The Exploration of Mercury by Spacecraft

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The planet Mercury is sufficiently close to the Sun to pose a major challenge to spacecraft exploration. The *Mariner 10* spacecraft flew by Mercury three times in 1974–1975 but viewed less than half of the surface. With the three flybys of Mercury by the *MESSENGER* spacecraft in 2008–2009 and the insertion of that probe into orbit about Mercury in 2011, our understanding of the innermost planet substantially improved. In its four years of orbital operations, *MESSENGER* revealed a world more geologically complex and compositionally distinctive, with a more dynamic magnetosphere and more diverse exosphere–surface interactions, than expected. With the launch of the *BepiColombo* dual-orbiter mission, the scientific understanding of the innermost planet has moved another major step forward.

Keywords: Mercury, *Mariner 10*, *MESSENGER*, *BepiColombo*

INTRODUCTION

The initial global exploration of the planet Mercury was recently completed by the *MErcury Surface, Space ENvironment, GEochemistry, and Ranging* (*MESSENGER*) mission of the US National Aeronautics and Space Administration (NASA). During three Mercury flybys and more than four years in orbit about Mercury, the *MESSENGER* spacecraft imaged the entire surface, mapped the composition of surface materials, determined the planet's magnetic and gravity fields, measured global topography, assayed the composition of Mercury's neutral atmosphere and charged-particle environment, and documented the structure of Mercury's magnetosphere and its dynamic response to changes in the solar wind and interplanetary magnetic field (Solomon and Anderson 2018). Now underway is the *BepiColombo* mission of the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA), scheduled to insert two spacecraft into coplanar orbits about Mercury in late 2025 (Benkhoff et al. 2010). This paper offers an overview of these two missions, from the rationale for a Mercury orbiter mission following the initial reconnaissance of the planet by the *Mariner 10* spacecraft, to the first concept studies that led to the selection of the *MESSENGER* and *BepiColombo* missions for flight, through instrument selection and spacecraft development and launch, to a summary of findings from the *MESSENGER* mission and current plans to build on that scientific framework with observations to be acquired by *BepiColombo*.

MARINER 10

Whereas the first spacecraft to visit Earth's nearest planetary neighbors, Venus and Mars, were launched early in the 1960s by the Soviet Union and the United States, more than a decade passed before the first spacecraft was sent to Mercury. NASA's *Mariner 10* spacecraft was launched in November 1973 on a trajectory that, with the aid of a gravity-assist flyby of Venus, led to an encounter with Mercury four-and-a-half months later. The spacecraft (Fig. 1) carried an imaging system, two magnetometers, an infrared radiometer, two ultraviolet spectrometers, two plasma detectors, two charged-particle telescopes, and a radio science experiment (Dunne and Burgess 1978).

In the original design for the mission, *Mariner 10* was to have flown by Mercury only once. In the early 1970s, Giuseppe ("Bepi") Colombo (1920–1984), a mathematician and celestial mechanics expert from the University of Padua (Italy), visited the Jet Propulsion Laboratory (California, USA) where the *Mariner 10* mission was developed and pointed out to mission designers that a propulsive maneuver after

