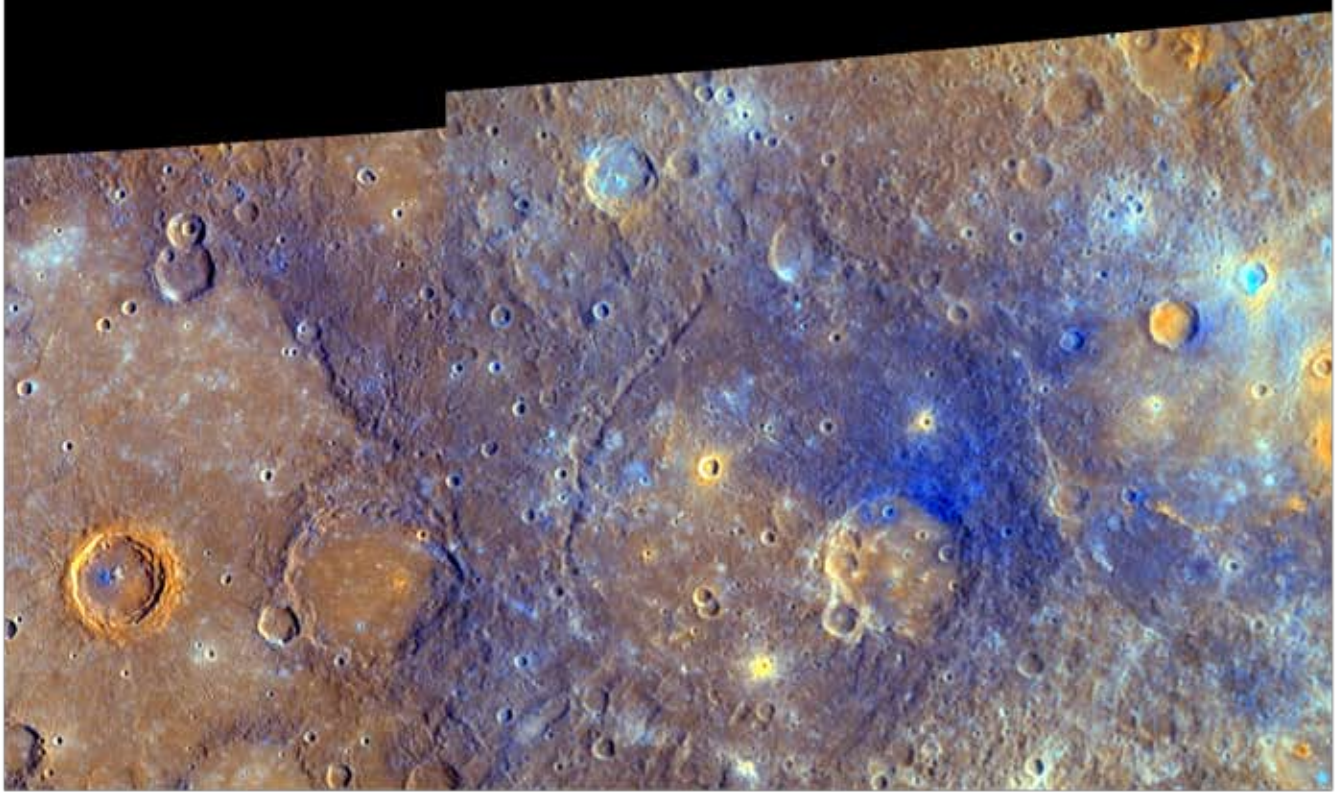
A NASA Discovery Mission

MESSENGER

MErcury Surface, Space ENvironment, GEochemistry, and Ranging

Mercury Flyby 3

September 29, 2009



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On the Cover:

This mosaic was created with images from MESSENGER's second flyby of Mercury that are the highest-resolution color images ever obtained of the innermost planet. MESSENGER took this sequence of images during the departure portion of the flyby. Each successively larger segment shows how the camera was imaging a progressively larger area on the planet's surface. The images were taken by MESSENGER's Mercury Dual Imaging System (MDIS) Wide Angle Camera (WAC). The WAC observes Mercury through 11 different color filters. The colors in this mosaic are not the "true" colors of Mercury's surface - the differences among the 11 colors have been greatly exaggerated for comparison in this enhanced-color view. The exaggerated-color variations in this mosaic indicate differences in the composition of materials at the surface. These color characteristics allow the Science Team to study the different kinds of rocks within Mercury's crust and how they are interlayered at depth.

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The information in this press kit was current as of September 11, 2009.
For mission updates, visit http://messenger.jhuapl.edu/.

Science during Mercury Flyby 3

On September 29, 2009, the MESSENGER spacecraft will pass 228 kilometers (141.7 miles) above Mercury's surface, for the mission's third flyby of its target planet. The flyby's primary purpose is to use Mercury for a gravity assist, a crucial encounter needed to enable MESSENGER, in 2011, to enter into an orbit around Mercury. MESSENGER's third flyby of Mercury also provides an opportunity to continue to make significant and exciting science observations and measurements.

During the third Mercury encounter, MESSENGER's camera system will again image much of the planet seen on the second Mercury flyby, but it will also view another small portion of Mercury's surface never previously seen by spacecraft. Some of the most interesting areas on Mercury's surface will be targets of simultaneous spectral measurements and high-resolution color images.

Imaging

The Mercury Dual Imaging System (MDIS) will acquire high-resolution, color images (using all eleven filters of the Wid-Angle Camera) of scientifically interesting targets identified from the second flyby, images that will be acquired simultaneously with spectral observations. The Narrow-Angle Camera (NAC) mosaic made on approach will cover yet more new, previously unseen terrain, while a NAC high-resolution mosaic of the southern hemisphere will be constructed from images taken during departure to complement the high-resolution, northern-hemisphere mosaic obtained during the MESSENGER's second Mercury flyby. In addition, sub-framing and commanding tests will check out new software features to be used during the mission orbital phase. Deep departure imaging (from 8 days before to 21 days past closest approach) will permit the construction of detailed phase curves of Mercury at multiple wavelengths, and searches will be conducted for possible satellites of Mercury as small as ~100 m in diameter. In total, 1559 images are planned for the core portion of the flyby encounter.

Topography

MESSENGER's third Mercury flyby will provide more data on the correlation between high-resolution topography and high-resolution images of Mercury. The Mercury Laser Altimeter (MLA) will range to Mercury's surface and make a topographic profile along the instrument ground track. A shift in the longitude of closest approach by 17° to the west and 3° north from the position of closest approach for the second flyby will allow the data from the third flyby to augment and complement those from the second flyby. In addition, the slower flyby speed (~1.5 km/s slower relative to the center of Mercury) will keep the trajectory closer to the planet longer.

Magnetic Field

Because the third flyby will yield a trajectory with a closest approach position near that for the second flyby, magnetic field measurements from this encounter, combined with the earlier observations, will yield improved models for Mercury's internal magnetic field. The similarity in trajectories will also allow for better limits on small-scale, longitudinal structure in the field, including possible crustal magnetic anomalies. Differing solar activity and Interplanetary Magnetic Field (IMF) orientation from the first two flybys will provide yet another snapshot of how Mercury's dynamic magnetosphere responds to external conditions.

Space Environment

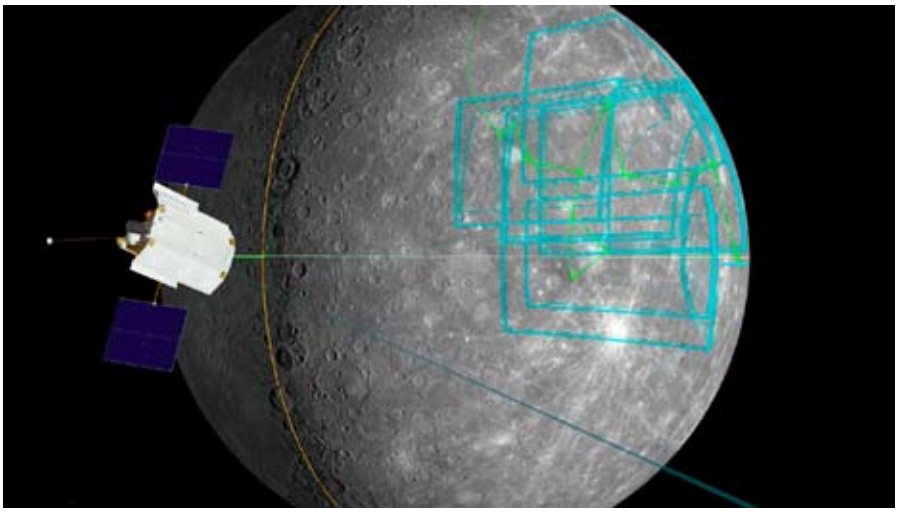
The Fast Imaging Plasma Spectrometer (FIPS) and the Energetic Particle Spectrometer (EPS) will, once again, be poised to measure the charged particles located in and around Mercury's dynamic magnetosphere, providing new data about the planet's complex interactions among the solar wind, planetary magnetic field, rocky surface, and thin exosphere. Differences in the encounter trajectory from that of the second flyby should provide a somewhat longer magnetospheric pass and better coverage of Mercury's magnetotail and its dynamics.

Exosphere

The Mercury Atmospheric and Surface Composition Spectrometer (MASCS) will again make high-spectral- and high-spatial-resolution measurements of Mercury's thin exosphere. Targeted scans of the exospheric "tail" using the MASCS Ultraviolet and Visible Spectrometer (UVVS) will permit a search for temporal variability in both the Na and Ca components. In addition, the north- and south-polar regions will be targeted for detailed observations of those species. Other potential exospheric species will also be sought.

Surface Composition

Determining the composition of Mercury's surface is a major goal of the orbital mission, and the instruments focused on compositional measurements will get their third opportunity to observe Mercury during the flyby. The MASCS sensors, both UVVS and the Visible and Infrared Spectrograph (VIRS), will spend ~30 seconds on each of eleven targeted observations, two on locations also targeted for photometry, focusing on end-member mineralogical features identified during the second flyby. The X-Ray Spectrometer (XRS) will once again look for X-ray fluorescence from surface elements, depending on the level of solar activity, and the Gamma-Ray Spectrometer (GRS) will acquire more counting data from approximately the same region that it surveyed during the second flyby. The Neutron Spectrometer (NS) will use two spacecraft maneuvers to provide better Doppler filtering of encountered neutron fluxes, including a 180° spacecraft roll on the nightside (inbound) and a 45° roll on the dayside (outbound). The nightside maneuver will provide more information on the composition on the side of the planet away from that sampled during the first flyby, and the combination of dayside and nightside measurements will enable a test of the influence of planetary surface temperature on the thermal neutron fluxes, data important for properly interpreting the neutron fluxes measured during the orbital phase of the mission.



