THE QUEST TO EXPLORE MERCURY

BY PETER D. BEDINI AND LOUISE M. PROCKTER

In September 2009, during **MESSENGER***'s third Mercury flyby, its Wide-Angle Camera (WAC) imaged the planet through all 11 of its narrow-band color filters, giving us these true- and enhanced-color views. The image at far left, created with three of the WAC filters, shows an approximation of how Mercury's color might appear to human eyes. The view at near left, produced with data gathered by all 11 filters, accentuates the subtle color differences on the planet's surface.* Images: NASA/JHUAPL/CIW

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. Over the centuries, humanity has pursued a quest to understand the elusive planet and has teased out information about its motions in the sky, its relationship to the other planets, and its physical characteristics.

Despite being visible to the unaided eye, Mercury is extremely difficult to observe from Earth because of its proximity to the Sun. 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. Three decades later, *MESSENGER* has visited the planet three times as well and is poised to add significantly to the study of the planet with a year-long orbital observation campaign.

Acknowledging and Naming the Sun's Nearest Neighbor

As one of the "wandering stars," Mercury has been observed since antiquity; 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. Hindu mythology refers to the planet as 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 and can be seen only during the days surrounding its greatest elongations, when it is visible just before sunrise or after sunset. These characteristics of swiftness and elusiveness 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.

This cuneiform tablet, made in Mesopotamia in the seventh century B.C.E., contains some of the first known written references to Mercury. Most likely written by Assyrian astronomers, the clay tablet, part of a series of Babylonian texts known as the MUL.APIN, describes observations taken between 1300 and 1000 B.C.E. Photo: British Museum, BM86378

The first known references to Mercury in writing are found from Mesopotamia in the seventh century B.C.E. The cuneiform tablets known as the MUL.APIN, most likely written by Assyrian astronomers, describe observations taken between 1300 and 1000 B.C.E. At the time that these tablets were created, the Maya also were charting the motion of the planet, and records of detailed observations can be found in the Dresden Codex.

Observations of Mercury figured prominently in early efforts to develop a geometric model of the heavens. The Greek astronomer Eudoxus made one of the first attempts to create such a model around 370 B.C.E. He compiled an extensive star catalog that included the visible planets, and his corresponding celestial model was extremely complex, including more than two dozen spheres to describe the observed motions of the heavenly bodies. In the second century C.E., Ptolemy published his great scientific treatise *Almagest*, in which he described a simpler geocentric model of the planets that was accepted as correct for centuries afterward.

THE AGE OF THE TELESCOPE

Throughout the Middle Ages, astronomers continued to observe and record the movement of Mercury and the other planets using instruments of growing complexity. The invention of the telescope in 1608 revolutionized astronomy, bringing humanity closer to the heavens than ever before, but the early lenses were too crude to reveal any of Mercury's secrets.

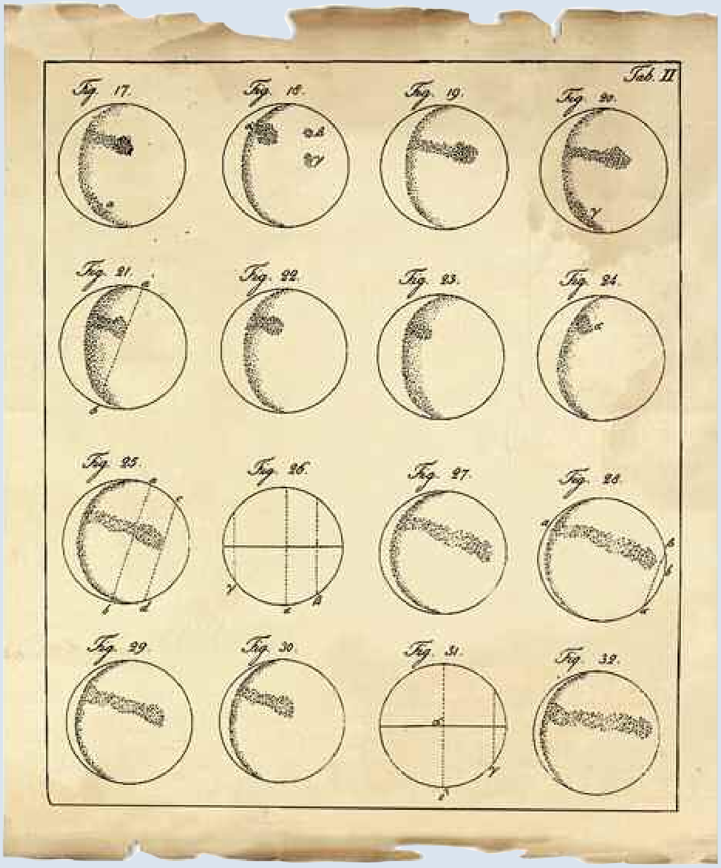
In 1627, Johannes Kepler predicted that a transit of Mercury across the face of the Sun would occur on November 7, 1631. Although the transit occurred slightly earlier than expected, French astronomer Pierre Gassendi observed it. Two decades earlier, Kepler had mistaken a sunspot for Mercury. When a spot first appeared on the Sun's image, Gassendi believed it to be too small to be Mercury, and he concluded that it was instead a sunspot. 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. 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 Kepler's planetary model, which was heliocentric, like that of Copernicus, but described the orbits of planets as ellipses rather than circles.