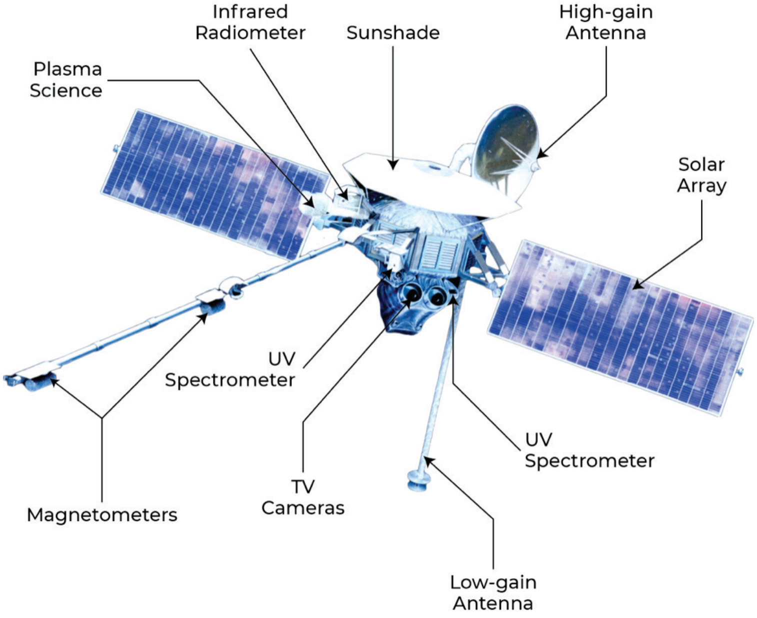

Figure 1 The *Mariner 10* spacecraft, including scientific instruments, telecommunications antennas, and solar arrays. UV = ultraviolet. Image credit: NASA

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the first Mercury encounter could transfer the spacecraft to an orbit with a period twice that of Mercury (Balogh et al. 2007). In such a resonant orbit, the spacecraft would reencounter Mercury every two Mercury years (a Mercury year lasts ~88 Earth days). *Mariner 10* flew by Mercury successfully a total of three times, in March and September 1974 and in March 1975.

Because of Mercury's 3:2 spin–orbit resonance—a dynamical state also first pointed out by Colombo—a solar day on Mercury (the period of the day–night cycle to an observer on the surface) is equal to two Mercury years. As a result, the same hemisphere of the planet was sunlit during each of the *Mariner 10* flybys. The spacecraft thus acquired images of only ~45% of the surface, but that fraction was sufficient to document the generally high areal density of impact craters, characterize the largest tectonic features on the planet, and discern the major types of morphological units on the surface. *Mariner 10* also discovered Mercury's global magnetic field, detected bursts of energetic charged particles inside Mercury's magnetosphere, and measured the abundances of neutral hydrogen and helium in Mercury's exosphere (Dunne and Burgess 1978).

MERCURY ORBITER CONCEPTS

After the *Mariner 10* mission, scientific advisory committees in the USA (e.g., COMPLEX 1978) recommended to NASA that the next logical step in the exploration of Mercury would be an orbiter mission. Moreover, the primary objectives of such a mission were also clear, including determining surface composition on global and regional scales, ascertaining the structure and state of the planet's interior, and improving the coverage and resolution of orbital imaging (COMPLEX 1978). In the 1970s, however, there were no mission designs that permitted orbit insertion at Mercury with conventional chemical propulsion systems, and it was thought that a Mercury orbiter mission would have to await the development for flight of a low-thrust propulsion system such as a solar sail or solar electric propulsion (COMPLEX 1978).

In 1985, mission design expert Chen-Wan Yen at the Jet Propulsion Laboratory devised a new class of trajectories that utilized multiple gravity assists at Venus and Mercury to place a spacecraft into orbit about Mercury with only a chemical propulsion system (Yen 1989). Her discovery stimulated detailed studies of Mercury orbiter missions over the next several years in both Europe and the USA (Balogh et al. 2007; McNutt et al. 2018). Moreover, at about the same time, important discoveries were made by ground-based astronomers, including the detection of sodium and potassium in Mercury's exosphere (e.g., Potter and Morgan 1985) and the documentation of radar-reflective deposits in Mercury's polar regions that were postulated to consist mostly of water ice (e.g., Slade et al. 1992). Notwithstanding this progress in both mission design concepts and scientific motivation, no spacecraft mission to Mercury was selected for flight until the end of the 1990s.

In the USA, the key to selecting a Mercury orbiter mission was NASA's Discovery Program, which was established early in the 1990s and soon began soliciting, on a regular basis, proposals for spacecraft missions led by a scientific investigator and limited in total mission cost, development time, and launch vehicle requirements. Missions to Mercury were among the earliest to receive funding for concept studies under that program (Kicza and Vorder Bruegge 1995), and at least two Mercury missions were proposed in response to each of the program's announcements of opportunity in 1994, 1996, and 1998. The *MESSENGER* mission was proposed to the Discovery Program in 1996 and 1998, and, on the basis of the second proposal, NASA selected the mission for flight in July 1999.