Visit the MESSENGER website (http://messenger.jhuapl.edu) to watch this animation showing the science observations planned during MESSENGER's third flyby of Mercury on September 29, 2009.

Third Mercury Encounter Timeline of Critical Events

Ground Receipt Time		Spacecraft Time		Event
Eastern Daylight Time (EDT)		Universal Coordinated Time (UTC) {DOY-hh:mm}	Time Relative to Closet Approach {hh:mm}	
Saturday September 26	9:16 p.m.	270-01:10	68:45	Start automated command load sequence for third Mercury encounter
Monday September 28	10:30 a.m.	271-14:24	31:31	Turn to start encounter core imaging sequence, beacon-only tracking of satellite begins
Tuesday September 29	5:48 p.m.	272-21:41	00:14	MESSENGER passes into shadow of Mercury (eclipse entry)
	6:02 p.m.	**272-21:55**	**00:00**	**Mercury closet approach point (228 km above surface)**
	6:06 p.m.	272-21:59	00:04	MESSENGER passes out of shadow of Mercury (eclipse exit)
	6:09 p.m.	272-22:03	00:08	MESSENGER loses contact with Earth (occultation enter)
	7:00 p.m.	272-22:54	00:59	MESSENGER regains contact with Earth (occultation exit)
	9:34 p.m.	273-01:27	03:32	Turn back to Earth following encounter, regain telemetry from spacecraft
	11:39 p.m.	273-03:32	05:37	Start on-board stored-data playback from spacecraft
Friday October 2	12:36 a.m.	276-04:29	78:34	Complete automated command load sequence for third Mercury encounter

Media Services Information

News and Status Reports

NASA and the MESSENGER team will issue periodic news releases and status reports on mission activities and make them available online at http://messenger.jhuapl.edu and http://www.nasa.gov/mission_pages/messenger/main/index.html.

When events and science results merit, the team will hold media briefings at NASA Headquarters in Washington, D.C., or the Johns Hopkins University Applied Physics Laboratory in Laurel, Md. Briefings will be carried on NASA TV and the NASA website.

NASA Television

NASA Television is carried on the Web and on an MPEG-2 digital signal accessed via satellite AMC-6, at 72 degrees west longitude, transponder 17C, 4040 MHz, vertical polarization. It is available in Alaska and Hawaii on AMC-7, at 137 degrees west longitude, transponder 18C, at 4060 MHz, horizontal polarization. A Digital Video Broadcast-compliant Integrated Receiver Decoder is required for reception. For NASA TV information and schedules on the Web, visit http://www.nasa.gov/ntv.

MESSENGER on the Web

MESSENGER information – including an electronic copy of this press kit, press releases, fact sheets, mission details and background, status reports, and images – is available on the Web at http://messenger.jhuapl.edu. MESSENGER multimedia files, background information, and news are also available at http://www.nasa.gov/messenger.

Quick Facts

Spacecraft

Size: Main spacecraft body is 1.44 meters (57 inches) tall, 1.28 meters (50 inches) wide, and 1.85 meters (73 inches) deep; a front-mounted ceramic-fabric sunshade is 2.54 meters tall and 1.82 meters across (100 inches by 72 inches); two rotatable solar panel "wings" extend about 6.14 meters (20 feet) from end to end across the spacecraft.

Launch weight: Approximately 1,107 kilograms (2,441 pounds); including 599.4 kilograms (1,321 pounds) of propellant and 507.6 kilograms (1,119 pounds) of "dry" spacecraft and instruments.

Power: Two body-mounted gallium arsenide solar panels and one nickel–hydrogen battery. The power system generated about 490 watts near Earth and will generate its maximum possible output of 720 watts in Mercury orbit.

Propulsion: Dual-mode system with one bipropellant (hydrazine and nitrogen tetroxide) thruster for large maneuvers; 4 medium-sized and 12 small hydrazine monopropellant thrusters for small trajectory adjustments and attitude control.

Science instruments: Wide-angle color and narrow-angle monochrome imager; gamma-ray and neutron spectrometer; X-ray spectrometer; energetic particle and plasma spectrometer; atmospheric and surface composition spectrometer; laser altimeter; magnetometer; radio science experiment.

Mission

Launch: August 3, 2004, from Launch Pad 17B at Cape Canaveral Air Force Station, Fla., at 2:15:56 a.m. EDT aboard a three-stage Boeing Delta II rocket (Delta II 7925-H).

Gravity assist flybys: Earth (1) August 2005; Venus (2) October 2006, June 2007; Mercury (3) January 2008, October 2008, September 2009.

Enter Mercury orbit: March 2011.

Total distance traveled from Earth to Mercury orbit: 7.9 billion kilometers (4.9 billion miles). Spacecraft circles the Sun 15.2 times from launch to Mercury orbit.

Primary mission at Mercury: Orbit for one Earth year (equivalent to just over four Mercury years, or two Mercury solar days), collecting data on the composition and structure of Mercury's crust, its topography and geologic history, the nature of its thin atmosphere and active magnetosphere, and the makeup of its core and polar materials.

Program

Cost: Approximately $446 million (including spacecraft and instrument development, launch vehicle, mission operations, and data analysis).

Mercury at a Glance

General

- One of five planets known to ancient astronomers, in Roman mythology Mercury was the fleet-footed messenger of the gods, a fitting name for a planet that moves quickly across the sky.
- The closest planet to the Sun, Mercury is now also the smallest planet in the Solar System.
- Prior to January of this year, Mercury had been visited by only one spacecraft; NASA's Mariner 10 examined less than half the surface (~45%) in detail during its three flybys in 1974 and 1975.

Physical Characteristics

- Mercury's diameter is 4,880 kilometers (3,032 miles), about one-third the size of Earth and only slightly larger than our Moon.
- The densest planet in the Solar System (when corrected for compression), its density is 5.3 times greater than that of water.
- The largest known feature on Mercury's pockmarked surface is the Caloris basin (1,550 kilometers or 960 miles in diameter – see http://messenger.jhuapl.edu/gallery/sciencePhotos/image.php?page=&gallery_id=2&image_id=149), likely created by an ancient asteroid impact.
- Mercury's surface is a combination of craters, smooth plains, and long, winding cliffs.
- There possibly is water ice on the permanently shadowed floors of craters in the polar regions.
- An enormous iron core takes up at least 60% of the planet's total mass – twice as large a fraction as Earth's.

Environment

- Mercury experiences the Solar System's largest swing in surface temperatures, from highs above 700 Kelvin (about 800° Fahrenheit) to lows near 90 Kelvin (about –300° Fahrenheit).
- Its extremely thin atmosphere contains hydrogen, helium, oxygen, sodium, potassium, calcium, and magnesium.
- The only inner planet besides Earth with a global magnetic field, Mercury's field is about 100 times weaker than Earth's (at the surface).

Orbit

- The average distance from the Sun is 58 million kilometers (36 million miles), about two-thirds closer to the Sun than Earth is.
- The highly elliptical (elongated) orbit ranges from 46 million kilometers (29 million miles) to 70 million kilometers (43 million miles) from the Sun.
- Mercury orbits the Sun once every 88 Earth days, moving at an average speed of 48 kilometers (30 miles) per second and making it the "fastest" planet in the Solar System.
- Because of its slow rotation – Mercury rotates on its axis once every 59 Earth days – and fast speed around the Sun, one solar day on Mercury (from noon to noon at the same place) lasts 176 Earth days, or two Mercury years.
- The distance from Earth (during MESSENGER's orbit) ranges from about 87 million to 212 million kilometers, about 54 million to 132 million miles.

Highlights from Mercury Flyby 1

By every measure MESSENGER's first flyby of Mercury on January 14, 2008, was a resounding success. The primary objective of the flyby was to use Mercury's gravity to alter the spacecraft's orbit to bring its orbit closer to that of Mercury. This crucial maneuver was executed flawlessly, and MESSENGER is on its way to becoming, in 2011, the first spacecraft ever to orbit Mercury. In addition, MESSENGER became the first spacecraft to visit Mercury since Mariner 10 did so during its last flyby in 1975. To make full use of this opportunity, the science team developed a comprehensive plan to conduct observations throughout the encounter. The data recorded by MESSENGER during its first flyby has been used to fine-tune the observation strategy for the prime orbital phase of the mission. Even now these data are providing exciting new insights into the history and dynamics of our Solar System's innermost planet.

