A Mercury Lander Mission Concept Study for the Next Decadal Survey. C. M. Ernst[1], N. L. Chabot[1], R. L. Klima[1], S. Kubota[1], P. K. Byrne[2], S. A. Hauck, II[3], K. E. Vander Kaaden[4], R. J. Vervack, Jr.[1], S. Besse[5], D. T. Blewett[1], B. W. Denevi[1], S. Goossens[6,7], N. R. Izenberg[1], C. L. Johnson[8,9], L. M. Jozwiak[1], H. Korth[1], R. L. McNutt, Jr.[1], S. L. Murchie[1], P. N. Peplowski[1], J. M. Raines[10], E. B. Rampe[11], M. S. Thompson[12], S. Z. Weider[13]. [1]Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland. [2]North Carolina State Univ., Raleigh, NC. [3]Case Western Reserve Univ., Cleveland, OH. [4]Jacobs, NASA JSC, Houston, TX. [5]ESA/ESAC, Madrid, Spain. [6]Univ. of Maryland Baltimore County, Baltimore, MD. [7]NASA GSFC, Greenbelt, MD. [8]Univ. of British Columbia, Vancouver, British Columbia, Canada. [9]Planetary Science Institute, Tucson, AZ. [10]Univ. of Michigan, Ann Arbor, MI. [11]NASA JSC, Houston, TX. [12]Purdue Univ., West Lafayette, IN. [13]NASA HQ, Washington, DC. (carolyn.ernst@jhuapl.edu)

Introduction: Mariner 10 provided our first close-up reconnaissance of Mercury during its three flybys in 1974 and 1975. MESSENGER's 2011–2015 orbital investigation enabled numerous discoveries, several of which led to substantial or complete changes in our fundamental understanding of the planet. Among these were the unanticipated, widespread presence of volatile elements (e.g., Na, K, S) [1–3]; a surface with extremely low Fe abundance [2–4] whose darkening agent is likely C [5–7]; a previously unknown landform—hollows—that may form by volatile sublimation from within rocks exposed to the harsh conditions on the surface [8, 9]; a history of expansive effusive [10] and explosive [11] volcanism; substantial radial contraction of the planet from interior cooling [12]; offset of the dipole moment of the internal magnetic field northward from the geographic equator by ~20% of the planet's radius [13]; crustal magnetization, attributed at least in part to an ancient field [14,15]; unexpected seasonal variability and relationships among exospheric species and processes [16–21]; and the presence in permanently shadowed polar terrain of water ice and other volatile materials, likely to include complex organic compounds [22–24].

Mercury's highly chemically reduced and unexpectedly volatile-rich composition is unique among the terrestrial planets and was not predicted by earlier hypotheses for the planet's origin. As an end-member of terrestrial planet formation, Mercury holds unique clues about the original distribution of elements in the earliest stages of the Solar System and how planets (and exoplanets) form and evolve in close proximity to their host stars. The BepiColombo mission [25] promises to expand our knowledge of this planet and to shed light on some of the mysteries revealed by the MESSENGER mission. However, several fundamental science questions raised by MESSENGER's pioneering exploration of Mercury can only be answered with *in situ* measurements from the planet's surface (Figure 1).

Science Goals: Our multidisciplinary team has identified four science goals, each addressable by landed *in situ* measurements, to guide a Mercury Lander mission concept study: 1) Investigate the highly chemically reduced, unexpectedly volatile-rich mineralogy and chemistry of Mercury's oldest terrain type, to understand the earliest evolution of this end-member of rocky planet formation; 2) Investigate Mercury's interior structure and magnetic field, to unravel the planet's differentiation and evolutionary history and to understand the magnetic fields at the surface; 3) Investigate the active processes that produce Mercury's exosphere and alter its surface, to understand planetary processes on rocky airless bodies, including the Moon; 4) Characterize the landing site, to understand the processes that have shaped its evolution, place *in situ* measurements in context, and enable ground truth for global interpretations of Mercury.

