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The Study of Mercury

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Abstract. When the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft enters orbit about Mercury in March 2011 it will begin a new phase in an age-old scientific study of the innermost planet. Despite being visible to the unaided eye, Mercury's proximity to the Sun makes it extremely difficult to observe from Earth. Nonetheless, over the centuries man has pursued a quest to understand the elusive planet, and has teased out information about its motions in the sky, its relation to the other planets, and its physical characteristics. A great leap was made in our understanding of Mercury when the Mariner 10 spacecraft flew past it three times in the mid-1970s, providing a rich set of close-up observations. Now, three decades later, The MESSENGER spacecraft has also visited the planet three times, and is poised to add significantly to the study with a year-long orbital observation campaign.

Keywords. History and philosophy of astronomy; Planets and satellites, general; Celestial mechanics, Space vehicles.

As one of the "wandering stars", Mercury has been observed since antiquity and references to it can be found in the lore of ancient civilizations around the world. The Chinese associated Mercury with the direction north and the element water. In Hindu mythology the planet was called Budha, a god who presided over Budhavara, or Wednesday. The Norse associated Mercury with their god Odin, who also presided over the middle day of the week (Woden's Day). Because Mercury is so close to the Sun, it travels quickly relative to other celestial bodies. It can be seen only during the days surrounding its greatest elongations, when it is visible just before sunrise or after sunset. It is these characteristics of swiftness and elusiveness that prompted a number of cultures to associate Mercury with their messenger gods, such as the Babylonian god Nabu, the Egyptian god Thoth, and the Greek god Hermes. The Maya represented Mercury as one or more owls, which served as messengers to the underworld. The English name for the planet comes from the Roman messenger god Mercurius, the Roman equivalent of Hermes.

The first known references to Mercury in writing are found in Mesopotamia in the 7^{th} century BCE. The cuneiform tablets known as the MUL.APIN were most likely written by Assyrian astronomers and describe observations taken between 1300 and 1000 BCE (Figure 1) (Schaefer, 2007). At the same time that these tablets were being created, the Maya also were charting the motion of the planet. Records of detailed observations are found in the Dresden Codex (Makemson, 1957). Observations of Mercury figured prominently in the early efforts to develop a geometric model of the heavens. One of the first attempts at this was around 370 BCE by the Greek astronomer Eudoxus, who compiled an extensive star catalog, which included the visible planets. To explain the measurements represented in his catalog, Eudoxus' planetary model incorporated more than two dozen spheres. Mercury, along with each of the other four visible planets, was assigned four spheres: one to describe daily motion, one for motion through the zodiac, and two to represent retrograde motion (Heath, 1921).

Figure 1. Cuneiform MUL.APIN tablet, found in Mesopotamia in the 7^{th} century BCE, thought to contain the first written references to Mercury.

In the second century AD Ptolemy published his great scientific treatise, *Almagest*, in which he describes a simpler geocentric model of the planets that was accepted as correct for centuries afterward. In this work he compiled all known observations of early Babylon and Hellenistic Egypt. He included seven observations of Mercury, the earliest of which was made on 15 November 265 BCE (Jones, 2006). Throughout the Middle Ages astronomers continued to observe the planets and to record their movements. Pre-optical instruments such as astrolabes and quadrants grew in sophistication and produced very accurate measurements. The German astronomer Bernard Walther is the first astronomer known to have used a clock for indicating the time of astronomical observations, and did so to record Mercury's appearance in the sky on 16 January 1484 (Beaver, 1970). In the following century, Copernicus used unpublished observations by Walther in developing his heliocentric planetary model.

In the first years of the seventeenth century, Johannes Kepler, using observations made by the Danish astronomer Tycho Brahe, calculated that on 29 May 1607 Mercury would pass directly between Earth and the Sun. Using a lens-less pinhole camera, he tracked "a little daub, quite black, approximately like a parched flea" passing across the bright image of the Sun. Convinced at first that he had witnessed a transit of Mercury, he published his results before realizing that he had indeed not observed Mercury after all (Caspar, 1993). As with similar observations thought to be of Mercury transits made in 807 AD and in 1278 AD, the dark spots moving on the Sun's disk were likely sunspots.

In 1608 the telescope was invented in Holland and it immediately revolutionized astronomy. Within one year of its introduction it was being used for astronomical studies throughout Europe, including those by Galileo Galilei in Padua, Italy, Thomas Harriot in London, England, and Simon Marius in Ansbach, Germany. Although the instrument brought man closer to the heavens than ever before, the early lenses were still too crude to reveal any of Mercury's secrets. As the state of the art of telescope manufacture developed, so did the number and quality of the observations.