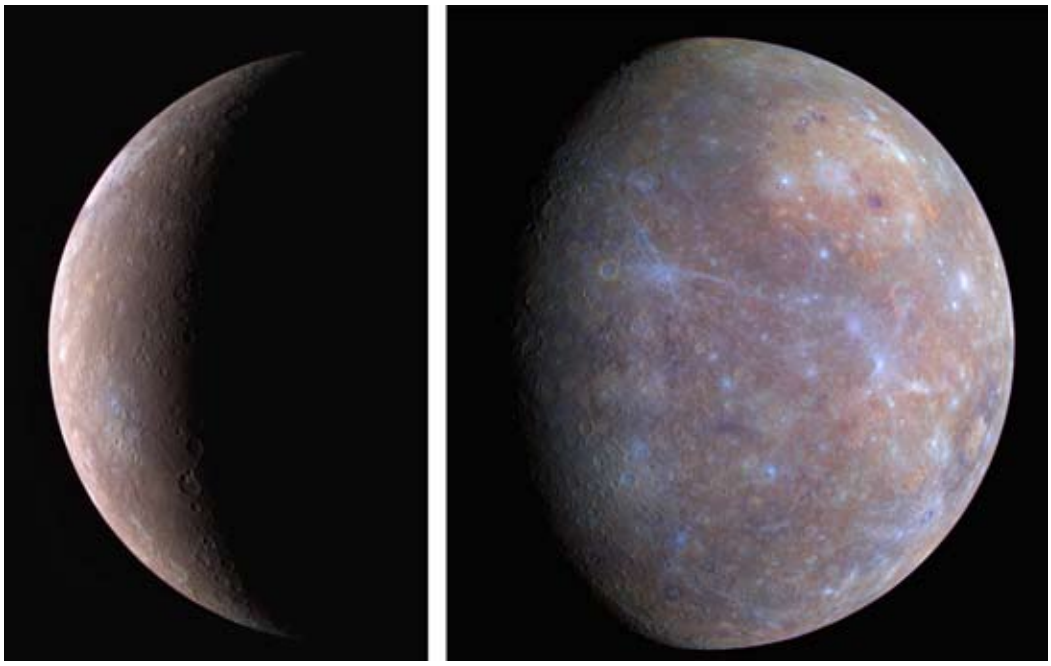
Firsts Accomplished during the Flyby

- The Mercury Dual Imaging System (MDIS) cameras imaged almost half of the planet including terrain that had never previously been viewed by spacecraft. The encounter added another 21% of Mercury's surface to the total imaged close-up by spacecraft. The camera data include high-resolution (less than 200 m per pixel) images and color images using the instrument's full complement of 11 color filters. This provides the most comprehensive color data of Mercury to date.
- The Mercury Laser Altimeter (MLA) provided the first measurements of the topography of Mercury as determined from spacecraft. These results provide evidence for a complex geologic history and indicate that Mercury's craters are shallower than those on the Moon at a given crater diameter, as expected because of the higher surface gravity.
- The Mercury Atmospheric and Surface Composition Spectrometer (MASCS) Visible and Infrared Spectrograph (VIRS) recorded the first spatially resolved spectra of Mercury's surface at infrared and near-infrared wavelengths. These high-spectral-resolution data provide new clues to identify the minerals comprising the surface.
- The Ultraviolet and Visible Spectrometer (UVVS) of MASCS obtained the highest-spatial-resolution measurements ever made of Mercury's exosphere spanning the entire range of the planet's ultrathin neutral atmosphere from the dayside, close to the surface, to the exosphere tail that extends hundreds of thousands of kilometers anti-sunward of the planet. The exosphere tail displayed a pronounced north–south asymmetry, which is attributed to a corresponding asymmetry in the relation between the interplanetary magnetic field and Mercury's own magnetic field at the time of the encounter.
- The Magnetometer (MAG) obtained continuous data through the lowest altitude ever achieved at Mercury, 201 km. The new magnetic field data provide the best assessment to date of the planet's magnetic field near the equator. The results suggest that the field is predominantly dipolar as expected if it is produced by a dynamo in a molten outer core.
- The Fast Imaging Plasma Spectrometer (FIPS) obtained the first-ever measurements of ions at Mercury and revealed a complex environment resulting from the mixture of the solar wind plasma with species originating from the surface. Numerous species were measured, reflecting a dynamic interaction of Mercury's surface with its exosphere and magnetosphere.
- The Energetic Particle Spectrometer (EPS), sensitive to energetic electrons and ions, was posed to solve some of the problems left by Mariner 10's observations of energetic particles at Mercury. Somewhat surprisingly, EPS recorded essentially no energetic particles in this encounter, confirming that the magnetosphere was relatively calm. Nonetheless, MAG observations reflect an array of dynamic magnetospheric phenomena: reconnection events, flux ropes, and both kinetic and fluid-driven plasma instabilities. All of these characteristics have intriguing parallels with Earth's magnetosphere, showing that even when quiet, Mercury's magnetosphere hosts a range of plasma physical processes.

- A suite of MESSENGER's instruments focused on determining Mercury's composition. The X-Ray Spectrometer (XRS), the Gamma-Ray Spectrometer (GRS), and the Neutron Spectrometer (NS) all made their first observations of Mercury. Much more compositional information will be obtained once the spacecraft is in orbit and these instruments conduct the long-term observations for which they were designed. Even with the limits imposed by the relatively rapid flyby the NS indicates that the average iron abundance on Mercury is less than 6% by weight.

Mercury – in Color!

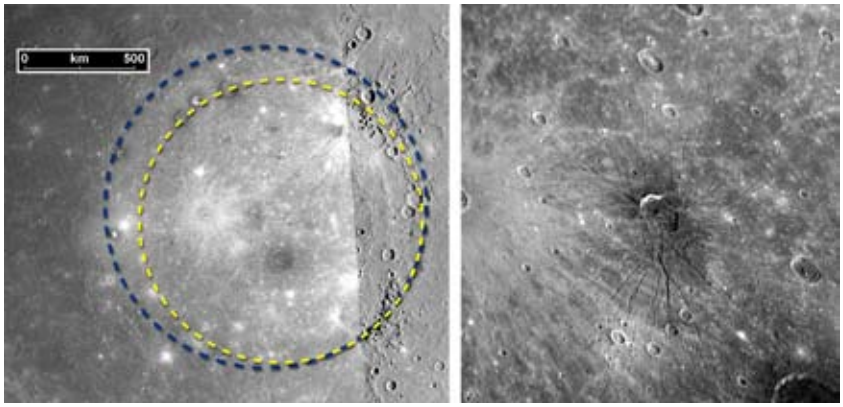
During the flyby, the MDIS Wide-Angle Camera (WAC) snapped images of Mercury through 11 different narrow-band color filters, which range from violet in the visible (395 nm) to the near-infrared (1040 nm). This first-of-its-kind color information showed Mercury's surface to be composed of a variety of materials with different color characteristics, such as smooth volcanic plains, darker material excavated from depth by impact craters, younger, less space-weathered material, reddish deposits near volcanic vents, and very bright material on some crater floors. The color images are complemented by images from the MDIS Narrow-Angle Camera (NAC), which provides higher-resolution views of these areas with interesting color properties. As the MESSENGER Science Team continues to study this valuable color dataset, the results will provide information about Mercury's composition and the processes that acted on Mercury's surface.



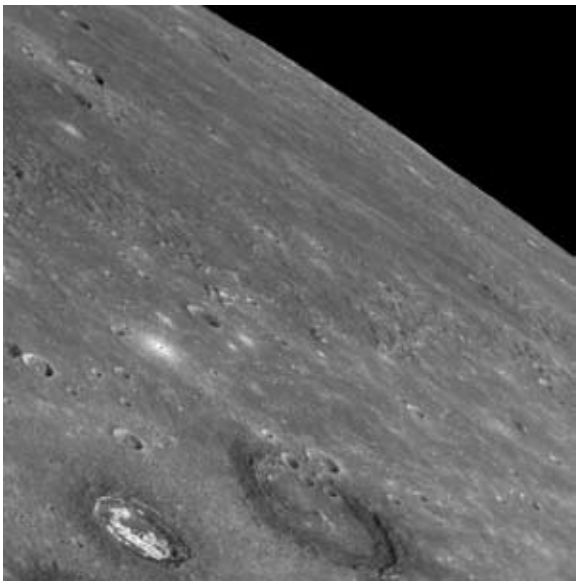
False-color images of Mercury obtained during approach to (left) and departure from (right) the planet during MESSENGER's first flyby. The false-color images were generated by combining images taken through different MDIS filters; images from filters that transmit light at wavelengths of 1000 nm (near-infrared), 700 nm (red), and 430 nm (violet) were placed in the red, green, and blue channels, respectively. Creating false-color images in this way accentuates color differences on Mercury's surface.

The Great Caloris Impact Basin

It was known from Mariner 10 photos that Mercury's Caloris basin was a large, well-preserved impact basin, but MESSENGER images showed the true extent of the feature for the first time. From Mariner 10 photos, only a portion of the eastern half of Caloris was visible and the diameter of Caloris was estimated at 1,300 km; MESSENGER's images of the entire Caloris basin show that the structure is larger than previously believed, with a diameter of about 1,550 km. Counting craters inside and outside Caloris basin shows that the basin is older than the surrounding, unrelated plains material outside the basin, supporting the idea that Caloris formed fairly early in the history of the Solar System, likely around 3.8 billion years ago. Near the center of Caloris basin, a set of over 200 narrow troughs, named Pantheon Fossae, radiate outward in a pattern unlike anything previously seen on Mercury. Structures interpreted as volcanic vents are seen around the margins of the great basin. Craters with intriguing dark- and light-color characteristics are found on the basin floor. Overall, understanding the formation and evolution of this giant basin will provide insight into the early history of major impacts in the inner Solar System, with implications not just for Mercury, but for all the planets, including Earth.



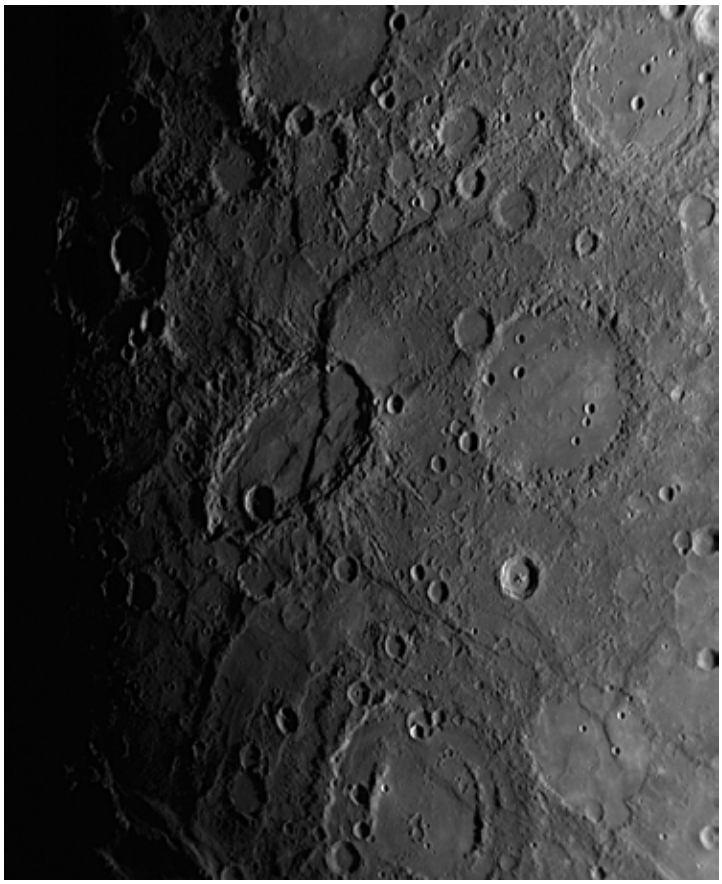
Mercury's Caloris basin (left image) is a large impact basin, and this image shows a mosaic of Mariner 10 photos (right portion of the image) and MESSENGER images (left portion of the image). MESSENGER imaged the entire basin for the first time during its January 2008 flyby and revealed that the basin is even larger than previously believed. (MESSENGER diameter in blue: 1,550 km. Previous Mariner 10 diameter in yellow: 1,300 km.) Located in the center of Caloris basin is Pantheon Fossae (right image), a set of hundreds of radiating troughs unlike any feature ever seen on Mercury. The crater near the center of Pantheon Fossae is Apollodorus, with a diameter of 41 km.