As improvements were made to telescopes, 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 not until the beginning of the 19th century did astronomers make serious attempts to map its surface.

Johann Hieronymus Schröter, working in Lilienthal, Germany, was one of the first to try to describe the features of Mercury. In 1800, he recorded seeing a mountain extending 20 kilometers (12 miles) in height and deduced a rotational period for the planet of slightly more than 24 hours.

From more than 200 observations made in Milan, Italy, between 1881 and 1889, Giovanni Virginio Schiaparelli produced a rather advanced map of Mercury that, for the first time, recorded observed features relative to a coordinate system. From comparisons 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 of the planet always faced the Sun. Although scientists at first resisted this conclusion, it was generally accepted by the end of the century and not successfully refuted until the 1960s.

Improved capabilities of telescopes made higher-



As telescopes improved, observers were better able to draw and map celestial bodies. Because Mercury was so elusive, it wasn't until about 1800 that Johann Hieronymus Schröter was able to produce this first known map of the innermost planet. Map: Schröter, 1800

fidelity observations possible, though the interpretations did not always match that quality. For example, using the 61-centimeter (24-inch) refracting telescope in Flagstaff, Arizona, in 1896–1897, Percival Lowell described Mercury's surface as covered with long, linear, canal-like features. Needless to say, such features have not been confirmed.

For the widely held theory that Mercury's rotation was Sun-synchronous to be true, the planet's dark face would need to be extremely cold. Measurements of radio emissions 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.

A new approach to the study of Mercury was taken in June 1962, when Vladimir Kotelnikov and colleagues obtained the first radar echoes from the planet. Three years later, radar observations by Gordon Pettengill and Rolf Dyce, using the 300-meter Arecibo Observatory radio telescope in Puerto Rico, showed conclusively that Mercury's rotational period was about 59 days, thereby putting to rest, once and for all, the notion of synchronous rotation.

Italian scientist Giuseppe "Bepi" Colombo noted that the rotation value was about two thirds of Mercury's orbital period, and he proposed that the planet's orbital and

This is one of the first images of Mercury captured by a spacecraft.* Mariner 10 *took this picture on March 28, 1974 as it approached the planet for what would be its first flyby on the following day. *Image: NASA/JPL*

rotational periods were locked into a 3:2 rather than a 1:1 resonance. Despite this correction in the planet's rotational period, 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.

Mercury: Up Close and Personal

With the advent of the Space Age came the first opportunity to study Mercury at close range. People had long demonstrated a desire to understand the innermost planet, and by the 1960s, the technology (and the funding) finally became available to visit the planet for the first time.

Flying through Venus' gravitational field could alter a spacecraft's trajectory, causing it to fall in toward the Sun and, with careful timing, enabling it to cross Mercury's path and encounter the planet. The discovery that such a trajectory was possible represented a breakthrough because, without the use of Venus to "slingshot" the spacecraft toward Mercury, a much larger launch vehicle would be needed, and it would be possible to fly by the planet only once on a trajectory toward the Sun.

In 1969, NASA approved a mission to be launched in 1973 that would make single flybys of both Venus and Mercury. At a conference on this new mission held at the Jet Propulsion Laboratory 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. With careful choice of the point at which it passed Venus, the craft would make repeated flybys of Mercury. It was determined that three flybys could be achieved before the spacecraft exhausted its supply of propellant.