The roots of the *BepiColombo* mission also go back to the 1990s (Balogh et al. 2007; Benkhoff et al. 2010; McNutt et al. 2018). A Mercury orbiter mission was proposed to ESA in 1993 in response to a "Call for Ideas," and such a mission was selected in 1996 as a candidate in the agency's Horizons 2000+ scientific program. In October 2000, ESA's Science Programme Committee approved *BepiColombo*—a mission name that had been adopted by the same committee 13 months earlier—as a "Cornerstone" mission. The mission concept at the time called for two orbiters, one focused on the planet and the other on the magnetosphere and planetary environment, as well as a lander, all delivered to Mercury by solar electric propulsion. Budget reductions one year later, however, led to the removal of the lander from the mission design and a baseline mission that involved a split launch of the orbiters on Soyuz–Fregat rockets. In 1997 and in parallel to ESA's plans, Japan's Institute of Space and Astronautical Science (ISAS)—later to become part of JAXA—formed a Mercury Exploration Working Group to develop plans for a Mercury orbiter mission focused on magnetospheric science. Discussions with ESA about collaboration on the *BepiColombo* mission began in 1999, and an agreement for ISAS to provide the magnetospheric orbiter for *BepiColombo* was formally approved in 2003. A new mission profile involved the common launch and transport to Mercury of the two orbiters. Selection of payload instruments for the orbiters was completed in 2004.

MESSENGER

Mission Objectives and Design

The *MESSENGER* mission was designed to address six key scientific questions (Solomon and Anderson 2018): (1) What planetary formational processes led to the high ratio of metal to silicate in Mercury? (2) What is the geological history of Mercury? (3) What are the nature and origin of Mercury's magnetic field? (4) What are the structure and state of Mercury's core? (5) What are the radar-reflective materials at Mercury's poles? (6) What are the important volatile species and their sources and sinks on and near Mercury? These questions built on the objectives for a Mercury orbiter mission set out after the *Mariner 10* mission (COMPLEX 1978) as well as on the results from ground-based astronomy in the two decades that followed. The key questions were deemed capable of being addressed by measurements that could be made from orbit, and their answers would bear not only on the nature of Mercury but more generally on the origin and comparative evolution of the inner planets as a group. From those questions followed specific scientific objectives, measurement requirements, payload instruments, and a mission design that would satisfy all requirements.

The *MESSENGER* payload consisted of seven scientific instruments plus the spacecraft communication system. There was a dual imaging system for wide and narrow fields of view, monochrome and color imaging, and stereo; gamma-ray, neutron, and X-ray spectrometers for mapping surface composition; a magnetometer; a laser altimeter; a combined ultraviolet (UV) and visible spectrometer and a visible–near-infrared (NIR) spectrograph to survey both exospheric species and surface mineralogy; and a combined energetic particle and plasma spectrometer to sample charged species in the magnetosphere (Fig. 2).

The *MESSENGER* spacecraft was launched on 3 August 2004, followed an interplanetary cruise phase that lasted 6.6 years, and included six planetary flybys: one of Earth, two of Venus, and three of Mercury itself. During the Mercury flybys, *MESSENGER* mapped nearly the entire planet in color, imaged most of the area unseen by *Mariner 10*, completed initial measurements of the composition of Mercury's exosphere and neutral tail, and made

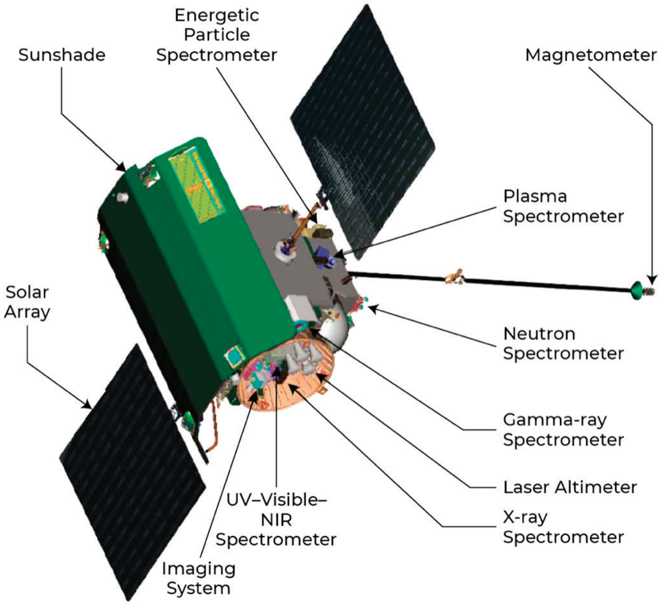

FIGURE 2 The instrument payload on the *MESSENGER* spacecraft. Spacecraft power was provided by two solar arrays. The ceramic-cloth sunshade protected the spacecraft bus and all electronic systems from solar heating. NIR = near infrared. IMAGE CREDIT: NASA

