

High Priority Science at Mercury

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Executive Summary

In July 2019, in preparation for the next Decadal Survey, NASA Planetary Science Division leadership requested input from the Planetary Science Analysis Groups to help frame the science questions of highest priority to the planetary community. As of August 2019, Mercury remains the only major Solar System body without an Analysis Group. Therefore, an *ad hoc* group was assembled to engage the Mercury community to ensure that the highest-priority questions for the innermost planet could be identified and communicated to NASA. Via an online survey distributed through email listservs and social media channels, respondents assigned a set of representative Mercury-focused questions a number from 1 (low priority) through 5 (high priority); responders were also able to provide additional feedback for each question and even offer new potential questions. Within one week, the survey had recorded responses from more than 30 individuals beyond the *ad hoc* committee.

The survey indicated that the following Mercury-focused questions are of high priority to the planetary science community:

- How did Mercury form?
- How did Mercury differentiate and acquire its interior structure?
- What is the history of Mercury's magnetic field and its generation?
- How do Mercury's surface and interior reflect the evolution of the planet?
- What is the nature of the complex interactions among Mercury's external drivers and the planet's magnetosphere, exosphere, surface, and interior?
- What is the origin, history, and inventory of Mercury's volatiles?

Respondents were also asked to consider broader planetary questions that encompass the focus of existing Analysis Groups. Community feedback placed importance on questions of Solar System formation, planetary formation and evolution, and active surface processes throughout the Solar System. Given the focus on Mercury, the survey results placed a secondary emphasis on questions regarding life in the Solar System, but nonetheless indicated Mercury as an important end-member in understanding planetary habitability.

Background

The planet Mercury is an end-member among the bodies of the inner Solar System in terms of its formation, composition, evolution, and interaction with the space environment. As the innermost planet in the Solar System, Mercury also represents the nearest analog environment to the large numbers of exoplanets that have been discovered proximal to their host stars. Visited by only two spacecraft to date, NASA's Mariner 10 in 1974–1975 and MESSENGER with a series of three flybys beginning in 2008 and an orbital campaign from 2011–2015, it is also the least explored of the major terrestrial bodies of the inner Solar System; although the ESA/JAXA BepiColombo dual orbiters are set to arrive in orbit about Mercury in late 2025.

MESSENGER's orbital reconnaissance of Mercury provided the first global measurements of the space environment, surface, and interior of the planet. The data that MESSENGER returned enabled understanding of the planet's general internal structure, surface composition, extensive volcanic and tectonic history, and the surrounding dynamic exosphere and space environment that surrounds the solid planet. Discoveries including (though not limited to) the existence of water ice in polar craters, the enigmatic hollows, an extraordinarily chemically reduced crust, the unusual geometry of the global magnetic field, ancient remanent magnetization of the crust, the different seasonalities of the exospheric species, and an exceptionally active magnetosphere all raise fundamental questions about the formation and evolution of planets and their interactions with the space environment. Exploration and study of this end-member planet is essential for understanding solar system and planet formation, how and why planets evolve, space weather, and the ways in which atmospheres, magnetospheres, and solid planets interact when close to their host stars.

This report has been developed in response to an inquiry from NASA about big-picture, high-priority science from the Mercury science community in advance of the initiation of the next Planetary Science Decadal Survey. The high-priority science questions presented here are collated from recent discussions at the [Mercury: Current and Future Science of the Innermost Planet Workshop](#) in 2018 workshop, community feedback for the [white paper on landed science at Mercury](#), the existing body of literature, as well as direct community engagement. Through a [survey](#) distributed through listservs (e.g., subscribers to the Mercury-Planet-List, Planetary Exploration Newsletter) and social media, the planetary science community was asked to participate in identifying and indicating the priority of big-picture, vital science to be accomplished at Mercury as well as more broadly in planetary science. The two specific inquiries from NASA are presented in order. Inquiry 1: *What are the highest priority questions for your community (think big!)?* and Inquiry 2: *What do you perceive as the highest priority questions for each of the other AGs: (CAPTEM, LEAG, MAPSIT, MEPAG, OPAG, SBAG, VEXAG)?* In addition to direct input and open feedback, individuals were invited to rate the priority of the

questions and themes identified in this document. A broad cross-section of the Mercury science community, disciplinary interest and otherwise, contributed to the development of these questions and themes. Using a 1–5 (1 = low priority and 5 = high priority) scale, each of the items discussed below were identified as having a score of 4 or 5 by considerably greater than a majority (*i.e.*, > 60% for all Mercury-specific questions, with most >75%). More than 30 individual scientists beyond the committee that prepared this report made contributions through responses to the survey.

Finally, it should be clear at the outset that the Mercury we see today is the result of a *system* of interconnected processes that have operated both consecutively and concurrently. Thus, the high-priority questions outlined below are all strongly synergistic with at least a majority of their companion questions. Multiple lines of inquiry are an essential element of understanding, and unraveling, a complex system such as the planet Mercury.

Inquiry 1: What are the highest priority questions for your community (think big!)?

How did Mercury form?