With the completion of better planetary position tables in 1627 (the Rudolphine tables), Kepler once again predicted a transit of Mercury, this time to occur on

7 November 1631. Although it occurred slightly earlier than expected, the transit was observed and documented by the French astronomer, Pierre Gassendi. Unlike Kepler, who two decades earlier had mistaken a sunspot for Mercury, when a spot first appeared on the Sun's image, Gassendi believed it to be too small to be Mercury, and concluded that it was instead a sunspot (Van Helden, 1976). Only after further observation did the astronomer realize that the dark object moved too quickly to be a sunspot, and that he indeed was recording the transit of Mercury. The transit took 5 hours and had occurred about 4.75 hours before the predicted time. Although observed by others, Gassendi is the only astronomer to publish the results of his observation. Unfortunately, Kepler died the year before his calculation was proven true. Nevertheless, the ability to predict the passage of Mercury in front of the Sun was of great importance in confirming his planetary model, which was heliocentric, like Copernicus', but which described the orbits of planets as ellipses rather than circles.

Although confirmation of the transit of Mercury was consistent with the heliocentric model, an important observation remained to be made. If Venus and Mercury orbited the Sun inside of Earth's orbit, then they should exhibit repeatable phases. Galileo published his observations of the phases of Venus in 1610, but it wasn't until 1639 that advances in the telescope allowed Mercury's phases to be confirmed. This was accomplished by the Italian Jesuit, Johannes Baptista Zupus, using telescopes made by Francesco Fontana. The results of these observations were published by Fontana in 1646 (Figure 2). The application of the new telescope to the study of the heavens led to huge advances in the understanding of our cosmos, as new worlds presented themselves for examination. As improvements were made to the telescope, descriptive astronomy emerged, and the features of Mars and the Moon could be characterized for the first time. Mercury, though, continued to be elusive, and it was not until the beginning of the nineteenth century that serious attempts were made to map its surface.

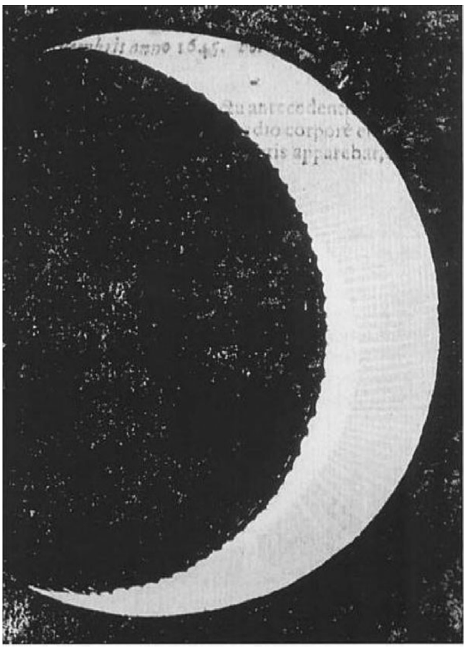

Figure 2. Drawing of Mercury by Francesco Fontana, Novae coelestium, terrestriumque rerum observations, Naples, 1646.

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One of the earliest known efforts to describe the features of Mercury was by Johann Hieronymous Schröter, working in Lilienthal, Germany, in 1800 (Figure 3). He recorded seeing a mountain extending 20 km in height, and deduced a rotational period of just over 24 hours (Denning, 1906). Others, such as Étienne Léopold Trouvelot and William Frederick Denning, made similar observations during the latter half of that century. Denning compared Mercury's surface with that of Mars, and derived a rotation period of 25 hours (Chapman, 1988a). Based on more than 200 observations made in Milan, Italy, between 1881 and 1889, Giovanni Virginio Schiaparelli produced a relatively advanced map of Mercury, which recorded observed features relative to a coordinate system for the first time (Antoniadi, 1934, per Davies, *et al.*, 1978). Based on comparison of the observed surface features throughout his campaign, he deduced that Mercury's rotation was synchronous with its 88-day orbital period and that the same side always faced the Sun (Holden, 1890). Although there was resistance at first to this conclusion, it was generally accepted by the end of the century and not successfully refuted until the 1960s.