initial characterizations of the structure and dynamics of Mercury's magnetosphere. Those three flybys not only returned the first new spacecraft data from Mercury in more than three decades, they were also invaluable to planning *MESSENGER*'s orbital operations. Science data acquisition planning for the flybys demonstrated the complex interplay between imaging and competing remote-sensing observations, as well as with spacecraft operational constraints on pointing, power management, navigation, and achievable rates of change to spacecraft attitude. The manual approach to the design of observational and spacecraft command sequences for the flybys was replaced for the mission orbital phase with a software system that combined observational requirements, spacecraft capabilities, and operational constraints with orbit solutions to conduct an automated search for optimal observation opportunities and convert such information to spacecraft attitude and instrument commands. This software greatly accelerated the science acquisition planning and command generation processes, enabled ready recovery from any loss of data, and easily accommodated the addition of targeted observations throughout orbital operations (Solomon and Anderson 2018).

On 18 March 2011, the *MESSENGER* spacecraft was inserted into a highly eccentric, 12-hour orbit about the planet Mercury. The initial orbit had an inclination of 82.5°, a periapsis (closest approach) altitude of ~200 km, a periapsis latitude of 60°N, and an apoapsis (orbital high point) altitude of ~15,200 km in the southern hemisphere. The primary mission originally approved by NASA included one Earth-year of orbital observations. After orbit insertion, because a second Earth-year of observations would provide a substantial advance in our understanding of Mercury beyond what would be achieved after one year in orbit, all spacecraft subsystems and payload instruments were healthy, and there was sufficient propellant to continue orbital operations for at least another year, NASA approved a first extended mission through 18 March 2013. A pair of propulsive maneuvers in April 2012 reduced *MESSENGER*'s orbital period from 12 to 8 hours, giving the spacecraft more time each day close to the planet's surface. The effect of the gravitational pull of the Sun during the primary and first extended missions was to raise both the altitude and latitude of periapsis between successive *MESSENGER* orbits, so several propulsive maneuvers were executed to keep periapsis altitude within the range 200–500 km.

MESSENGER's first extended mission raised fresh questions about Mercury that could be addressed only with new measurement campaigns. As the end of the first extended mission drew near, and given the healthy state of the spacecraft and instrument payload, the ample power margin, and the remaining propellant, NASA approved a second extended mission of approximately two Earth-years in duration. There were two novel aspects of *MESSENGER*'s second extended mission. First, a maximum in the solar cycle occurred during the first year of the second extended mission operations, and the remainder of that year and all of the second year captured the waning phase of the solar cycle. Moreover, the second year of *MESSENGER*'s second extended mission featured periapsis altitudes lower than at any earlier time in the mission, i.e., closer to Mercury's surface than any spacecraft had been before. In contrast to the primary and first extended missions, during the second extended mission the effect of the gravitational attraction of the Sun was to decrease periapsis latitude and altitude progressively between successive orbits. An optimized set of propulsive maneuvers conducted with *MESSENGER*'s remaining propellant permitted four separate campaigns of several days to one week each during which the periapsis altitude was nearly steady at 15 to 25 km, providing opportunities to observe regions of Mercury with the full instrument suite at horizontal resolutions markedly superior to those attained earlier. Once propellant was exhausted, the spacecraft finally impacted the planet on 30 April 2015.