MESSENGER revealed much about Mercury, such as its extremely chemically reduced nature, exotic chemistry with S and C present on the surface and Si likely in the core, and its enormous metallic core that remains still partially molten today. All of these observations add to the fundamental fact that Mercury is unlike any of the other planets in our Solar System, leading to the basic question: how did Mercury form? Mercury is an end-member of planet formation in our Solar System and as such, provides compelling and unique opportunities to investigate planetary formation through Mercury exploration. This high-priority question is foundational to understanding the origin of Mercury and the formation of planets in our Solar System.

Example focused questions:

- What were the building blocks of Mercury and how did they compare to those of the other terrestrial planets?
- What roles might giant impact(s), planet migration, or location of planetary formation have had on the structure and composition of Mercury?
- How do terrestrial bodies with high metal to silicate ratios form and what are the implications for terrestrial planet formation?
- What is the bulk elemental composition of Mercury?

- What is the stable isotopic composition of Mercury?
- What does the composition of Mercury tell us about the protoplanetary disk?

How did Mercury differentiate and acquire its interior structure?

Mercury's internal structure reflects both its unique metal to silicate ratio among the planets and the set of processes that separated its materials into layers. MESSENGER data enabled the discovery that Mercury is a chemically reduced, end-member planet. Indeed, MESSENGER found evidence of an ancient graphite flotation crust as well as a Mg-rich, Fe-poor silicate crust and mantle, overlying a very large metallic core. Understanding how this end-member planet processed its starting materials into its internal layering is crucial for constraining the starting point of its geological and internal evolution, and for how differentiation and magma oceans operate.

Example focused questions:

- Why does Mercury have such a large metal to silicate ratio?
- What are the compositional constraints on Mercury's interior layers, such as its solid and liquid core, mantle, and other layers?
- Did Mercury have a magma ocean, and, if so, how did its crystallization affect the subsequent evolution of the planet?
- What processes led to the presence of graphite and sulfides contained in the crust?
- When did Mercury accrete and differentiate relative to the formation of calcium-aluminum-rich inclusions?
- When did Mercury's core form?

What is the history of Mercury's magnetic field and its generation?

Mercury's enigmatic magnetic field is unique among the planets due to its relative weakness and particular geometry. The MESSENGER-based discovery of crustal magnetization in terranes older than 3.5 Ga point to the operation of an ancient magnetic field. Understanding how Mercury's magnetic field is, and has been, generated is an essential, high-priority component of understanding both Mercury and planetary magnetic fields everywhere, and is intimately tied to understanding the planet's interior structure. Indeed, electromagnetic induction has already been used to independently confirm the core size inferred from geodesy and could in the future provide constraints on the electrical conductivity structure of the silicate mantle and crust.

Example focused questions:

- What is the source of Mercury's weak, axisymmetric, and hemispherically asymmetric internal magnetic field?
- What are the distribution and age(s) of crustal remanent magnetization?
- What are the minerals that carry magnetization on Mercury?
- Has Mercury's internal field operated continuously throughout the planet's history?
- Were the geometry and strength of an ancient field different from that observed today?
- What can magnetic induction reveal about the electrical conductivity structure of the interior?

How do Mercury's surface and interior reflect the evolution of the planet?

While it is the smallest planet, with the thinnest mantle and fractionally largest metallic core among the solid bodies in the Solar System, Mercury also has an extended history of volcanism and a uniquely both global and dominantly contractional tectonic history. It is essential to understand how the surface history is connected to the internal processes of cooling and mantle convection, as well as large basin formation. Mercury's bombardment history, particularly since ~4.1 Ga, is well preserved and provides a robust opportunity to understand the bombardment history of the inner Solar System and the role that major impacts have had in shaping the evolution of terrestrial planetary bodies.

Example focused questions:

- How much, if any, of Mercury's crust represents a primary crust composed of graphite?
- What does Mercury's history of volcanism indicate about the composition and depth of melting?
- How and why has the nature and extent of volcanism changed so dramatically through time on Mercury?
- To what degree have secondary processes affected the surface composition and mineralogy of Mercury (*e.g.*, smelting, space weathering, thermal transport of volatiles)?
- What is the origin of the largest physiographic unit on Mercury, the intercrater plains?
- Are geological processes such as formation of hollows and scarps actively taking place today?
- How has the bombardment history of Mercury influenced the planet's evolution?
- How and when did Mercury enter its current 3:2 spin-orbit resonance, and what role has the coupled orbital and rotational history had on the planet's evolution?

What is the nature of the complex interactions among Mercury's external drivers and the planet's magnetosphere, exosphere, surface, and interior?