This MDIS image looking towards Mercury's horizon shows two craters in the Caloris basin with intriguing properties. The lower left crater, named Sander (50-km diameter), has highly reflective, bright material on its floor, while the neighboring, unnamed crater to the right lacks this bright material but has a distinctive halo of dark material. Understanding the nature of these different materials will help to understand the evolution of Mercury.

Mercury's Unique History – Global Fault Scarps

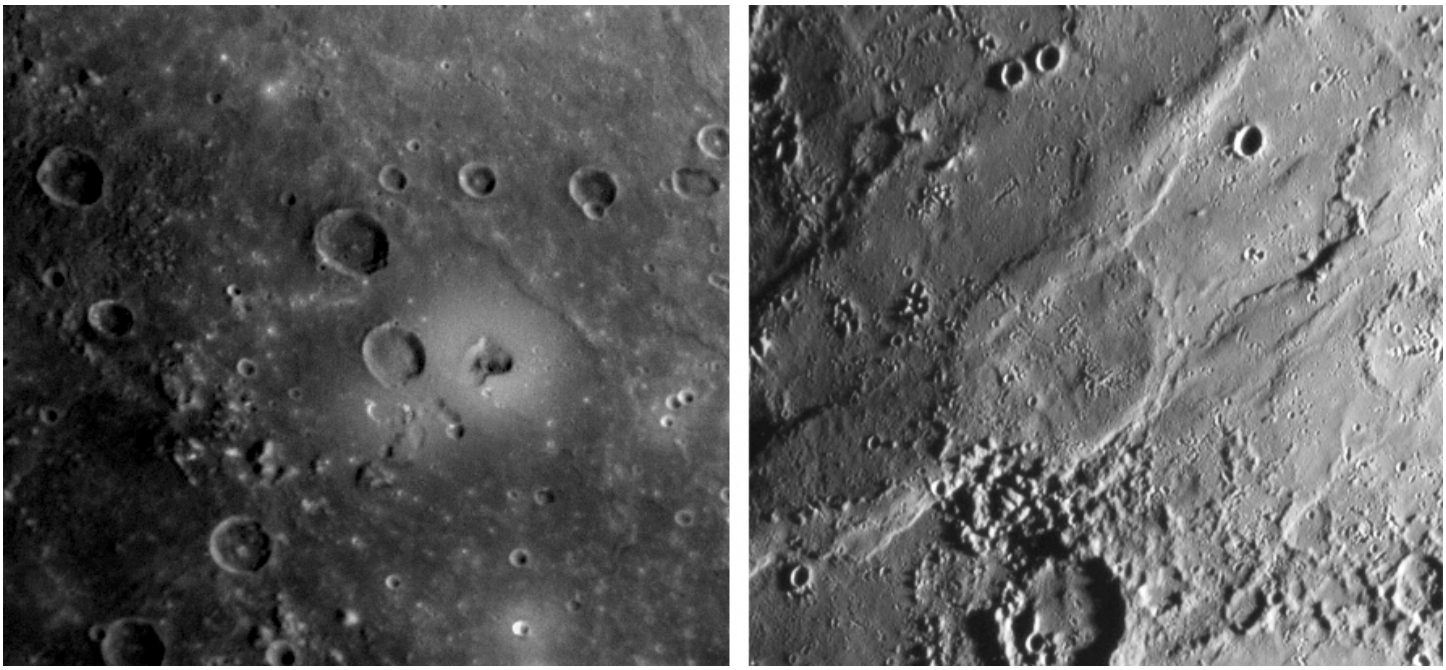
Pictures from Mariner 10 showed many long and high scarps (cliffs) on Mercury's surface, suggesting that Mercury's history is unlike that of any other planet in the Solar System. These giant scarps are believed to have formed when Mercury's interior cooled and the entire planet shrank slightly as a result. Images from MESSENGER's first flyby have revealed new examples of scarps that extend for hundreds of kilometers and suggest that Mercury shrank by even more than previously thought. MESSENGER images show that scarps are widespread across the surface of the planet. The different lighting conditions allowed MESSENGER to discover scarps not previously identified on parts of Mercury's surface seen by Mariner 10, meaning that the Mariner 10 estimate for the amount of global contraction is too low. Additionally, the MESSENGER images show promise for constraining the timing of global contraction by using relationships observed between the embayment of surface features and the cross-cutting of the scarps. Timing information will be very valuable for modeling Mercury's unique thermal evolution.



Discovered by MESSENGER in a region previously unseen by spacecraft, Beagle Rupes, the long, curving scarp (cliff) shown in the center of this MDIS image, is one of the largest scarps on the planet and deforms the distinctive, elliptically shaped Sveinsdóttir crater. The scarp is believed to have formed when Mercury cooled and the entire planet shrank slightly. (The image is about 650 km across.)

Volcanism on Mercury

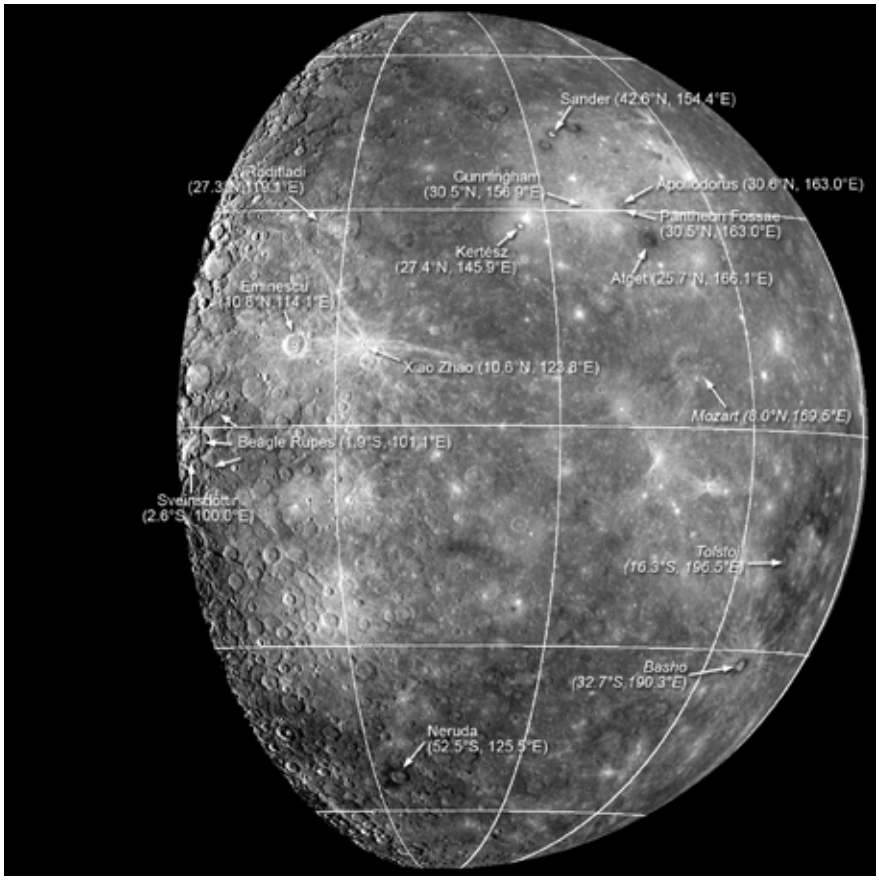
The role volcanism played in shaping the landscape of Mercury has been a subject of scientific debate since the flybys of Mariner 10. From MESSENGER's flyby, high-resolution images combined with complementary color information have led to the first identification of volcanic vents on Mercury. The vents are seen as irregularly shaped, rimless depressions, which distinguish them from impact craters. Smooth deposits surround the vents, similar to volcanic vents seen on other planets. High-resolution MDIS images also reveal many examples of flooded and embayed impact craters. By measuring the shallow depth of craters flooded by volcanic processes, lava flow thicknesses as great as 5 km have been estimated. Thus, MESSENGER results from the mission's first flyby indicate that volcanism was an important process in the geologic history of Mercury, and additional MESSENGER data will further elucidate the extent of volcanism on the Solar System's innermost planet.



MESSENGER identified volcanic vents on Mercury for the first time. The irregularly shaped depression for this vent (left image) is about 20 km across in its longest dimension and is surrounded by a smooth deposit. Several other irregular depressions, smaller in size, can also be seen on the southwestern portion of the smooth deposit. A flooded impact crater (right image), about 60 km in diameter, shows further evidence of the role of volcanism in shaping Mercury's surface.