As the capability of the telescope increased, higher-fidelity observations were possible, although their interpretations did not always match that quality. Using the 61-cm refracting telescope in Flagstaff, Arizona in 1896-7, Percival Lowell described a Mercury surface covered with long, linear, canal-like features. Needless to say, such features have not been confirmed to exist. A relatively sophisticated map of Mercury was, however, drawn by Eugené Michael Antoniadi in 1934 based on observations taken in Meudon, France (Figure 4). His results were consistent with the proposed 88-day rotation, and he justified it in terms of tidal forces.

A new approach to the study of Mercury was taken in June 1962 when Vladimir Kotelnikov and colleagues were the first to obtain radar echoes from Mercury (Thompson, 1963). Three years later, radar observations by Gordon Pettengill and Rolf Dyce using the 300-meter Arecibo Observatory radio telescope in Puerto Rico showed conclusively

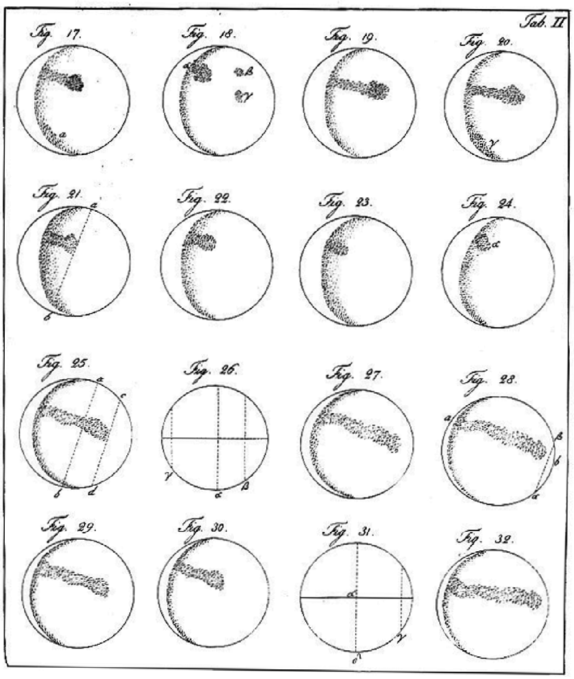

Figure 3. The first known map of Mercury by Johann Hieronymous Schröter (1745-1816).

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that Mercury's rotational period was about 59 days (Pettengill and Dyce, 1965). The widely held theory that Mercury's rotation was Sun-synchronous would require its dark face to be extremely cold, but measurements of radio emission revealed temperatures much higher than expected. Astronomers were reluctant to drop the synchronous rotation theory and searched for evidence of an atmosphere that might transfer heat from the day to nighttime surfaces (Murray and Burgess, 1977).

Italian astronomer Giuseppe Colombo noted that the rotation value was about two-thirds of Mercury's orbital period, and proposed that the planet's orbital and rotational periods were locked into a 3:2 rather than a 1:1 resonance (Colombo, 1965). Despite this correction in the rotational period of Mercury, the early visual observations were not completely invalid. Because the planet rotates three times for every two orbits about the Sun, after three synodic periods, the same face of the planet presents itself at the same phase. Because the conditions for viewing Mercury are favorable every three synodic periods, most early observations were made at those times. As a result, the same face of Mercury was indeed being mapped.

With the advent of the Space Age came the first opportunity to study Mercury at close range. The desire to understand the innermost planet had been demonstrated for centuries, and by the 1960's the technology (and the funding) was finally available to visit the planet for the first time. Although multiple-planet orbits were first considered in the 1920's and 1930's, the first systematic development of the technique did not occur until the 1960's, at the Jet Propulsion Laboratory (JPL) in Pasadena, California. Soon thereafter, JPL trajectory designers discovered Earth-Venus-Mercury trajectory opportunities for launches in 1970 and 1973, and the spacecraft exploration of Mercury became a viable possibility for the first time. It was found that by flying through Venus' gravitational field, a spacecraft's trajectory could be altered causing it to fall in toward the Sun and, with careful timing, enable it to cross Mercury's path and encounter the planet. Without the use of Venus to "slingshot" the spacecraft toward Mercury, a much larger launch vehicle would be needed, and it would only be able to fly by the planet once on a trajectory toward the Sun.