Scientific Findings

MESSENGER's measurements of Mercury's surface composition and global magnetic and gravitational fields and the documentation of Mercury's volcanic features and processes are described in other papers in this issue. Noteworthy findings include the unexpectedly high surface abundances of volatile elements in, and the chemically reduced character of, Mercury's surface materials (Ebel and Stewart 2018; Nittler et al. 2018); the planet's axially symmetric but equatorially asymmetric magnetic field (Johnson et al. 2018); an internal structure characterized by a larger metallic core and a thinner silicate shell of crust and mantle than anticipated prior to the mission (Margot et al. 2018; Phillips et al. 2018); tectonic features that accommodated substantially more crustal shortening than previously recognized, thereby resolving a long-standing discrepancy between photogeological observations and the predictions from thermal history models (Byrne et al. 2018a; Hauck et al. 2018); and evidence from images that plains volcanism was widespread on Mercury and probably dominated the emplacement of Mercury's crust but had largely ended by 3.5 Ga (Byrne et al. 2018b; Chapman et al. 2018; Denevi et al. 2018). The youngest large-scale effusive volcanic deposits on Mercury, the smooth plains, are concentrated within a single hemisphere (FIG. 3), indicating a hemispherical difference in temperature or melt extraction during the era of plains formation that may have left associated hemispherical differences in modern core–mantle boundary characteristics related to the offset of Mercury's dipolar magnetic field from the planetary center (Hauck et al. 2018; Johnson et al. 2018).

Magnetosphere

MESSENGER observations showed that Mercury's magnetosphere is much smaller than, but broadly similar in structure to, that of Earth, and it effectively acts to energize solar wind plasma and channel it to the planetary surface.

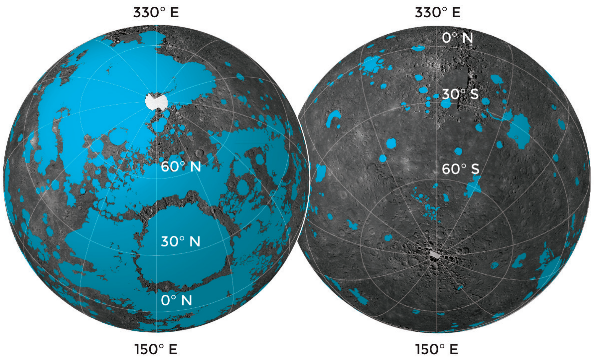

Figure 3 The distribution across Mercury's surface of smooth plains deposits (blue), the vast majority of which are volcanic (Denevi et al. 2018). Most smooth plains deposits are located in Mercury's northern hemisphere. The background planetary image is a *MESSENGER* global mosaic: the left and right views are in orthographic projection centered at 60°N, 150°E, and 60°S, 330°E, respectively.

Magnetic reconnection between the planetary and solar wind magnetic fields at Mercury occurs with an intensity an order of magnitude greater than at Earth (Slavin et al. 2018). Plasma pressures within 1,000 km of the planetary surface often exceed the magnetic pressure, leading to intense precipitation of plasma electrons and ions onto the planetary surface (Korth et al. 2018). The existence of bursts of energetic particles in Mercury's magnetosphere—a major discovery from the *Mariner 10* flybys—was confirmed almost as soon as *MESSENGER* began orbital observations, and the energetic particles were shown to be electrons. The most energetic bursts appeared to be produced in the midnight sector of Mercury's magnetosphere, in support of the view that energetic electrons are accelerated in the near-tail region and then injected onto closed magnetic field lines on the planetary nightside during substorm-like events (Slavin et al. 2018). *MESSENGER*'s magnetic field observations demonstrated the presence of electric currents that flow along magnetic lines of force toward and away from the planet above Mercury's northern hemisphere; such currents are analogous to Birkeland currents at Earth but close through the planet rather than in an ionosphere (Korth et al. 2018).