Naming the New Discoveries

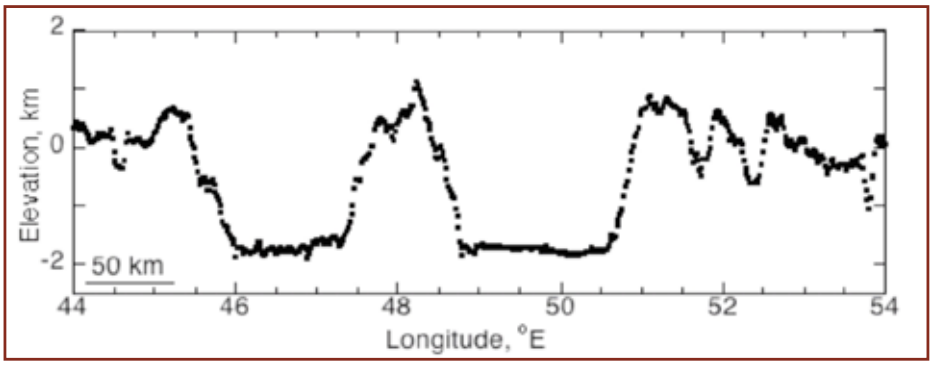
As MESSENGER reveals portions of Mercury's surface never previously seen in detail, numerous new features are discovered. And those new features need names. The International Astronomical Union (IAU) is the internationally recognized authority for naming landforms on planets and satellites, and in April 2008 the IAU officially accepted a proposal by the MESSENGER team for 12 new names for features on Mercury's surface. The new names include 10 craters identified for the first time by MESSENGER images. Craters on Mercury are named for individuals who have made significant contributions to the arts and humanities. A newly identified long scarp on Mercury's surface was named Beagle Rupes. Rupes is Latin for cliff, and rupes on Mercury are named for the ships of famous explorers, in this case after the ship of naturalist Charles Darwin. In the center of Caloris basin, a set of hundreds of radiating narrow troughs unlike anything previously seen on Mercury is now named Pantheon Fossae. The word fossa is Latin and means trench. Fossae, the plural of fossa, have been found (and named) on planetary bodies including Mars, Venus, and the Moon, but Pantheon Fossae are the first to be seen on Mercury. Consequently, the IAU also had to adopt a naming convention for fossae on Mercury, which are now named after significant works of architecture (the crater Apollodorus, near the center of the formation, is named for the reputed architect of the Pantheon). As the MESSENGER mission continues, more features on Mercury, many yet to even be discovered, will receive names.



The locations of newly named features on Mercury are shown, along with three features named previously from Mariner 10 photos (labeled in italics). The newly named landforms were all discovered in images from MESSENGER's first Mercury flyby.

High-Precision Topography from Laser Ranging

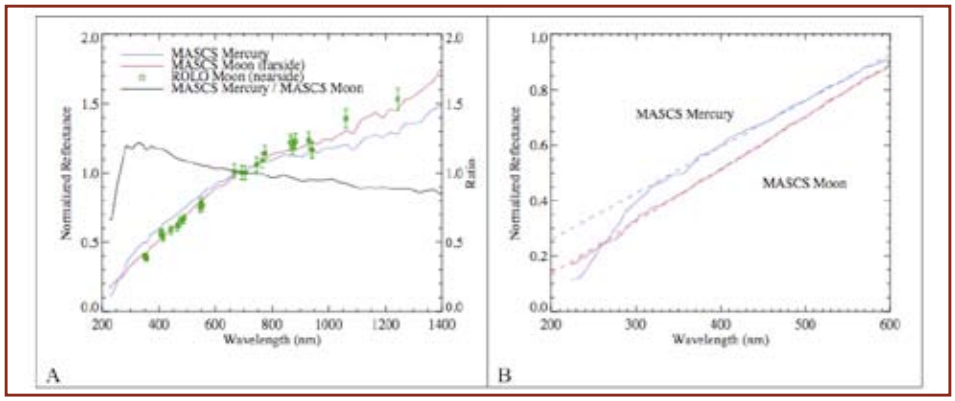
The very first laser ranging measurements by MLA from Mercury's surface obtained transects across multiple craters, smooth plains, and other terrain. Because MLA was within range only over the nightside of Mercury and the surface within view of MLA was not imaged by Mariner 10, the ranging results were correlated with Earth-based, radar-derived maps of the surface. The correlation was superb between the craters observed by MLA and those inferred from the radar mapping. The MLA ranging provided the first definitive observations of terrain slopes and crater depths on Mercury, showing that the slopes are more gradual and the craters shallower than those on the Moon. The results also clearly show that there is great variation in the surface roughness of crater floors, suggesting possibly significant differences in ages or geologic processes operating in different craters.



Close-up of two craters transected by MLA ranging observations during the first MESSENGER Mercury flyby showing crater depths up to nearly 3 km with marked contrast in floor roughness and tilt. The vertical exaggeration is 30:1.

First Clues to Mineralogy: Clear Differences from Earth's Moon

High-resolution, ultraviolet-to-infrared spectra of Mercury's surface acquired by MASCS revealed differences in color from the Earth's Moon that, despite some general similarities, indicate a different composition. For mineralogical identification, spectral differences of a few percent are significant, and the differences found by MASCS are up to 20%, indicating that the surface of Mercury has a number of important surprises in store. Identifying the classes of minerals consistent with the observed spectra will require extensive analysis and comparison with the color imaging from MDIS, but it is already clear that these spectra will play a key role in sifting out the geologic history of the range of materials evident on the surface and, ultimately, in telling the story of Mercury's unique history.



First ultraviolet-to-infrared spectra of Mercury's surface returned by the MASCS instrument. Left panel shows disk-averaged reflectance of Mercury (blue) and the Moon (red) along with full-disk spectrum (green) of the waxing phase (87°) of the lunar nearside, which is predominantly composed of highlands terrain. These spectra are scaled to a value of 1.0 at 700 nm. The black curve shows the ratio of Mercury reflectance to that of the Moon and indicates clear differences between the spectral reflectance of the two bodies that reach 20%. The right panel shows a close-up of the short-wavelength portion of the spectrum comparing the MASCS spectra from the Moon and Mercury. Note the sharp departure of the Mercury spectrum from that of the Moon below 300 nm.

Mercury's Dynamic Space Environment

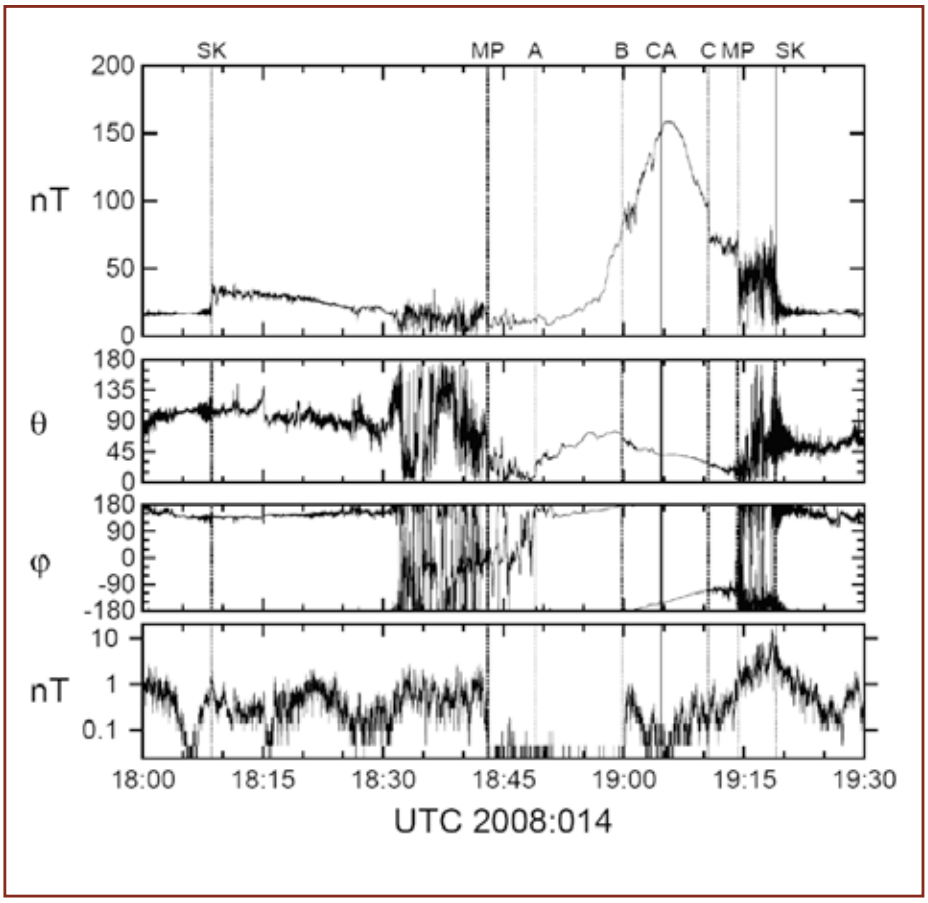
MESSENGER's full suite of particle and fields instruments was used during the mission's first flyby. To understand fully this complex and dynamic system we will need the observations planned for the orbital phase of the mission, but even now the flyby data have provided new science contributions and insights. The MESSENGER spacecraft was within Mercury's magnetosphere for about 30 minutes during the flyby, and magnetic field measurements showed that the planet has a dipole magnetic field, similar in strength and direction to that measured by Mariner 10 over three decades earlier. Mercury's magnetosphere displayed many phenomena reminiscent of Earth's own magnetosphere, but with new twists owing to the small size of Mercury's system relative to key physical scale lengths. A cloud of planetary ions interacts with the magnetosphere, and MESSENGER made the first measurements of ions in Mercury's magnetosphere, revealing a complex interaction of the plasma, solar wind, and surface. During the flyby, the highest spatially resolved measurements of sodium in Mercury's exosphere were made, and the measurements showed spatial variations indicative of multiple processes operating to generate and maintain the tenuous planetary exosphere. These results revealed a dynamic planet, where interactions among the central metallic core, the rocky surface, the thin exosphere, the dipolar magnetic field, the complex magnetosphere, and the interplanetary solar wind environment are strongly interlinked.