The National Academy of Sciences Space Science Board conducted a planetary exploration study in 1968 in which they endorsed a mission to Mercury, via Venus, recommending a 1973 launch and suggesting scientific experiments that could be carried by the

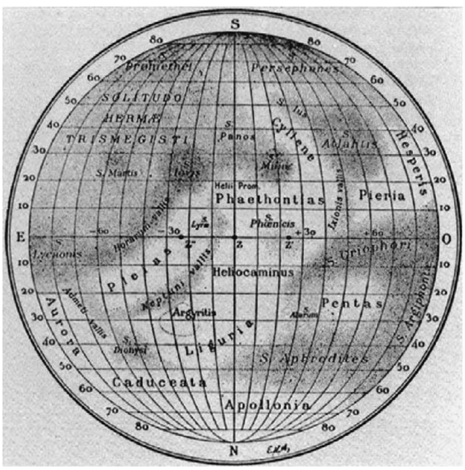

Figure 4. Antoniadi's map of Mercury, 1934.

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spacecraft. NASA approved the mission in 1969, and by January 1970, a Venus/Mercury project office had been established at JPL (Dunne and Burgess, 1978).

At a conference on the new mission held at JPL in 1970, Giuseppe Colombo noted that once the proposed Mariner 10 spacecraft passed Mercury, its orbital period would be approximately twice that of the planet itself. If the point at which it passed Venus were well chosen, the craft would make repeated flybys of Mercury. JPL mission designers performed analyses that confirmed this, and determined that three flybys could be achieved before the mission exhausted its supply of propellant.

The Mariner 10 spacecraft was the seventh successful launch in a series that had previously explored Venus and Mars from 1962 to 1971 (Murray and Burgess, 1977). The spacecraft mass at launch was 533.6 kg, which included 29 kg of hydrazine propellant and a scientific payload of 78 kg. Unlike the previous Mariner spacecraft, Mariner 10 had to be able to survive much closer to the Sun, requiring modifications that included a sunshade, louvers and thermal blankets, and the ability to rotate the solar panels along their long axes in order to keep their temperature relatively stable as they were carried inward through the Solar System. In order to meet its objective to explore Mercury as thoroughly as possible, more science instruments were carried than on previous spacecraft in the program. The payload consisted of seven science experiments, including television photography, extreme ultraviolet spectroscopy, infrared radiometry, energetic particle, plasma, and magnetic-field detectors, and radio science (Figure 5).

On 2 November 1973, the Mariner 10 spacecraft was launched from Cape Kennedy in Florida. Within the first week of flight, data from the Earth and Moon were returned as calibration tests for the Mercury encounters. In January 1974, Mariner 10 was able to take ultraviolet scans of the comet Kahoutek that were not possible from Earth. Despite some issues with the onboard guidance and control system, the encounter with Venus went as planned, on 5 February 1974, with a closest approach of 5790 km (3600 mi). The gravity assist maneuver was successful and Mariner 10 was on its way to Mercury.

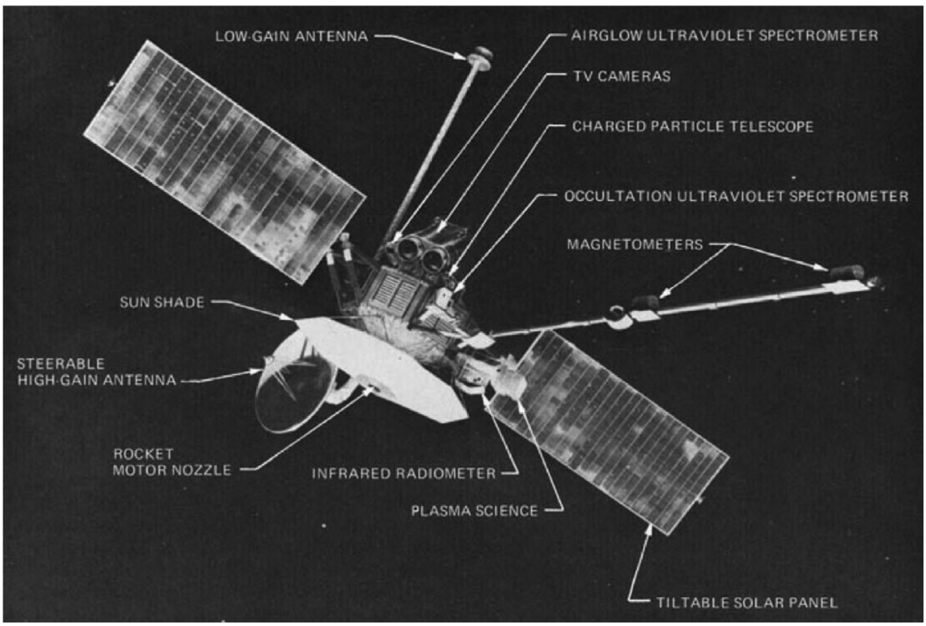

Figure 5. The Mariner 10 spacecraft (NASA/JPL).

