MERCURY EXPLORATION: LOOKING TO THE FUTURE. K. E. Vander Kaaden[1], D. T. Blewett[2], P. K. Byrne[3], N. L. Chabot[2], C. M. Ernst[2], S. A. Hauck, II[4], F. M. McCubbin[5], E. Mazarico[6]. [1]Jacobs, NASA Johnson Space Center, Mail Code XI3, Houston, TX 77058, [2]The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, [3]Planetary Research Group, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC, [4]Department of Earth, Environmental, and Planetary Sciences, Case Western Reserve University, Cleveland, OH, [5]ARES NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058, [6]NASA Goddard Space Flight Center, Greenbelt, MD. Corresponding Author E-mail: Kathleen.E.VanderKaaden@nasa.gov.

Past Exploration of Mercury: Prior to the return of data from the NASA MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft [1], information relating to Mercury was limited. From the NASA Mariner 10 flybys, in 1974 and 1975, ~45% of the planet was imaged, its magnetic field was detected, H, He, and O in the exosphere were measured, and other physical characteristics of the planet were determined [e.g., 2]. Despite these data, much information about Mercury still had to be inferred. It was over 30 years before MESSENGER provided the first in-depth study of the innermost planet. Orbiting Mercury from 2011 to 2015, the MESSENGER spacecraft was able to image the entirety of the planet and thus provide the first global view of Mercury. Coupling multispectral images with data from MESSENGER geochemical instruments, we have developed a better understanding of the geochemical terranes on the planet and the unique nature of Mercury's composition compared to the other terrestrial planets [e.g., 3]. MESSENGER also provided data that have led to great advancements in understanding the internal structure, exosphere, and magnetosphere of Mercury [e.g., 4]. The treasure trove of MESSENGER data reveal Mercury as a geochemical end-member among the terrestrial planets. However, we are left with many questions that can only be answered with further exploration.

Present Exploration of Mercury: Launched on October 20, 2018, the joint ESA/JAXA dual-orbiter BepiColombo mission is due to arrive at Mercury in December 2025 [5]. The Mercury Planetary Orbiter is set to study the surface and the internal composition of the planet. The other orbiter, Mio, will study Mercury's magnetosphere. Combined, these two spacecraft will provide insight into the origin and evolution of Mercury, by conducting a global characterization of the planet and investigating its interior, surface, exosphere and magnetosphere [5]. BepiColombo will build upon the legacy of MESSENGER by advancing our understanding of the planet's magnetic field, volcanic activity, permanently shadowed craters, the planet's global contraction, unique surface features like hollows, the origin of the carbon component of the planet's crust, its dynamic magnetosphere, and the evolution of its exosphere.

Future Exploration of Mercury: Despite the influx of data from the Mariner 10 and MESSENGER spacecraft and the much-anticipated data that will be collected by BepiColombo, there is a limit to their scientific return. While orbiters could still provide finer valuable context, they cannot directly sample surface materials, nor probe the interior as a landed mission can. Furthermore, an orbiter cannot retrieve a sample to be sent to Earth for laboratory-based analyses. Currently, there is no Mercury mission in the planning stages to follow BepiColombo. Here, we advocate for the future exploration of Mercury through landed science and sample retrieval.

Landed Science. There are several major aspects of Mercury's character and evolution where substantial knowledge gaps exist but where our current understanding would be dramatically improved with data acquired from the planet's surface via landed instruments. Specifically, our view of the planet's geochemical makeup, its interior structure, geological evolution, and present-day processes at work there, as well as the planet's polar volatile inventory, would be substantially advanced by landed measurements [6]. In situ compositional and petrological observations would improve our knowledge of 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. A seismometer, heat-flow probe, and magnetometer on a lander would robustly characterize the interior structure of the planet, the present-day level of seismicity, pertinent heat flow related to the core dynamo, and the electrical and thermal conductivity structure of the crust and mantle. In situ geochronological measurements of the surface materials and investigations of the remnant magnetization would provide additional information regarding the age of materials on Mercury's surface, surface geological processes and evolution, and the history of interior melt production and dynamo generation, as well as crucial calibration of impact flux in the inner Solar System. Furthermore, in situ imaging of the surface would return key data on the regolith properties such as grain size, shape, and mechanical strength. In addition, a lander on the surface of Mercury would have the unique opportunity to provide in situ measurements to understand the origin and composition of the volatile compounds within Mercury's polar deposits, the purity of the ice in these deposits, as well as the physical and mechanical properties of the volatiles, such as volume, grain size, strength, thickness, and evidence for layering.