The *Mariner 10* spacecraft—with a payload of seven science experiments designed for television photography, extreme ultraviolet spectroscopy, infrared radiometry, radio science, and energetic particle, plasma, and magnetic-field detection—was launched from Cape Canaveral Air Force Station, Florida, on November 2, 1973 (UTC). After a successful encounter with Venus three months later, the spacecraft made its first flyby of Mercury on March 29, 1974, following up with two more flybys, on September 21, 1974 and March 16, 1975.

Mariner 10 was able to make close-up, unencumbered observations of Mercury for the first time and revealed a wealth of details about the elusive planet. In three passes during 1974 and 1975, the closest at an altitude of just more than 320 kilometers (200 miles), the spacecraft took images of Mercury's abundant impact features, including multiringed basins, secondary crater chains, and bright rays. Cliffs or scarps up to 1.5 kilometers (1 mile) high and 500 kilometers (300 miles) in length were visible across much of the surface, their lobate form suggesting that they were the result of compressional forces. These scarps were thought to have resulted from a readjustment of the surface in response to a slight shrinking of the planet's interior.

A huge basin situated near one of Mercury's "hot" poles—equatorial locations that are closest to the Sun

Radar observations of the half of Mercury not seen by* Mariner 10 *revealed highly reflective regions near the planet's poles—suggesting that despite the planet's proximity to the Sun, ice might still exist in the permanently shadowed craters there. This radar image was taken from the Arecibo Observatory in July 1999. *Image: Arecibo Observatory* at perihelion and estimated to be about 1,300 kilometers (800 miles) in diameter—was named Caloris, from the Greek word for heat. High-resolution images identified features as small as 137 meters, including ridges and fractures in the floor of this basin.

Between many of the heavily cratered areas were smooth, less-cratered plains. Observations of similar plains on the Moon had not made it clear whether these plains were volcanic in origin or if they were the result of fluidized impact ejecta, a question that remained unresolved for more than three decades.

Gravity measurements determined the mass of Mercury to an accuracy of two orders of magnitude greater than previously possible and confirmed that Mercury has a core that is surprisingly large compared with its radius. *Mariner 10*'s infrared radiometer found the surface temperature range to be extremely large: these and subsequent ground-based observations have shown that, at perihelion, the dayside equatorial temperature can reach about 720 Kelvin (roughly 450 degrees Celsius or 840 degrees Fahrenheit) or can dip as low as about 90 Kelvin (–180 degrees Celsius or –300 degrees Fahrenheit).

Perhaps the most surprising discovery was that Mercury possesses an internal magnetic field, estimated to be about two orders of magnitude smaller at the planetary surface than that of the Earth but still strong enough to deflect the solar wind around the planet, creating a magnetosphere. The field is dipolar and intrinsic to the planet, like a scaled-down version of Earth's.

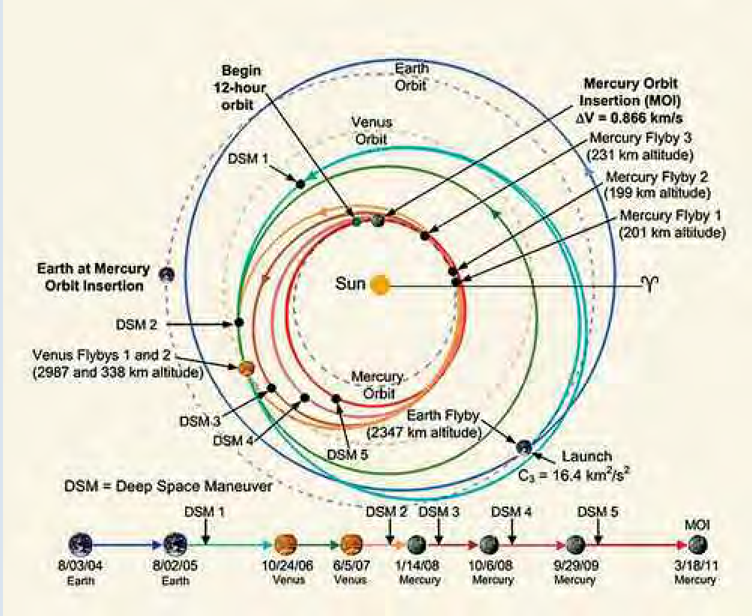
Eight days after *Mariner 10*'s third encounter with Mercury, the mission ended when the spacecraft's supply of nitrogen maneuvering gas was exhausted. The next step in Mercury exploration was widely recognized to be an orbiter, which could characterize more fully the planet's interior, surface, exosphere, and magnetosphere. In the mid-1980s, researchers discovered multiple gravity-assist trajectories that would allow Mercury orbit insertion with conventional chemical propulsion systems. It was almost 20 more years, however, before such a mission became a reality.