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Only a few weeks later, on 24 March 1974, the first blurry images of Mercury were sent back to Earth. As the spacecraft approached the planet, more and more detail appeared in the view of the television cameras revealing the planet to be a heavily cratered world similar to the Moon and parts of Mars. The first flyby was over the night hemisphere of Mercury, with a closest approach of 705 kilometers (438 miles). This meant that the imaging team was only able to acquire images of the Mercury crescent as the spacecraft approached the planet, then as it departed, and was not able to join the two sets of images together. In addition, the images were highly foreshortened because of the viewing geometry. Nevertheless, it was revealed that Mercury contained abundant impact features, including multi-ringed basins, secondary crater chains, and bright rays (Murray *et al.*, 1975). Cliffs or scarps up to 3 km (2 mi) high and 500 km (300 mi) in length were visible across much of the surface, their lobate form suggesting they were the result of compressional forces. These scarps were thought to be due to a readjustment of the surface in response to a slight shrinking of the planet's core.

A huge basin was discovered lying across the terminator such that less than half of its eastern portion was visible. The basin was estimated to be about 1300 km in diameter, larger than the Imbrium basin on the Moon. Because of its situation at one of Mercury's "hot poles" - locations that are closest to the Sun at perihelion - the basin was named Caloris, which is the Greek word for hot. In between many of the heavily cratered areas were smooth, lightly-cratered plains. Based on observations of the Moon, it was not

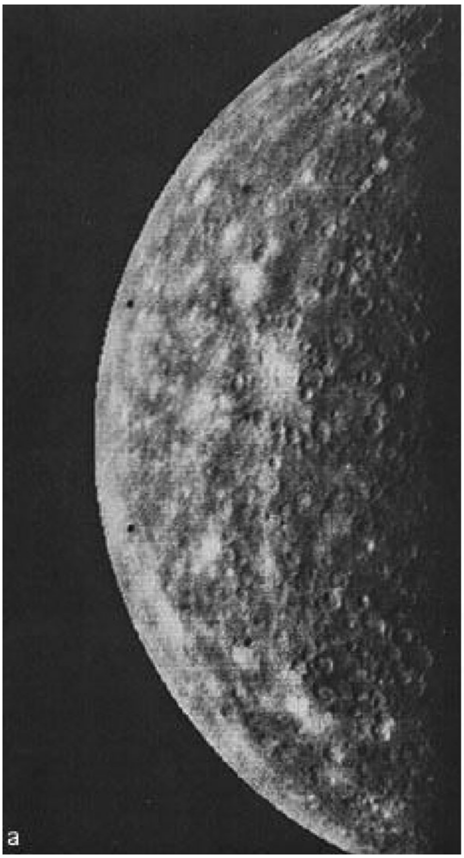

Figure 6. M10 early image of Mercury, acquired by Mariner 10 on March 28 at 952,000 km (590,240 mi).

known whether these plains were volcanic in origin, or whether they were the result of fluidized impact ejecta, a question that was to remain unresolved for over three decades.

Gravity measurements determined the mass of Mercury to two orders of magnitude greater than previously possible, and the surface temperature range was measured by Mariner 10's infrared radiometer to vary from 90 K (-297^{o}F) on the nightside to 460 K (369^{o}F) on the dayside (although the temperature can go even higher - 650 K (1170^{o}F) - at perihelion, higher than any other planet). Perhaps the most surprising measurement was that Mercury possessed a magnetic field, estimated to be about $1/60^{th}$ as strong as Earth's, the source of which was a mystery (see review in Ness *et al.*, 1979).

Six months after this first flyby, on 21 September 1974, Mariner 10 returned to Mercury, flying by on the sunlit side at a distance of 47,000 kilometers (29,200 miles), allowing images to be taken to fill in the missing areas of the surface from the first encounter, and thereby increasing coverage to 75% of the illuminated hemisphere. Because of this favorable viewing geometry, this second encounter was primarily devoted to imaged science, and it did not disappoint. Images were obtained of Mercury's south pole, showing that the compressional scarps extended into this area. A number of images were obtained to determine the angular separation between Mercury and stars, which showed for the first time that the technique of optical navigation was viable for planetary missions, and that reliance on Earth-based radio measurements was no longer essential (Dunne & Burgess, 1978).