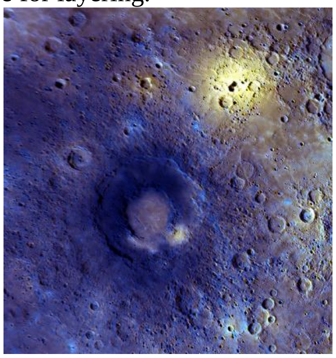

Figure 1. Enhanced color image of Rachmaninoff Basin (dark blue, center) obtained by the MESSENGER Mercury Dual Imaging System.

Sample Retrieval. Although the data from remote-sensing and in-situ analysis missions provide a wealth of knowledge regarding the physical and chemical characteristics of a planetary body, there are critical science questions that can only be fully addressed via examination of a sample in Earth-based laboratories, where sustained, highly sensitive analytical measurements are possible. The exact mineralogy of a Mercury sample could be fully characterized, yielding insight into trace element abundances, isotopic ratios, mineralogy, and petrology at microscopic levels. The presence or absence of key mineral phases (e.g., Si-metal and graphite) would directly test published hypotheses for the history of Mercury and lend insight into the early evolution of the planet. Additionally, radiometric dating of a sample would place unprecedented constraints not only on the various geologic features across the surface of the planet but on the inner Solar System impact flux itself. Further, Mercury has been likened to some exoplanets in terms of the highly reducing conditions under which it formed. Therefore, examination of a sample from Mercury would lend insight into the formation and evolution of small, iron-rich rocky planets in general. Lastly, as demonstrated by ongoing analysis of Apollo lunar samples, a sample from Mercury would be an invaluable scientific resource for decades to come, with ever more sophisticated tools brought to bear as they become available.

Potential Sites. Although there are legions of locations for future exploration of Mercury, a few particularly useful sites for advancing our understanding of the planet include the Rachmaninoff Basin (Figure 1), the polar deposits, and an ancient low-reflectance material (LRM) deposit. A lander and/or sample retrieval from these locations would be able to answer key scientific questions including: What is the composition of Mercury's oldest crust? How does this material compare with the other terrestrial planets? How old is the crust of Mercury? What were the conditions during Mercury's core formation? What are the dominant volatile species associated with pyroclastic eruptions and polar deposits? What are the major, trace, and rare earth element compositions of these various deposits? What is the mineralogy and petrology associated with pyroclastic, polar ice, and LRM deposits? What are the radiometric ages of these deposits? How pure is the ice in these deposits?

Challenges. Despite strong scientific promise, the landed exploration of Mercury and the delivery to Earth of a sample of the planet for laboratory analyses would be a substantial undertaking. One of the main concerns, and perhaps the greatest challenge, is the large amount of launch energy and ΔV required for both reaching Mercury and landing on its surface [7]. Furthermore, the thermal environment that a lander must endure will need to be carefully considered. The large fluctuation in temperature on Mercury is challenging for the longevity of the instruments. Regardless, the sending of any landed mission to Mercury must include consideration of the diversity of materials present on the surface. Similarly, the size of any retrieved sample should be sufficiently large that some of the materials can be preserved for future analysis when technology has far exceeded our current abilities.

Conclusion: To ensure the continued exploration of the Sun's closest planetary neighbor, development of mission concepts need to begin now. The planned seven-year cruise of the BepiColombo mission, comparable to some outer Solar System missions, reflects the difficulty in reaching the innermost planet, hence time is of the essence. Landed instruments and sample retrieval from Mercury would lead to transformative Solar System science that places new and vital constraints on the building blocks and thermochemical evolution of Mercury and the other terrestrial planets. Any delay in the planning and execution of missions to follow BepiColombo will be a detriment to our exploration and understanding of enigmatic Mercury.

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