In the meantime, the study of Mercury continued. In 1991, radar experiments designed to image the half of Mercury not photographed by *Mariner 10* 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 high temperatures at lower latitudes, ice might exist in the permanently shadowed craters near the poles.

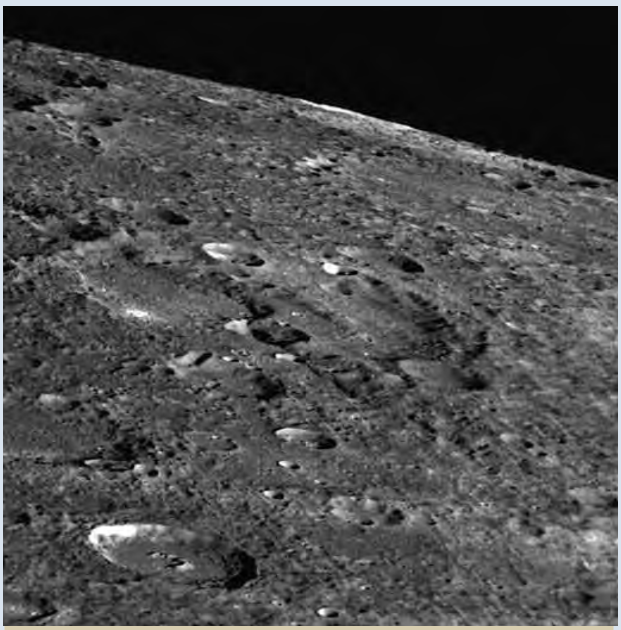
MESSENGER Encounters the Winged Messenger

Although the *Mariner 10* mission answered many questions about Mercury, much remained to be learned. The first proposal for the *MESSENGER* mission came to NASA's newly created Discovery program in 1996, and the proposal eventually was selected for flight in July 1999, with Sean C. Solomon of the Carnegie Institution of Washington (CIW) as principal investigator. The Johns Hopkins University Applied Physics Laboratory (JHUAPL) in Laurel, Maryland, built the spacecraft and is managing and operating the mission.

Designing a Mercury orbiter mission within the constraints of a relatively small NASA budget required innovation. To achieve orbit around Mercury using as little propellant as possible, mission planners incorporated six planetary flybys (one of Earth, two of Venus, and three of Mercury) and five deep-space maneuvers as part of the spacecraft's 6.6-year journey of 7.9 billion kilometers (4.9 billion miles).



Gravity assists from six planetary flybys (one of Earth, two of Venus, and three of Mercury) have helped to speed* MESSENGER *along on its mission. *Graphic: NASA/JHUAPL/CIW*



Our spacecraft explorers have revealed mysterious Mercury to be a world of extremes. The scarp that cuts across this image from upper left to lower right is a long cliff face that may have formed when the planet's interior cooled and its surface contracted.
Image: NASA/JHUAPL/CIW

MESSENGER ***has imaged 80 percent of Mercury's surface in color. The enhanced-color images highlight subtle differences in the composition of crustal rocks on the planet's surface. The large, bull's-eye feature at top left of the upper image is Caloris basin, its bright center surrounded by a dark annulus.***

Images: NASA/JHUAPL/CIW

The custom-made propulsion system was integrated into the graphite-composite structure to save mass. To simplify the thermal design, miniaturized electronics and instruments are harbored behind a ceramic-cloth sunshade measuring 2.0 x 2.5 meters. To avoid the mass, operational complexity, and test requirements of a traditional gimbaled antenna, an electronically steerable phased-array antenna system was developed.

The data that are needed to answer the guiding science questions will be collected by a payload of seven scientific instruments: 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). Radio-science measurements will be made using the spacecraft's telecommunications system.

On August 3, 2004, *MESSENGER* was launched from Cape Canaveral Air Force Station, Florida, and it has now completed all six planetary encounters and five deep-space maneuvers. Although the primary purpose of *MESSENGER*'s flybys was to achieve the gravity assists needed to place the spacecraft in the desired orbit about Mercury, they also proved to be tremendously valuable in terms of science return.

During the Mercury encounters, *MESSENGER* made high-resolution measurements of the planet's exosphere and tail, which extends millions of kilometers anti-Sunward. Near-simultaneous measurements of sodium, magnesium, and calcium showed that the spatial distributions of these elements are complementary to each other and that they vary spatially and temporally.