Mariner 10's third encounter with Mercury took place six months later, on 16 March 1975. This flyby was primarily focused on obtaining more information about Mercury's magnetic field, and the closest approach point was only 327 kilometers (203 miles) from the surface. Data from this flyby showed unequivocally that Mercury's magnetic field was not created by the solar wind, but is intrinsic to the planet itself, and that the magnetosphere is very like a scaled-down version of Earth's (see review in Ness *et al.*, 1979). Predictions were made as to when the spacecraft would pass through the bow shock, magnetopause, and maximum field, and the actual times of these events were almost exactly as expected. In addition, Mercury, like Earth, was found to have a magnetically neutral tail. Gravity measurements from this and the previous flybys were interpreted to show that Mercury has a surprisingly large core compared to its radius (Chapman, 1988b). The close approach to Mercury allowed some spectacularly high-resolution images to be obtained, enabling features as small as 137 m (450 ft) to be identified, such as small fresh craters and detail of ridges and fractures in the floor of the Caloris basin. Eight days after Mariner 10's third encounter with Mercury, the spacecraft's supply of nitrogen maneuvering gas was exhausted and commands were sent to turn off its transmitter. The Mariner 10 spacecraft had vastly increased scientific knowledge of Mercury.

The next step in Mercury exploration was widely recognized to be an orbiter, to investigate the planet's interior, improve imaging coverage, and determine the chemical composition of the surface (COMPLEX, 1978). However, it was thought that conventional propulsion systems were insufficient to enable the change in spacecraft velocity that would be required for orbit insertion about the planet. This view persisted until the mid-1980's, when multiple gravity-assist trajectories were discovered that would allow Mercury orbit insertion with chemical propulsion systems (Yen, 1985, 1989). However, it was almost 15 more years before such a mission became a reality.

In the meantime, the study of Mercury did not rest. In 1991, radar experiments designed to image the half of Mercury not photographed by Mariner 10 (Slade *et al.*, 1992) revealed highly reflective regions near the planet's poles. The similarity of the radio echoes to those of icy regions of Mars and icy outer-planet satellites strongly suggested that, despite the harsh environment, ice exists in the permanently shadowed craters near Mercury's poles.

The Mariner 10 mission answered many questions about Mercury, yet much remained to be learned. The MESSENGER mission was first proposed to NASA's newly-created Discovery program in 1996, and was eventually selected for flight in July 1999 (McNutt *et al.*, 2006). The spacecraft was built and the mission managed by the Johns Hopkins University Applied Physics Laboratory (APL), in Laurel, MD. The spacecraft takes advantage of lightweight materials, miniaturized electronics, and an ingenious trajectory design to achieve orbit insertion around Mercury under the constraints of a relatively low NASA budget (Santo *et al.*, 2001; Leary *et al.*, 2007). In order to withstand the searing heat at Mercury, the MESSENGER spacecraft employs a combination of thermal blankets, coolers, and a 2-m $\times$ 2.5-m ceramic-fabric sunshade that protects the wiring, electronics, and science instruments.

The MESSENGER payload consists of seven scientific instruments and a radio science experiment (Gold *et al.*, 2007). The instruments include the Mercury Dual Imaging System (MDIS), the Mercury Atmospheric and Surface Composition Spectrometer (MASCS), the Mercury Laser Altimeter (MLA), the Gamma-Ray and Neutron Spectrometer (GRNS), the X-Ray Spectrometer (XRS), the Magnetometer (MAG), and the Energetic Particle and Plasma Spectrometer (EPPS).

The MESSENGER spacecraft was launched from Cape Canaveral Air Force Station, Florida, on 3 August 2004. The long cruise phase includes six planetary flybys - one of Earth, two of Venus, and three of Mercury - as part of a 7.9-billion-km journey that includes more than 15 orbits around the Sun (McAdams *et al.*, 2007). The Earth and Venus flybys afforded opportunities for flight tests of the instruments in preparation for the spacecraft's first encounter with Mercury. At the time of writing, MESSENGER has recently completed its third and final Mercury flyby, and is en route for orbit insertion on 18 March 2011.

