volatiles. North polar stereographic view. Figure from Deutsch et al. [62]
the composition of the volatile compounds within Mercury’s polar deposits;
the purity of the ice; and
the physical properties of volatiles, including 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.

2.6 The logical next step in Mercury exploration: a Mercury lander

The concept of sending a lander to Mercury’s surface is not new. A Mercury Surface Element (MSE) lander module was considered in the initial planning of the BepiColombo mission [69]. Indeed, this lander element was proposed to “perform in situ ground-truth physical, optical, chemical and mineralogical observations” ([69], p. 12), reflecting the scientific questions we discuss above. To address these objectives, the BepiColombo lander would have been equipped with an instrument for sub-surface heat flow measurement, a seismometer, a magnetometer, cameras, and a spectrometer. Unfortunately, the lander could not be implemented within the BepiColombo mission due to cost limitations.

However, some of these proposed instrument designs have been used on NASA’s InSight Mars lander [30], including the Heat Flow and Physical Properties Package (HP3) and the Seismic Experiment for Interior Structure (SEIS). With the experience obtained from InSight and from deploying small landers such as Philae on Rosetta [70] and Mascot on Hayabusa-2 [71], the technological development of such readily deployable and miniaturized instruments need not start from scratch.

A rapid mission-architecture study into the feasibility of a Mercury landed mission was conducted in support of NASA’s Planetary Science Decadal Survey 2023–2032 [72]. This study found that any such mission would face challenges given the enormous launch energy and relative velocity involved in safely landing a spacecraft on Mercury, but is consistent with the scope of a NASA New Frontiers-class mission [72]. In terms of an ESA mission, then, a Mercury lander would likely be an L-Class mission. Importantly, within the open forum at the “Mercury: Current and Future Science of the Innermost Planet” meeting, held in May 2018 (with a follow-on meeting planned for 2022), the idea to perform in situ observations on the surface of Mercury was enthusiastically supported by the scientific community. Key to ensuring a firm footing for continued Mercury science, then, is supporting the Mercury science community to organize and discuss the future priorities of the scientific exploration of Mercury—including the development of detailed, specific Mercury science goals such as those listed in this paper. By doing so, future Mercury lander mission concepts would have strong scientific motivation backed by community-generated priorities.

Our improved knowledge of Mercury now enables us to understand more fully the evolution of terrestrial planets in general, potentially including those in orbit about other stars. For example, it is possible that Mercury is an important model for extrasolar planets in high-C solar systems. Planets that are carbon rich are expected to have low oxygen fugacities, and may therefore feature sulfur-rich crusts and, if present, atmospheres. Mercury is also a useful analog for studying exoplanets with major iron mass
fractions (e.g., [73]). We therefore support the Mercury science community in fostering closer collaboration with ongoing and planned exoplanet investigations.

Finally, the development and eventual dispatch to Mercury of a lander—whether targeting low latitudes, the poles, or a particular surface unit (e.g., [72])—should not signify the end of exploration efforts for the planet. Indeed, following the decades-long established protocol of flyby, orbiter, and lander approach taken by NASA [3], it follows that an aspirational goal should be the collection from the surface and the delivery to Earth of a sample of Mercury [15]. Such a sample would enable transformative planetary science that would not only place vital constraints on the thermochemical evolution of Mercury, but would provide critical insight into the building blocks that formed the terrestrial worlds in this and other star systems. We propose 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, and that the landed exploration of Mercury be considered a high scientific priority by ESA in the Voyage 2050 long-term planning.

**Author contributions** All authors contributed to the writing of this paper, and read and approved the final manuscript.

**Data availability** Not applicable.

**Code availability** Not applicable.

**Declarations**

**Conflict of interest** The authors declare that they have no conflict of interest.

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