Exosphere

With UV- and visible-wavelength spectrometry, *MESSENGER* showed that neutral Na, Ca, and Mg are the dominant constituents in Mercury's exosphere; additional constituents detected from orbit included H, Al, Ca^+, and Mn (Killen et al. 2018; McClintock et al. 2018). The distributions of exospheric Na, Ca, and Mg with altitude and local time differ, and these different distributions indicate a different mix of source and transport processes for each atomic species (Killen et al. 2018). Sodium, the most abundant constituent, exhibits a two-component structure, implying that multiple source processes supply exospheric atoms with different energies. In contrast, Ca and Mg show predominantly single-component altitude profiles that are indicative of high-energy processes. Whereas sodium is distributed approximately uniformly over the dayside, calcium emission exhibits a strong dawn enhancement. Magnesium distribution is similar to that of calcium except that the dayside emission is distributed over a larger range of local time and the dawn–dusk contrast is less pronounced (McClintock et al. 2018). *MESSENGER* observations of the Na exosphere did not show evidence for strong short-term spatial and temporal variability, a result at odds with many ground-based observations, suggesting that the short-term variations originate almost completely in mid- to high-latitude dayside regions of the exosphere not well viewed by *MESSENGER*. The Na, Ca, and Mg exospheres exhibit a persistent exospheric morphology from one Mercury year to another, and variations in emission intensity during each year generally match those expected from variations in solar flux with Mercury's position in its orbit (Killen et al. 2018; McClintock et al. 2018). Exospheric Mg is enhanced over a large high-Mg region identified on Mercury from orbital geochemical remote sensing (McCoy et al. 2018), the first clear link demonstrated between surface composition and exospheric characteristics (Merkel et al. 2018) (Fig. 4).

Polar Deposits

MESSENGER imaging confirmed that all of Mercury's polar deposits identified from Earth-based radar measurements are confined to areas of permanent or persistent shadow (Chabot et al. 2018). Neutron spectrometry indicated that Mercury's northern-hemisphere polar deposits contain, on average, a hydrogen-rich layer at least tens of centimeters thick, generally covered by a surficial layer 10–30 cm thick that is lower in hydrogen content. Measurements of NIR surface reflectance with *MESSENGER*'s laser altimeter revealed that some polar deposits near the north pole are brighter than Mercury's average surface, but polar deposits farther from the pole are darker than average. Correlation of observed reflectance with surface and near-surface temperatures derived from insolation models tied to measured topography indicated that the optically bright regions are consistent with the presence of surficial water ice, whereas polar deposits with dark surfaces have temperature structures consistent with water ice buried beneath an insulating surface layer of other volatile materials, most likely complex organic deposits, that are stable to variable but higher temperatures than water ice. Long-exposure images of the polar deposits, those with both bright and

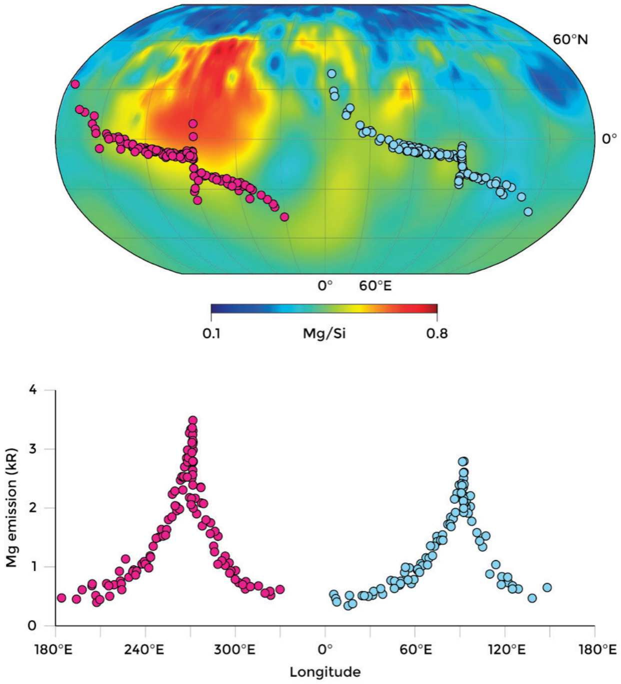

Figure 4 (**Top**) Locations of *MESSENGER* observations of Mg emission at 300-km tangent altitude near the dawn terminator. Red and blue symbols indicate alternating Mercury years. The background plot is a map of the Mg/Si weight ratio of surface material determined from orbit by X-ray spectrometry (Nittler et al. 2018) shown in Robinson projection centered at 0°N, 0°E. (**Bottom**) Mg emission values (kR = kiloRayleigh) versus Mercury longitude. The variation within a given Mercury year is a function of Mercury's position in its eccentric orbit about the Sun, but the difference between alternating years reflects enhanced emission over Mercury's high-Mg region. Adapted from Merkel et al. (2018).

dark surfaces, indicate that the deposits appear to be draped over small impact craters and display sharp edges, characteristics that are consistent with geologically recent, or even ongoing, emplacement. Impacts onto Mercury of comets or volatile-rich asteroids could have provided both the water ice and the dark, organic-rich material (Chabot et al. 2018).