Although the primary purpose of MESSENGER's three Mercury flybys was to achieve the gravity assists needed to place the spacecraft in orbit about Mercury, they proved

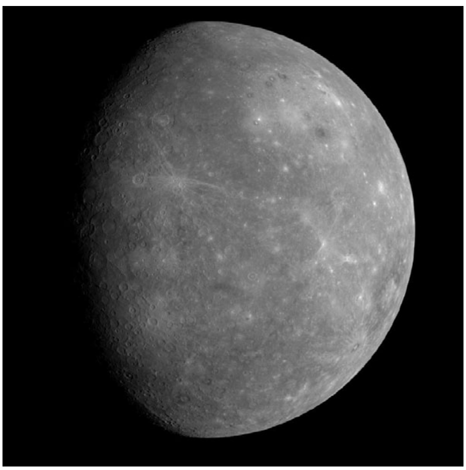

Figure 7. This MESSENGER image of Mercury's previously unseen hemisphere was acquired about 80 minutes after the spacecraft's closest approach to Mercury on the first flyby, from a distance of about 27,000 kilometers (about 17,000 miles). The giant Caloris basin is the large bullseye feature in the top right of the image, with the bright center surrounded by a dark annulus (NASA/JHUAPL).

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to be tremendously valuable in terms of scientific return. During the first flyby, on 14 January 2008, acquisition of science data began weeks before the closest approach and continued throughout the encounter and for weeks afterward. During the approach to Mercury, high-resolution measurements were made of the planet's exosphere tail, extending hundreds of thousands of kilometers anti-sunward (McClintock *et al.*, 2008). Mariner 10 had only been able to view one hemisphere of Mercury, but much of the opposite hemisphere was sunlit during the first encounter, enabling MESSENGER to image almost half of the planet that had never before been viewed by a spacecraft (Figure 7). The first ever measurements of ions at Mercury revealed a complex environment resulting from a mixture of solar wind plasma and species originating from the surface. Although Mercury's magnetosphere was found to be surprisingly calm, it was still found to possess an array of dynamic plasma physical processes, similar to Earth's (Slavin *et al.*, 2008). Magnetometer measurements were made throughout the flyby, and provided the best assessment yet of the field at the equator, suggesting that it is predominantly dipolar, as would be expected if it was produced by a dynamo in a molten outer core (Anderson *et al.*, 2008).

The closest approach on the first flyby was at a mere 201 km (125 mi). The close flyby allowed the first ever laser altimeter profile of Mercury's surface to be obtained. The profile indicated that Mercury's craters are shallower than similar-sized craters on the Moon, probably because of the higher surface gravity (Zuber *et al.*, 2008). The close approach also allowed high-resolution (200-m/pixel) images to be captured, and much of the surface was imaged in 11 colors, providing the most comprehensive color data of Mercury. The western portion of the Caloris basin was imaged for the first time, and it was found to be 250 km larger than previously thought, measuring 1550 km in diameter (Murchie *et al.*, 2008). Lobate scarps were found to be widespread across the surface, indicating that compression had been global, rather than confined to one hemisphere. High spectral-resolution data at infrared and near-infrared wavelengths were obtained, providing new clues as to the composition of surface minerals (Robinson *et al.*, 2008). One question that had been unresolved for over 30 years was whether Mercury's smooth plains were the result of volcanic processes or whether they were formed by impact ejecta. MESSENGER images showed a number of different surface features that were interpreted to be volcanic in nature, such as flooded and embayed impact craters and volcanic vents, thereby firmly establishing volcanism as a significant process in Mercury's evolution (Head *et al.*, 2008).

MESSENGER's first encounter with Mercury was a resounding success, but the spacecraft would soon be back for more. Nine months later, on 6 October 2008, the spacecraft flew by Mercury a second time, dipping to only 199 km (124 miles) above the surface. The closest approach point was on the opposite hemisphere than was seen during the first encounter, allowing more of the surface to be imaged for the first time. During the approach, the first simultaneous measurements of sodium and calcium tails in Mercury's exosphere were made, showing that their spatial distributions are complementary to each other, and that they vary according to solar wind conditions (McClintock *et al.*, 2009). Measurements of the magnetic field throughout the flyby showed that the types of interactions between the magnetic field and the solar wind at Mercury that produce auroras and magnetic storms are similar to those found on Earth (Slavin *et al.*, 2009). The MESSENGER spacecraft returned the only magnetic data to date from the planet's western hemisphere, key to understanding the geometry of Mercury's internal field. These data, combined with earlier results, showed that the planet's magnetic moment is closely aligned with its rotation axis to within 2^o (Anderson *et al.*, 2008).

In total, MESSENGER had by this time imaged about 80% of the surface of the planet. A large new basin, Rembrandt, was discovered on the opposite hemisphere from that viewed by Mariner 10 (Watters *et al.*, 2009). At 715 km in diameter, this basin is half the size of the Caloris basin, yet has a floor which bears witness to a complex geological history of volcanic flows and tectonic deformation. Soon after closest approach, when MESSENGER was still relatively close to the surface, images were acquired in 11 colors, the highest resolution color data yet obtained, allowing clear compositional variations to be distinguished. It appears that Mercury has a complex and heterogeneous crust created over time from numerous volcanic flows (Figure 8), impact crater events, and tectonic deformation (Denevi *et al.*, 2009). Further geological information was acquired by the laser altimeter, which took profiles over lobate scarps and impact craters.