Mercury is unique in that it is an airless body possessing a relatively substantial magnetosphere while also orbiting close to the Sun. As such, Mercury exhibits a range of complex interactions with several external drivers that make it a peerless empirical laboratory for understanding these interactions in both our Solar System and others. Mercury's interaction with the solar wind has features similar to those of the Earth, but with more extremes. The generally higher solar-wind pressure and near-ubiquitous reconnection with the interplanetary magnetic field cause the magnetosphere to be much more solar-wind-driven than at the Earth. Solar-related phenomena such as coronal mass ejections and solar energetic particle events are more intense at Mercury than at Earth and further contribute to highly dynamic effects on the magnetosphere. Magnetospheric convection, particle energization, and particle precipitation are just some of the aspects that are greatly affected by Mercury's interactions with the Sun. Mercury's exosphere is populated by several species that derive from distinct combinations of source processes related to these same external solar drivers, as well as other non-solar ones. Mercury provides unique opportunities to study these processes by understanding how the exosphere is generated and maintained as well as how the exosphere and magnetosphere respond to one another. Mercury's planetary field also responds to these external drivers through magnetic induction, contributing yet another dimension to this dynamic interaction.

Example focused questions:

- How does the continual bombardment of the surface by various solar and non-solar drivers and the escape of material from the system via the exosphere and magnetosphere affect the long-term evolution of the surface composition (*i.e.*, space weathering)?
- How is material driven from the surface by solar wind and interplanetary dust particles as well as by solar radiation and regular cometary dust stream encounters?
- How does material that returns to the surface affect the distribution of volatiles?
- How does neutral exospheric material that is ionized and driven back to the surface by the magnetosphere provide a feedback on the generation of the exosphere?
- How does Mercury's internal field protect the nightside of the planet from plasma precipitation and how is this affected by space weather conditions?
- What are the geometry and dynamics of the high-latitude dayside cusp regions on Mercury and how do these relate to the internal field structure?
- What controls the formation, geometry, and dynamics of field-aligned currents at Mercury?
- What are the causes of observed asymmetries, including plasma and magnetic field properties, as well as substorm signatures, in Mercury's magnetotail?

What are the origin, history, and inventory of Mercury's volatiles?

The highly chemically reducing nature of Mercury as well as its surface enrichment in volatile elements has led to a complex and exotic thermal and magmatic evolution of the planet. Mercury's surface features indicate past explosive volcanism, consistent with the presence of magmatic volatiles in its interior. Furthermore, the permanently shadowed craters near Mercury's poles show evidence for extensive water ice and organic-rich volatiles exposed at the surface, providing a vital opportunity for *in situ* scientific exploration. Understanding the origin of Mercury's volatiles provides key insight into the sources and distributions of volatiles across the inner Solar System and their availability to the terrestrial planets. In addition, advancements towards understanding Mercury's volatile record will place tighter constraints on the planet's formation and differentiation history, presumably through a magma ocean event, as well as the composition of its interior, furthering our knowledge of how Mercury acquired its current interior structure.

Example focused questions:

- What role did volatiles play in melting of the interior, the ascent and transport of magmas, and on the styles of surface eruptions?
- Do alkali abundances on Mercury's surface reflect magmatic abundances or were they thermally redistributed?
- What is the reason for Mercury's low oxygen fugacity, and did volatiles play a role in its origin?
- What is the source(s) of the polar deposits?
- What is the origin of the hollows?
- What can the exosphere tell us about the redistribution of volatiles over time?
- What do the volatile abundances of Mercury tell us about their distribution in the inner Solar System and within the protoplanetary disk?

Inquiry 2: What do you perceive as the highest priority questions for each of the other AGs: (CAPTEM, LEAG, MAPSIT, MEPAG, OPAG, SBAG, VEXAG)?

Planetary science is a diverse and complex subject and the individuals who engage in this science organize themselves and identify with several overlapping components of the community. Although each of these communities, generally represented by an existing Analysis Group, has a set of priorities consistent with the focus of their attention, it is the connections among all the planetary science communities that are most vital. Indeed, whereas the level of knowledge about each of the types of bodies, and thus the detail of new questions, varies considerably across the communities, there exists a core set of ideas that are common across all communities. Here, these ideas are identified as a set of themes with example questions that typify those themes.

Solar System Formation

How did the Solar System get to be the way it is today and what are the implications for planetary systems beyond our own?

Planet Formation

What processes led from the building blocks of planets to the diversity of planets we have today, including their compositions, interior structures, and atmospheres?

Planetary Evolution

How have planetary bodies evolved since their formation? What processes have shaped their surfaces, influenced their interiors, and driven the evolution of their atmospheres and magnetic fields? How common (or unique) are these processes across the Solar System?

Active Processes

What processes continue to influence planetary bodies today and how have these processes changed over the billions of years of Solar System history?

Life

What conditions allowed our Solar System to develop life and what are the implications for life beyond the planet Earth? What processes influence how planetary bodies transition to and from habitable through their history?

Preparation and Community Input

This document, and the community engagement that led to its contents, were the result of a request by Dr. Shoshana Weider, NASA HQ to identify high-priority science questions about Mercury. The goal is to provide input to inform discussions and decisions regarding the statement of task for the upcoming Planetary Science Decadal Survey. Other communities within the larger planetary science community were engaged through the Analysis Groups. At present, the community that researches the planet Mercury and its environment remains the only one not represented by an Analysis Group. Contributions to the formation of this document were provided by the *ad hoc* committee and more than 30 additional individual scientists who provided input on questions, feedback, and priority rankings through an open community survey.

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