A Magnetosphere Rich in Ion Diversity

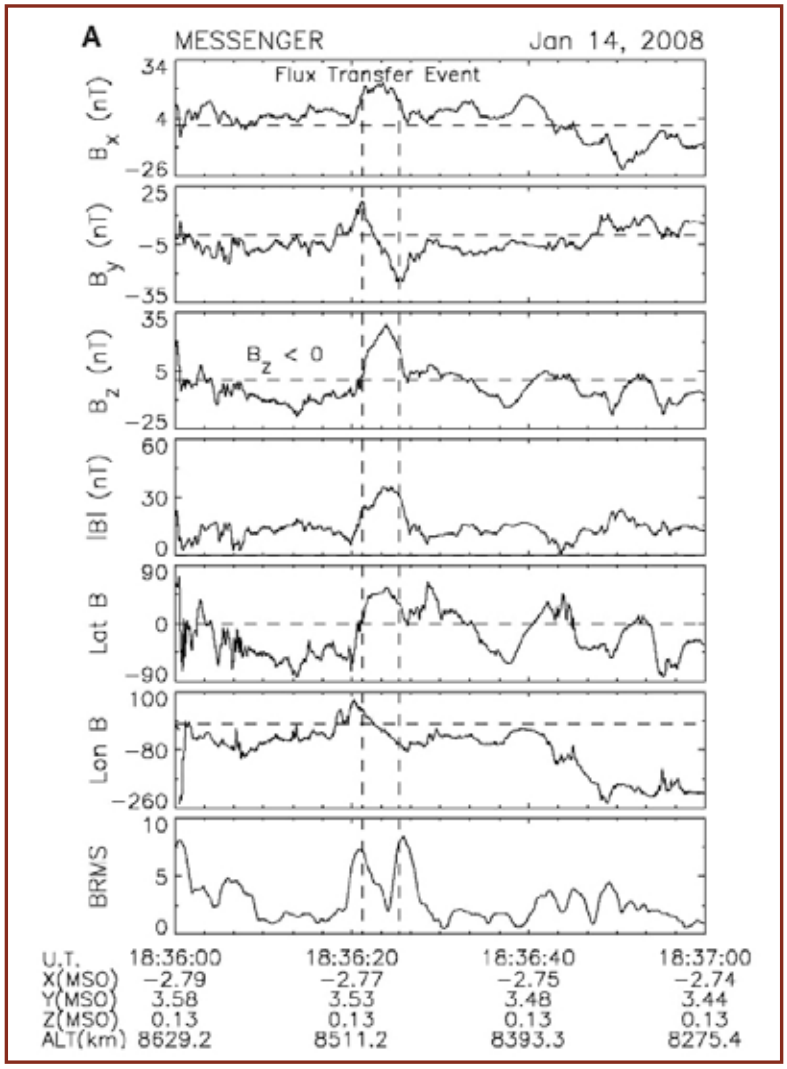
The very first measurements of ions in Mercury's magnetosphere revealed a remarkable richness in the species present. In addition to the solar wind protons that make up the bulk of the solar wind and are ubiquitous in planetary magnetospheres throughout the Solar System, FIPS discovered that Mercury's magnetosphere is host to a plethora of heavy ions. Charge-to-mass ratios indicate the presence of many singly charged ions much heavier than solar wind species. This startling variety of ion species confirms that material is driven off the surface and can be effectively detected as charged species, providing another window for deducing the planetary surface composition.

A Clean Sample of the Equatorial Magnetic Field

The only other measurements of Mercury's magnetic field near the equator are from Mariner 10 in 1974. At that time Mercury's magnetosphere put on a show of highly variable magnetic fields that, while fascinating for understanding the solar wind interaction, have made accurate assessment of the intrinsic field uncertain. For the first MESSENGER flyby, the magnetosphere was considerably calmer, allowing the first sample at the equator through an entire pass of the magnetosphere. These results allowed a more constrained estimate of the intrinsic field, and, after accounting for the contributions to the field from magnetospheric currents, the field appears to be consistent with a dipole, favoring an active dynamo in Mercury's molten outer core as the source of the field.



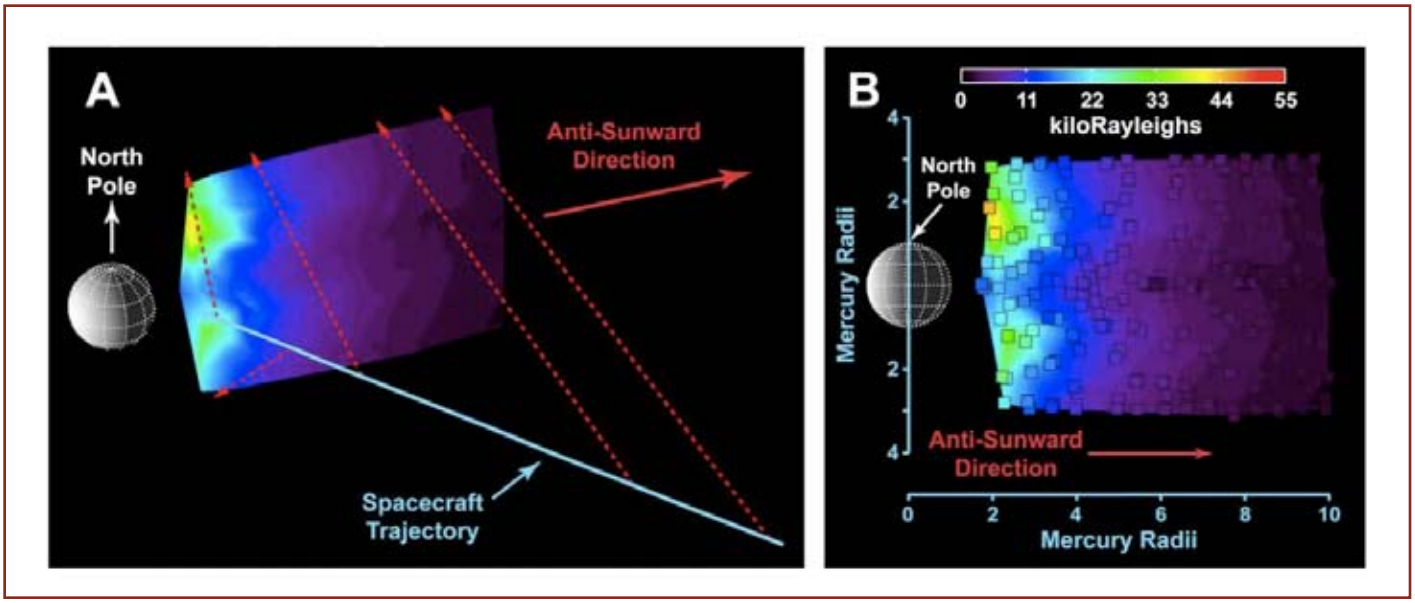
MESSENGER Magnetometer observations for January 14, 2008. From the top, panels show: field magnitude; polar (θ, 0° is northward) and azimuth (ϕ, 0° is to the Sun) angles of the field direction; and the 1-10 Hz bandpass fluctuation amplitude. Vertical lines indicate key boundaries: bow shock (SK) and magnetopause (MP) crossings, closest approach (CA), and three transitions within Mercury's magnetosphere (A, B, and C). The step at point B may indicate a layered magnetopause structure. No evidence of strong dynamics is observed, indicating that these data provide a complete equatorial sampling of the relatively undisturbed system.



The interval labeled with the vertical dashed lines is a flux transfer event observed by MESSENGER on the dusk flank of Mercury's magnetosheath just outside the magnetopause near the magnetotail. The rotation evident in the longitude slope (sixth panel from top), with a fairly constant latitude of the field direction (fifth panel), indicates a north-south-aligned flux rope. The peaks in magnetic fluctuations at the edges of the feature (seventh panel) are consistent with hot plasmas that normally encompass such flux ropes. The flux rope signals the release of magnetic flux from the magnetotail in a manner similar to features seen at Earth associated with substorms.

Signatures of Strong Solar Wind Coupling: Magnetotail Flux Ropes

Despite the apparent calm of the magnetic field during the magnetospheric transit, detailed examination of the high-resolution magnetic field data, with 0.05 nT resolution at 20 vectors every second, revealed signatures of strong electrodynamic coupling to the solar wind. Flux transfer events, signatures of ropes of magnetic flux connected between the interplanetary medium and Mercury's magnetic field, were observed on both the inbound and the outbound legs of the encounter. The strongest of these (next page) shows a classic signature of a twisted rope of magnetic field passing over the spacecraft. For the typical plasma flow speeds expected, this signature corresponds to a feature with a cross-sectional dimension of about half a Mercury radius, surprisingly large for a rapid event. The results reveal just how quickly things happen in Mercury's miniature magnetosphere and how much there will be to learn in the upcoming flybys and, of course, in orbit.



Viewing geometry and observed line-of-sight radiances (color scale) due to Na ultraviolet emissions detected by UVVS on the inbound flyby trajectory. These are projected onto a north-south plane extending anti-sunward. The left panel shows examples of line-of-sight vectors (dashed red lines) from the trajectory (blue line). The right panel shows projections of the line-of-sight directions of observations (squares) onto the plane anti-sunward of the planet. The minimum radiance near the mid-tail is due to the planet's shadow, as the Na emission is stimulated by exposure to ultraviolet sunlight at the Na electron transition level detected by UVVS.

The Sodium Exosphere Tail as We've Never Seen It Before

Ground-based telescopic observations have shown that Mercury carries with it an ultrathin cloud of neutral Na atoms that extend in a tail behind the planet in a manner reminiscent of a comet tail. The MASCS UVVS sensor obtained the most detailed measurements of this tail ever made during the inbound leg of MESSENGER's encounter (next page). The results reveal a stronger northern peak. It is thought that this bias is related to the orientation of the interplanetary magnetic field (IMF), because this orientation governs the hemisphere to which the shocked solar wind plasma has most direct access. For this encounter the IMF was directed away from the Sun, which provides direct magnetic connection between the solar wind and the northern cusp and surface of the planet, while the magnetic connection to the southern surface is less direct. The UVVS observations provide stunning evidence of the close relationships between the exosphere structure and the magnetospheric topology. More than any other solar-system object studied to date, Mercury's near-space environment is governed by the interplay of all aspects of the system, and Mercury will serve as a proving ground for many of our theories of surface-exosphere-magnetosphere interactions.

Highlights from Mercury Flyby 2

MESSENGER's second flyby of Mercury, on October 6, 2008, echoed the success of the previous flyby on January 14 that year. As with the first, the primary objective of the flyby was to use Mercury's gravity to alter the spacecraft's trajectory to bring its orbit about the Sun closer to that of Mercury. Once again, this crucial maneuver was executed flawlessly. The data recorded by MESSENGER during both flybys continues to be used to fine-tune the observation strategy for the prime orbital phase of the mission. Even now these data are providing exciting new insights into the history and dynamics of our Solar System's innermost planet.