MESSENGER's third and final flyby of Mercury took place almost a year later, on 29 September 2009. On this occasion, the closest approach point and lighting were similar to that of flyby 2, but offset by $\sim$20 degrees of longitude. Speeding past the surface at an altitude of 229 km (142 miles), this flyby provided the final boost needed to keep the spacecraft on track for Mercury orbit insertion 18 months later. Although the gravity assist was executed flawlessly, the science observation sequence was interrupted minutes before closest approach by the fault protection system, which halted it as a protective measure, which later proved unnecessary. Despite this, some substantial new scientific data were acquired during Mercury approach, including observations of a newly-discovered basin which appears to contain the youngest identified volcanic deposit on Mercury (Prockter *et al.*, 2010) as well as observations of the loading and unloading of Mercury's magnetotail (Slavin *et al.*, 2010) and detection of ionized calcium from Mercury (Vervack *et al.*, 2010). Between Mariner 10 and MESSENGER, 98% of the surface of Mercury has been imaged by a spacecraft.

The MESSENGER team is now preparing for Mercury orbit insertion on 18 March 2011. At the time of writing, the spacecraft is healthy, the instruments are performing well, and the trajectory is on course. The spacecraft will remain in orbit about Mercury for at least one Earth year, orbiting Mercury twice each day. These orbits are highly elliptical in order to protect the spacecraft from the extreme thermal environment at Mercury. At periherm the spacecraft will pass the planet at distances ranging from 200 to 500 km at 60-70^o north latitude, and at apoherm up to 15,200 km, south of the planet. Because

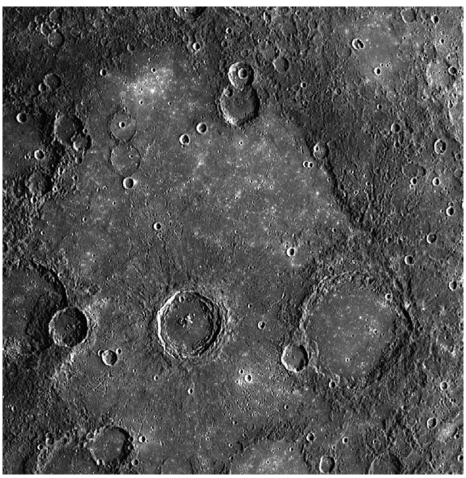

Figure 8. Close-up view of the crater Rudaki, showing examples of craters in the plains that appear to have been significantly flooded with volcanic lava, leaving only their circular rims preserved.

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of the orbital motion and spin of Mercury, the spacecraft will, at different times, reside in a "dawn-dusk" orbit, where it essentially flies over the terminator, which is ideal for monochrome imaging, or a "noon-midnight" orbit, which, when on the dayside, is ideal for multispectral imaging. The MESSENGER orbital observation campaign will seek to characterize the planet's interior, surface, exosphere, and magnetosphere, answering questions about the nature of the planet and its history.

The next step in the study of Mercury is already under development. The BepiColombo mission, named after the same man who explained Mercury's 3:2 spin orbit resonance and suggested that Mariner 10 could achieve multiple flybys, is an international collaboration between the European Space Agency and the Japan Aerospace Exploration Agency (Grard *et al.*, 2000; Anselmi and Scoon, 2001). The mission comprises a pair of spacecraft that will be placed in orbit about Mercury, one to study the magnetosphere and its interactions with the solar wind, and one to characterize the planet with a variety of different instruments (Hayakawa *et al.*, 2004; Schulz and Benkhoff, 2006). The two spacecraft are scheduled to launch in 2014 on a single rocket and will be placed in coplanar polar orbits in 2020.

The story of man's quest to understand Mercury is one of perseverance and ingenuity. Just as the telescope in the seventeenth century transformed the planet from a featureless light in the sky to a cratered world cloaked in mystery, robotic space probes three hundred years later have uncovered its true nature as a planet of intriguing extremes. The six flybys of Mercury have revealed a great deal, but much more remains to be learned. MESSENGER's yearlong observation campaign will return a wealth of information not previously available, but will undoubtedly leave questions to be answered by BepiColombo and perhaps future missions.

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