Landing Site Characteristics: There are numerous compelling terrain types that could be targeted by a Mercury lander. Science goals 2–4 could be addressed

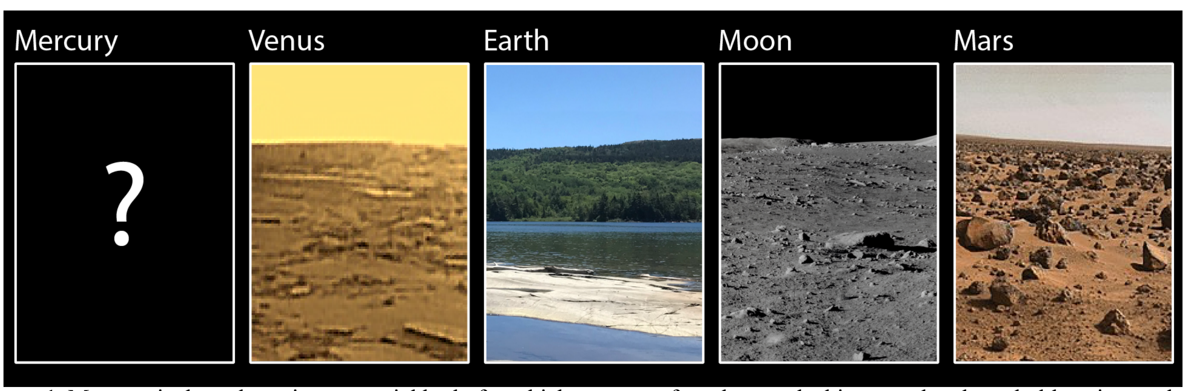

Figure 1. Mercury is the only major terrestrial body for which *in situ* surface data are lacking, yet the planet holds unique value in understanding how rocky worlds form and evolve.

Table 1. Key trades for the new Mercury Lander mission concept study

Mission Area	2020 PMCS Mercury Lander Study
Launch Vehicle	**Heavy lift capabilities have advanced** (Falcon Heavy has launched; SLS development well advanced; commercial entities offer other possibilities). Consider a wide range of launch vehicles.
Trajectory & Propulsion	**SEP technology has advanced substantially since 2010**. Apply the latest SEP options to look at the effects on the feasibility and the associated costs, in addition to new ballistic options.
Spacecraft Stages	**Consider SEP and a wide range of potential launch vehicles** and implications for stages. Explore whether new commercially developed propulsion systems could improve efficiency of cruise stage or reduce risk of braking stage.
Landing Approach	Hazard avoidance needed but no requirement for landing at a precise pre-identified location, as LRM exposures are extensive. Investigate the **latest technology advancements in hazard avoidance** (e.g., Autonomous Landing and Hazard Avoidance Technology (ALHAT), Dragonfly) to evaluate mission options.
Landing Location	Landing in LRM terrain is a science priority; LRM exposures are large and globally distributed. **Investigate which LRM landing locations are possible,** given thermal and direct-to-Earth communications needs.
Landed Operations	**Re-evaluate thermal constraints on landed operation options, time of day, and mission duration**. 2010 study [26] concept of operations plan remains a viable option.
Landed Power Source	A radioisotope power system still required, the 2010-baselined Advanced Radioisotope Sterling Generator is not available; **explore newer options under development by NASA and compare against the MMRTG.**
Payload	**Possibilities of robotic arm, sample handling, and/or surface interactions require iterative science and engineering discussions** to make payload decisions.

by landing in many terrain types; however, from a geochemical standpoint (Goal 1), the most critical data to be obtained from Mercury landed science are the mineralogical hosts of the measured elements of Mercury's low-reflectance material (LRM), the oldest terrain type which hosts the hollows. Understanding mineralogy of Mercury's surface materials opens a window into thermochemical evolution of the planet that does not currently exist. Therefore, we will identify a range of possible landing regions within LRM-rich terrain (Table 1).