Hollows

One of the most surprising results of *MESSENGER*'s high-resolution imaging of Mercury's surface was the discovery of what are termed "hollows." Hollows are fresh-appearing depressions, without raised rims, commonly with high surface reflectance and often with bright halos, but morphologically distinct from impact and volcanic craters (Blewett et al. 2018). Hollows are concentrated on Mercury's low-reflectance material color unit (Denevi et al. 2018; Murchie et al. 2018) within impact craters and basins (Blewett et al. 2018), material inferred to have been excavated from depth by impact (Denevi et al. 2018). Candidate mechanisms for forming these hollows involve recent loss of volatiles through sublimation, space weathering, or outgassing (Blewett et al. 2018). High-resolution images of hollows indicate a narrow range of hollows depths, favoring the hypothesis that hollows cease to deepen when a volatile-depleted lag deposit becomes sufficiently thick to protect the underlying surface. Even the highest-resolution images reveal no superposed impact craters, implying that hollows are geologically very young (Blewett et al. 2018).

BEPICOLOMBO

The joint ESA–JAXA *BepiColombo* mission, like *MESSENGER*, was designed to address a broad menu of scientific objectives. These include improving our understanding of the origin and evolution of a planet near its parent star; the form, interior structure, geology, and composition of Mercury; the composition and dynamics of the planet's exosphere; the structure and dynamics of its magnetosphere; the origin of Mercury's magnetic field; and tests of Einstein's theory of general relativity (Benkhoff et al. 2010).

BepiColombo launched on an Ariane 5 rocket from the Guiana Space Centre northwest of Kourou (French Guiana) on 20 October 2018 (UTC). The mission architecture includes four spacecraft elements: the two probes that will independently operate at Mercury—the *Mercury Planetary Orbiter* (*MPO*) and the *Mercury Magnetospheric Orbiter* (*MMO*), the latter renamed *Mio* by JAXA in June 2018—a sunshield (termed the Magnetospheric Orbiter Sunshield and Interface) to protect *Mio* during the cruise to Mercury, and the Mercury Transfer Module. This last element houses the solar electric propulsion system, which will provide the majority of thrust required to reach orbit about Mercury, and a chemical bi-propulsion system for smaller maneuvers and attitude control during cruise (Benkhoff et al. 2010; McNutt et al. 2018).

The trajectory *BepiColombo* will take to Mercury is similar to that employed by the *MESSENGER* mission. *BepiColombo* will fly past Earth in April 2020 before making two flybys of Venus, in October 2020 and August 2021. The spacecraft ensemble will then make six close approaches to Mercury from October 2021 through January 2025, progressively decreasing its velocity relative to its target until it is weakly captured by Mercury's gravitational field in December 2025 (McNutt et al. 2018). Upon capture, *Mio* will be decoupled from the *MPO* before being spin-stabilized by its own propulsion system, after which a chemical propulsion system integrated into the *MPO* will make final orbit-insertion maneuvers for that spacecraft (Benkhoff et al. 2010).

The *MPO* will operate in a 2.3-hour orbit of 480 × 1,500 km altitude, whereas *Mio* will take 9.3 hours to complete its orbit with altitudes of 590 × 11,640 km. Unlike *MESSENGER*, neither the *MPO* nor *Mio* features a single large, sunward-pointed sunshade. Instead, the *BepiColombo* spacecraft will manage their thermal loads with low-solar-absorptivity coatings, thermal blankets, spin stabilization for *Mio*, and for the *MPO* a large radiator that will never face the Sun (Benkhoff et al. 2010; McNutt et al. 2018). Both spacecraft will be powered by solar cells and will communicate directly with Earth via high- and medium-gain antennas. The orbital phase of the mission will last one Earth year, and there will be an option for a one-year extended mission.