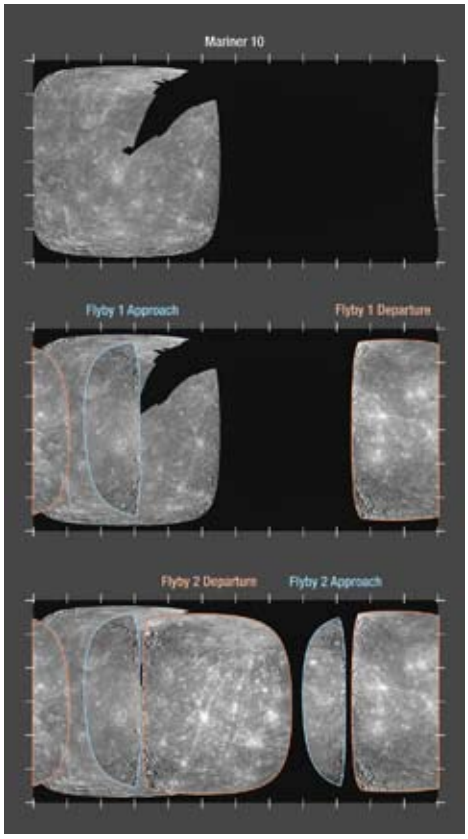
Firsts Accomplished during the Flyby

- The Mercury Dual Imaging System (MDIS) cameras imaged the opposite half of the planet from that seen during the first MESSENGER flyby, including terrain never previously been viewed by spacecraft. The encounter added another 30% of Mercury's surface to the total imaged at close range by spacecraft. The camera data include high-resolution (less than 200 m per pixel) images and color images with the instrument's full complement of 11 color filters. These observations provide the most comprehensive color data of Mercury to date. With no atmosphere or oceans, Mercury has no Earth-like weathering or erosional processes that can alter and remove evidence of impacts by meteoroids early in the history of the Solar System. While one might expect the surface of Mercury to be much like that of the Moon, the new data from the second flyby confirm there are significant differences. The dark maria ("seas" on the Earth-facing side of the Moon) are absent on Mercury, but smooth plains cover almost half of Mercury's surface and are thought to have been produced primarily by volcanic activity early in the planet's history. Bluer (slightly) material is also present and apparently excavated by some of the larger crater-forming events. Mercury presents a major puzzle, as the planet is so dense that an iron-rich core must make up more than half the mass, but the Mercury Atmospheric and Surface Composition Spectrometer (MASCS) Visible and Infrared Spectrograph (VIRS) shows that there is very little iron oxide in the silicates of the planet's crust.
- MDIS also provided the first measurements of the Rembrandt basin, the second largest easily seen large impact basin on Mercury. It is on the opposite side of the planet from that seen by Mariner 10 and is roughly the same age as – but half the diameter of – the Caloris basin, the largest on the planet. These objects were formed by very large impacts, as were basins on the Moon such as Imbrium. Like Caloris, Rembrandt has a "floor" covered by volcanic material from the planet's interior, but the geologic activity did not end there, and the subsequent geologic history differs from that of Caloris. Rembrandt sports "wrinkle ridges" and troughs produced by contraction and extension of the basin floor, as well as a "lobate scarp" such as are seen across the planet and thought to be the result of planetary cooling and contraction. Whatever the sequence of events that formed these basins, the significant differences between Caloris and Rembrandt show that on Mercury, if you have seen one basin you have not seen them all, and the planet may have a more patchwork underlying structure than originally thought.
- The Ultraviolet and Visible Spectrometer (UVVS) of MASCS obtained the first simultaneous measurements of sodium and calcium "tails" in Mercury's exosphere (by definition, an "atmosphere" so tenuous that the atoms comprising it never collide with each other!). The spatial distributions of these two atomic species are complementary to each other: while the sodium "tail" exhibits peak intensities toward the north and south of the planet's equator (as during the first MESSENGER flyby), calcium emissions tend to be concentrated toward the equator. In addition, MESSENGER has added magnesium to calcium and sodium on the list of magnetospheric constituents, all of which form different aspects of the exospheric tail. The tail varies with solar wind conditions, although its presence and basic form are primarily the result of light from the Sun, or radiation pressure, "pushing" individual atoms away from the planet.

- The Magnetometer (MAG) has shown that the type of interaction between a planetary magnetic field and the solar wind field that produces Earth's aurorae and "magnetic storms" also occurs at Mercury - at about 10 times the rate as at Earth. There are no aurorae at Mercury (because the atmosphere is too thin), but the magnetic affects at this miniature version of Earth can teach us more about magnetic storms, which on Earth can disable communications satellites, power lines, communication cables, and sometimes even electrical generator stations.
- The Fast Imaging Plasma Spectrometer (FIPS) obtained measurements complementary to those of the first flyby, and the Energetic Particle Spectrometer (EPS), sensitive to energetic electrons and ions, continued to see minimal activity in its energy range, perhaps a consequence of the continued low levels of solar activity that characterized the first flyby.
- The suite of MESSENGER's instruments focused on determining Mercury's composition surveyed the opposite side of the planet from that viewed during the first flyby. The X-Ray Spectrometer (XRS), Gamma-Ray Spectrometer (GRS), and Neutron Spectrometer (NS) all made observations of Mercury. Low solar activity precluded X-ray fluorescence measurements by the XRS, but the instrument may have indirectly detected energetic magnetospheric electrons. The low activity of the Sun, anomalous for this phase of the solar cycle, did allow for larger fluxes of galactic cosmic rays at Mercury, increasing the signatures of the planet in gamma-rays and X-rays. Much more compositional information will be obtained once the spacecraft is in orbit and these instruments conduct the long-term observations for which they were designed.

Mapping an Old World

Initial mapping of the innermost world of the Solar System is now almost complete. MESSENGER has now seen about 80% of Mercury from two encounters this year (14 January and 6 October, middle and bottom maps, respectively). The narrow regions outlined in blue are the sunlit crescents seen as MESSENGER approached Mercury prior to each flyby (Mercury flyby 1 approach crescent; Mercury flyby 2 approach crescent). The larger areas outlined in orange are the sunlit portions of the surface seen as MESSENGER departed the Solar System's innermost planet (Mercury flyby 1 departure view; Mercury flyby 2 departure view). The second flyby on October 6 filled in most of the areas that had never before been imaged by spacecraft. Between Mariner 10 and MESSENGER, we have now mapped about 90% of Mercury at a resolution of 1 kilometer or better. Because of the fast encounter velocity and Mercury's slow rotation, the lighting angle within the global mosaic varies from high noon to just over the horizon, resulting in a non-uniform look at the planet. After MESSENGER enters orbit about Mercury in 2011, a higher-resolution (250 meters/pixel) global mosaic will be built up with more uniform illumination.

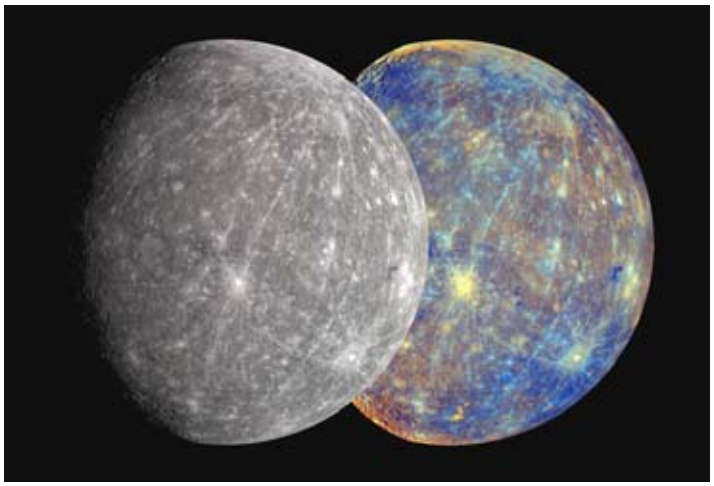


Three imaging coverage maps of Mercury. MESSENGER has now seen about 80% of Mercury from two encounters last year (14 January and 6 October, middle and bottom maps respectively). The narrow regions outlined in blue are the sunlit crescents seen as MESSENGER approached Mercury during each flyby (Mercury flyby 1 approach crescent; Mercury flyby 2 approach crescent). The larger areas outlined in orange are the sunlit portions of the surface seen as MESSENGER departed the Solar System's innermost planet (Mercury flyby 1 departure view; Mercury flyby 2 departure view). The second flyby on October 6 filled in most of the areas that had never before been imaged by spacecraft.

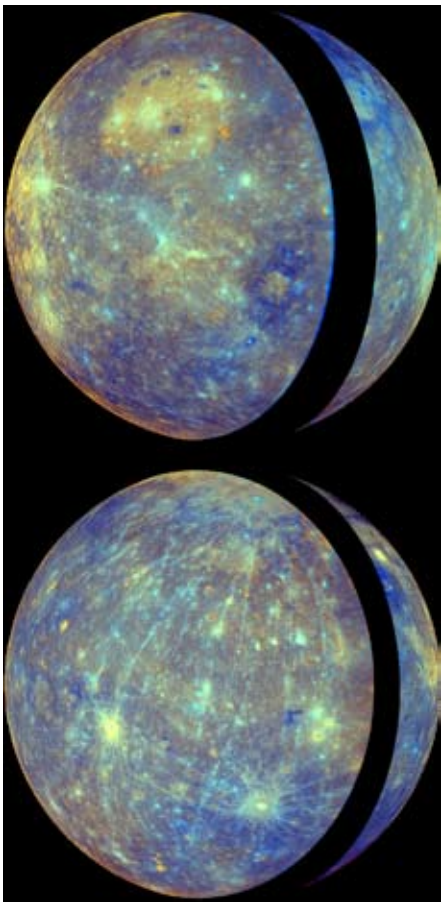
Mercury – in Color, Again!

The MDIS has 11 narrow-band spectral filters covering visible and near-infrared wavelengths (395 to 1040 nm). The specific colors of the filters were selected to discriminate among common minerals. Three-color images (480 nm, 560 nm, 630 nm) were combined to produce an approximation of Mercury's true color as might be seen by the human eye (left). From this rendition of Mercury, it is obvious that color differences on the surface are slight. Statistical methods that utilize all 11 filters in the visible and near-infrared enhance subtle color differences (right) and aid geologists in mapping regions of different composition.