Mission Concept Study: The major effort of this mission concept study is a systems-engineering design analysis (and development of precursor materials) to be performed at the Johns Hopkins University Applied Physics Laboratory (APL) Concurrent Engineering (ACE) facility in late February 2020. A Mercury Lander Mission Concept Study was completed in 2010 [26], but predated MESSENGER's orbital results, so the science justification for landed *in situ* measurements was less informed. The main challenges of landing a spacecraft on Mercury identified in that previous mission concept study have not changed—namely, 1) the large ΔV required by such a mission, 2) safely landing on Mercury's surface, and 3) working in the harsh thermal environment. The successful completion of the MESSENGER mission, launch of BepiColombo, and technological advancements made since the 2010 study warrant consideration in a new mission concept study. Table 1 details the key trades to be examined as a part of the engineering design study.

Forward to Mercury: This high-fidelity Mercury Lander mission concept study will both inform the 2023 Decadal Survey and allow for a future proposal team to adapt in response to BepiColombo's orbital findings. At least a decade is needed to go from project start to landing on Mercury, including a cruise comparable in duration to an outer Solar System mission. Postponing a mission option until the 2030s would break the continuity of Mercury exploration and specifically risk the loss of US-based expertise in Mercury science and exploration. The active and engaged Mercury community is ready to build upon the legacy of MESSENGER and the forthcoming BepiColombo, to address the next stage of Mercury exploration by defining the framework for the first landed mission to the innermost planet [27].

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References: [1] Peplowski, P.N. et al. (2011) *Science*, *333*, 1850–1852. [2] Nittler, L.R. et al. (2011) *Science*, *333*, 1847–1850. [3] Evans, L.G. et al. (2012) *JGR*, *117*, E00L07. [4] Weider, S.Z. et al. *LPS*, 45, #1866. [5] Murchie, S.L. et al. (2015) *Icarus*, *254*, 287–305. [6] Peplowski, P.N. et al. (2016) *Nature Geosci., 9*, 273–276. [7] Klima, R.L. et al. (2018) *GRL*, *45*, 2945–2953. [8] Blewett, D.T. et al. (2011) *Science*, *333*, 1856–1859. [9] Blewett, D.T. et al. (2016) *JGR: Planets*, *121*, 1798–1813. [10] Head, J.W. et al. (2011) *Science*, *333*, 1853–1856. [11] Kerber, L. et al. (2011) *Planet. Space Sci.*, *59*, 1895–1909. [12] Byrne, P.K. et al. (2014) *Nature Geosci.*, *7*, 301–307. [13] Anderson, B.J. et al. (2011) *Science*, *333*, 1859–1862. [14] Johnson, C.L. et al. (2015) *Science*, *348*, 892–895. [15] Johnson, C.L. et al. (2018) *Mercury: The View after MESSENGER*, 114–143. [16] Burger, M.H. et al. *Icarus,* 238, 51–58. [17] Cassidy, T.A. et al. (2015) *Icarus*, *248*, 547–559. [18] Cassidy, T.A. et al. (2016) *GRL*, *43*, 11,121–11,128. [19] Vervack, R.J. et al. (2016) *GRL*, *43*, 11,545–11,551. [20] Merkel, A.W. et al. (2017) *Icarus*, 281, 46–54. [21] Merkel, A.W. et al. (2018) *GRL*, *45*, 6790–6797. [22] Lawrence, D.J. et al. (2013) *Science*, *339*, 292–296. [23] Neumann, G.A. et al. (2013) *Science*, *339*, 296–300. [24] Paige, D.A. et al. (2013) *Science*, *339*, 300–303. [25] Benkhoff, J. et al. (2010) *Planet. Space Sci*., 58, 2–20. [26] Hauck, S.A. et al. (2010) Mercury Lander Mission Concept Study. [27] McNutt, R.L. et al. (2018) *Mercury: The View after MESSENGER*, 544–569.