The two *BepiColombo* spacecraft carry a total of 16 instruments, with 11 on the *MPO* and five on *Mio* (Benkhoff et al. 2010). The *MPO* carries imaging, geochemical and exospheric remote sensing, and particle spectrometers, a laser altimeter, a magnetometer, an accelerometer, and a radio science package (Fig. 5). *Mio* is equipped with a plasma particle experiment and plasma wave instrument, a spectral imager, a dust monitor, and another magnetometer. The *MPO* will also test gravitational theory and make precise measurements of the temporal variation of the gravitational constant (Benkhoff et al. 2010).

OUTLOOK

Although the *MESSENGER* and *BepiColombo* missions were conceived and selected by their sponsoring agencies at similar times, their development schedules differed markedly. The *MESSENGER* mission was proposed, designed, and developed within the tight budgetary and schedule constraints of the NASA Discovery Program by a scientific and engineering team that was in place and with an instrument payload that was well defined at the time of the mission proposal. In contrast, the *BepiColombo* mission is a more ambitious and costly endeavor, one that faced the

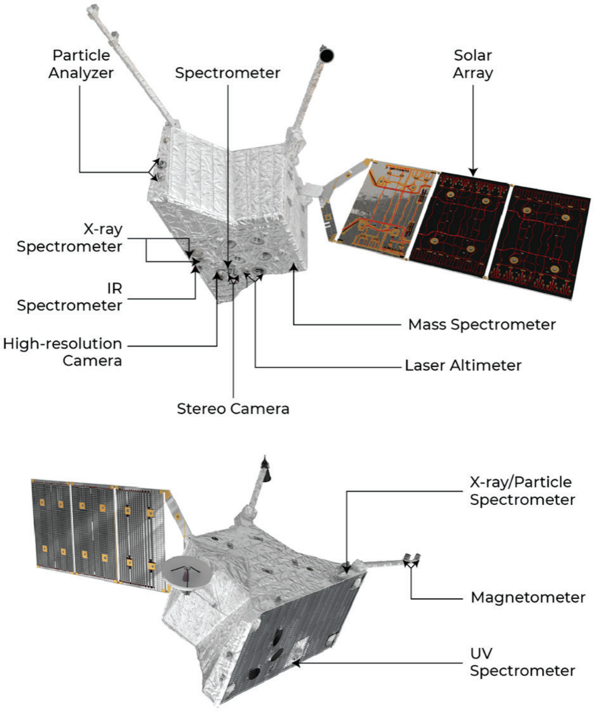

Figure 5 Two views of the *Mercury Planetary Orbiter* spacecraft (one of the *BepiColombo* mission's two independent orbiters) and its instrument payload. The solar array powers the spacecraft. In addition to the instruments shown, a radio science package, another particle analyzer, an accelerometer, a gamma-ray spectrometer, and a neutron spectrometer are housed within the spacecraft bus itself. IR = infrared, UV = ultraviolet. Image credit: ESA.

challenges of multinational and multiagency cooperation and involved payload selection well after mission approval. Although not originally planned to be sequential, the two missions will build on one another in a synergistic fashion.

By including many instruments that are similar to those that flew on *MESSENGER*, *BepiColombo* will return measurements that can be readily compared with those from, and will enhance the findings of, the earlier mission. That the *Mercury Planetary Orbiter* will have a much less eccentric orbit than *MESSENGER* will enable measurements of surface properties and topography and gravity at substantially higher resolution in Mercury's southern hemisphere. Data from the magnetometers on the *Mercury Planetary Orbiter* and *Mio* will allow, for the first time, the acquisition of simultaneous observations of Mercury's heliospheric environment and the magnetospheric response to changes in that environment (McNutt et al. 2018). Moreover, *BepiColombo* carries instruments not previously flown to Mercury, such as a thermal infrared imager, which promises new information on the mineralogy of Mercury's surface materials, and plasma wave receivers, which will provide novel insight into Mercury's magnetospheric dynamics (Benkhoff et al. 2010; McNutt et al. 2018).

Although the exploration of Mercury by spacecraft has lagged behind that of Venus and Mars for more than half a century, our understanding of the innermost planet and its distinctive characteristics is undergoing a scientific renaissance, begun with the successful completion of the *MESSENGER* mission in 2015 and continuing with the *BepiColombo* mission in the coming decade.

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