The first 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 exhibited an array of dynamic plasma physical processes similar to Earth's. Magnetometer measurements made during the flybys provide the best assessment yet of the internal field; together with *Mariner 10* measurements, they suggest that the field is predominantly dipolar, as would be expected if it were produced by a dynamo in a molten outer core.

The *MESSENGER* spacecraft returned the only magnetic data to date from the planet's western hemisphere. These data, combined with earlier results, showed that the planet's magnetic moment is closely aligned with its rotation axis, to within 2 degrees.

During all three Mercury flybys, the spacecraft passed very close to the planet, with closest-approach altitudes of approximately 200 kilometers (125 miles). These low-altitude passes enabled the collection of the first laser altimeter profiles of Mercury's surface, which indicated that Mercury's craters are shallower than similar-sized craters on the Moon, probably because of the higher surface gravity.

Whereas the geometry of its flybys allowed *Mariner 10* to view only one hemisphere of Mercury, *MESSENGER* has now imaged 80 percent of the entire planetary surface, and almost 98 percent of the planet has now been imaged by one or both of the spacecraft. During *MESSENGER*'s close approaches, it captured high-resolution (200 meters per pixel) images, and much of the surface was imaged in 11 colors, providing the most comprehensive color data of Mercury to date.

The western portion of the Caloris basin was imaged for the first time, and that basin was found to be 250 kilometers (155 miles) larger than previously thought, measuring 1,550 kilometers (960 miles) in diameter. Lobate scarps were found to be widespread across the surface, indicating that compression had been global. High spectral resolution data at near-ultraviolet, visible, and near-infrared wavelengths were obtained, providing new clues as to the composition of surface minerals.

Analysis of *MESSENGER* flyby data addressed the issue of whether Mercury's smooth plains were the re-

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sult of volcanic processes or were formed by impact ejecta. A number of surface features appear to have volcanic origin, such as flooded and embayed impact craters and irregular vents, thereby firmly establishing volcanism as a major process in Mercury's evolution.

The Next Chapter

The *MESSENGER* team is now preparing for orbital operations. At the time of writing, the spacecraft is healthy, the instruments have been well tested, and trajectory analysis shows the craft to be on track to the required aim-point for orbit insertion on March 18, 2011.

The spacecraft will remain in orbit about Mercury for at least one Earth year, circling the planet twice each day. These orbits are highly elliptical in order to protect the spacecraft from the extreme thermal environment close to Mercury's surface. At periapsis, the spacecraft will pass the planet at distances ranging from 200 to 500 kilometers (125–310 miles) at 60–70 degrees north latitude, and at apoapsis up to 15,200 kilometers (9,440 miles) south of the planet.

Because of the orbital motion and spin of Mercury, at times, the spacecraft will reside in a "dawn-dusk" orbit, where it essentially flies over the terminator, which is ideal for monochrome imaging. At other times, it will occupy a "noon-midnight" orbit, which 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 for Giuseppi Colombo—the 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 (ESA) and the Japan Aerospace Exploration Agency (JAXA). The mission comprises a pair of spacecraft that will be placed in coplanar orbits about Mercury: one to study the magnetosphere and its interactions with the solar wind and one to characterize the planet with a variety of instruments. The two spacecraft are scheduled to launch in 2014 on a single rocket and to be inserted into orbit in 2020.

The story of humanity's quest to understand Mercury is one of perseverance and ingenuity. Just as the telescope in the 17th century transformed the planet from a featureless light in the sky to a cratered world cloaked in mystery, robotic space probes 300 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 year-long observation campaign will return a wealth of information not previously available but will undoubtedly leave questions to be answered by *BepiColombo* and future missions.

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Acknowledgment: The authors thank Bob Strom, a member of both the *Mariner 10* and *MESSENGER* science teams, for inspiring us to delve deeper into the history of Mercury exploration.

Two bright dots huddle close together among a field of distant stars. These are Earth and the Moon, seen by* MESSENGER *on May 6, 2010 from its unique position much closer to the Sun, near the orbit of Mercury. In the final stages of its long cruise,* MESSENGER *is busily searching space outward from the Sun for vulcanoids, the elusive asteroids that scientists believe reside in the space between Mercury and the Sun. No such bodies have yet been discovered, but the search did yield this evocative photo of our home.* MESSENGER *is scheduled to enter orbit about Mercury in March 2011. *Image: NASA/JHUAPL/CIW*