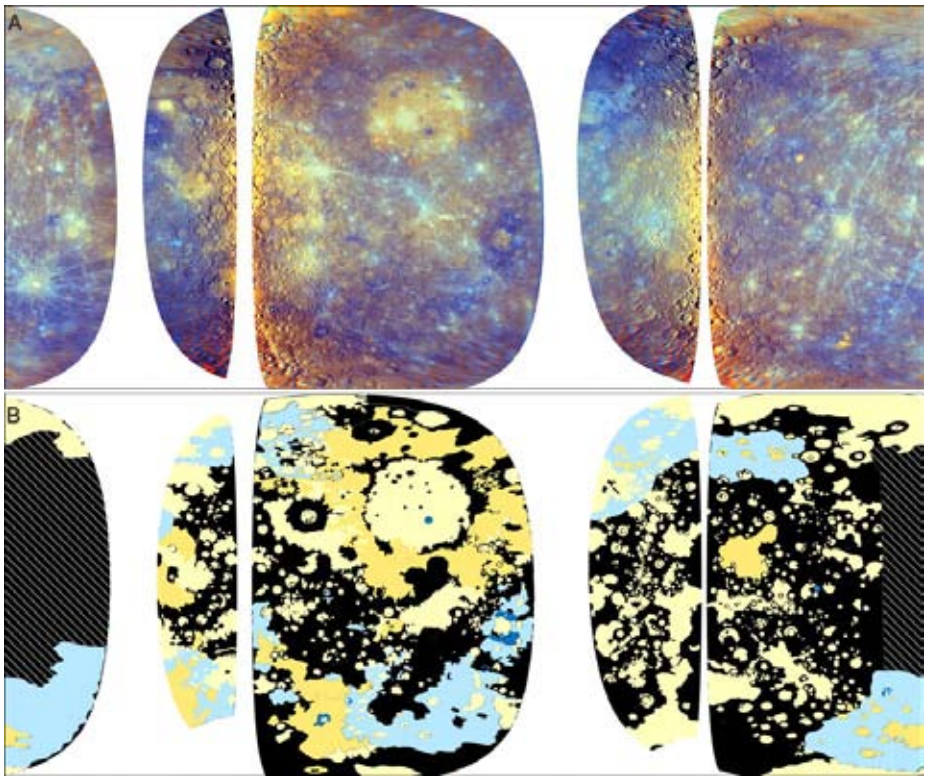
What do the exaggerated colors tell us about Mercury? The nature of color boundaries, color trends, and brightness values help MESSENGER geologists understand the discrete regions (or "units") on the surface. From the color images alone it is not possible to determine unambiguously the minerals that comprise the rocks of each unit. During the brief flybys, MESSENGER's other instruments sensitive to composition lacked the time needed to build up adequate signal or gain broad areal coverage, so only MESSENGER's cameras were able to acquire comprehensive measurements. Once in orbit about Mercury, MESSENGER's full suite of instruments will be brought to bear on the newly discovered color units to unlock their secrets.



At left is a combination of three color images (480 nm, 560 nm, 630 nm) that yield an approximation of Mercury's true color as might be seen by the human eye. At right is a depction of the same view in exaggerated color..



MESSENGER's two flybys of Mercury in 2008 have greatly increased the portion of the planet's surface that has been imaged by spacecraft, from approximately 45% coverage obtained by Mariner 10 to about 90% coverage following the second flyby. This significant increase in imaging coverage is enabling global studies of Mercury's surface for the first time. Both images are orthographic map projections of Mercury created with WAC enhanced-color images. The orthographic projection produces a view that has the perspective that one would see from deep space. The WAC enhanced color uses a statistical analysis of images from all 11 WAC filters to enhance subtle differences in the crustal rocks on Mercury's surface. The top view uses images from Mercury flyby 1, with the thin crescent of Mercury imaged during approach forming the right portion of the globe and the fuller departure view showing Caloris basin forming the left side and majority of the view. The black strip between the approach and departure images is a portion of Mercury's surface not viewed by MESSENGER during the flybys. Similarly, the approach and departure images obtained during Mercury flyby 2 yielded the bottom view. The top and bottom projections are centered on 180° and 0° longitude, respectively.



This image was recently featured in an article in Science magazine about the evolution of Mercury's crust. The top mosaic (A) is an enhanced-color view of the planet created from images taken through the WAC's eleven color filters during MESSENGER's first and second flybys of Mercury. White areas are those that MESSENGER has not yet observed. The bottom half of this image (B) is a map of major terrain types on Mercury. It was made by examining enhanced-color WAC mosaics (as shown at the top) that highlight color and compositional differences on the surface as well as higher-resolution Narrow-Angle Camera (NAC) mosaics that provide information about the surface texture and relationships among surface features.

On the geologic map (bottom), the pale yellow and darker yellow areas represent different types of smooth plains. The Caloris basin, for example, appears all in the pale yellow color, while the area around it is a darker yellow, indicating two different types of smooth plains in these neighboring areas. This global mapping study has indicated that smooth plains are widespread and cover about 40% of Mercury's surface. Many large areas of smooth plains also show evidence for a volcanic origin, leading to the conclusion that volcanism may have been extensive in Mercury's history. The light and dark blue colors highlight areas of the surface that have a lower reflectance and different composition than the smooth plains. The black areas on this map represent other kinds of terrain. The crosshatched areas were not included in the map because the high Sun angle during the flybys made them unsuitable for interpreting surface texture.

The Eye of the Beholder

So what is Mercury's "true" color? Given the WAC's ability to take images through 11 narrow-band color filters, it is natural to wonder what Mercury looks like in "true" color as would be seen by the human eye. However, creating such a natural color view is not as simple as it may seem. Shown below are four images of Mercury. The image in the top left is a grayscale monochrome image taken with a single WAC filter (430-nanometer wavelength) image; the remaining three images are three-color composites, produced by assigning WAC images obtained through three filters with peak sensitivities at 480, 560, and 630 nanometers to the blue, green, and red channels, respectively.

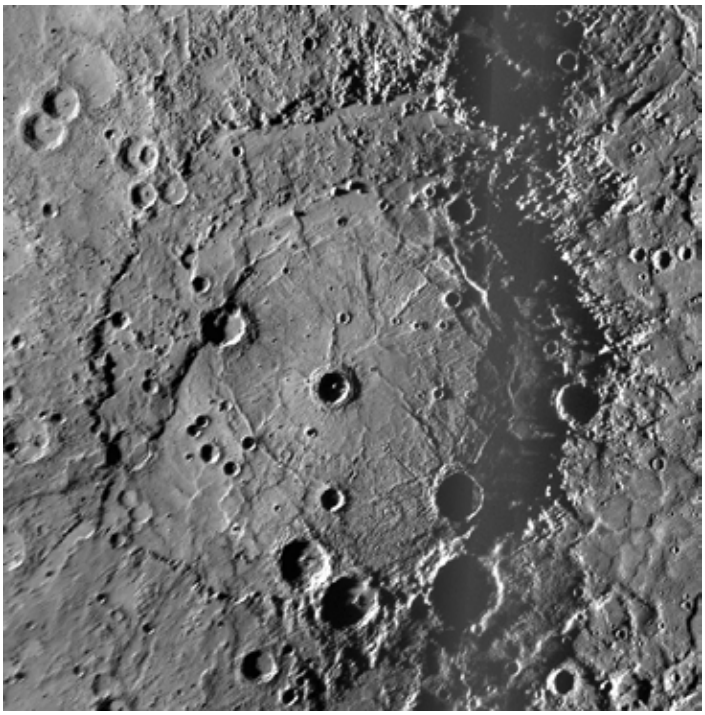
The differences between the color representations result from how the brightness and contrast of each individual WAC filter image was adjusted before it was combined into a color picture. In the top right view, all of the three filter images were stretched using the same brightness and contrast settings. In the bottom left picture, the brightness and contrast of each of the three filter images were determined independently of the others. In the bottom right, the brightness and contrast settings used in the upper right version were slightly adjusted to make each of the three filter images span a similar range of brightness and contrast values.

So which color representation is "correct" for Mercury? The answer to that question would indeed depend on the eye of the beholder. Every individual sees color differently; the human eye has a range of sensitivities that vary from person to person, resulting in different perceptions of "true" color. In addition, the three MDIS filter bands are narrow, and light at wavelengths between their peaks is not detected, unlike the human eye. In general, in light visible to the human eye, Mercury's surface shows only very subtle color variations, as seen in the three images here. However, when images from all 11 WAC filters are statistically compared and contrasted, these subtle color variations can be greatly enhanced, resulting in extremely colorful representations of Mercury's surface.

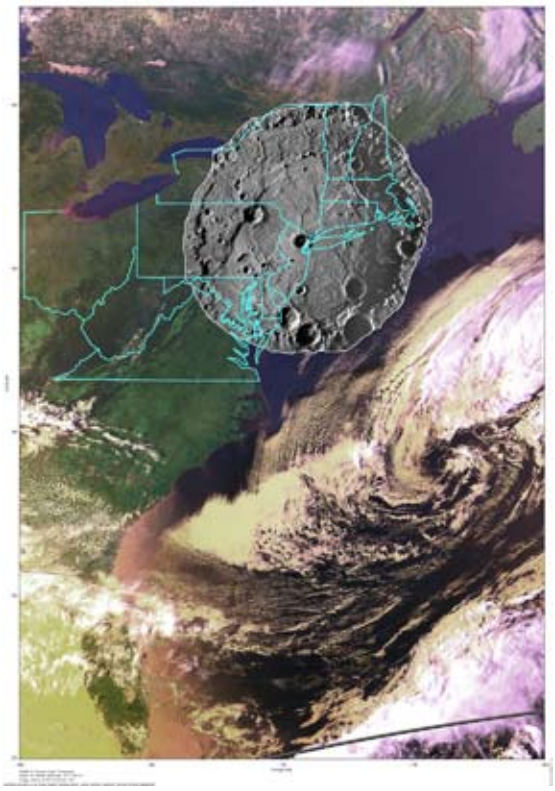
Shown here are four images of Mercury. The differences between the color representations result from how the brightness and contrast of each individual WAC filter image was adjusted before it was combined into a color picture.

Rembrandt – A Newly Discovered Impact Basin

Impact basins are formed by impactors much larger than those that form craters, resulting in much larger structures as well as multiple rings of elevated terrain formed during the impact process. During MESSENGER's first flyby of Mercury, the full extent of Caloris, the largest well-preserved impact basin on Mercury, was reveled for the first time. MESSENGER's images of the entire Caloris basin show that the structure has a diameter of about 1,550 km. The second flyby has revealed a basin not previously known, Rembrandt, which has a diameter of 715 km (440 miles). The number per area and size distribution of impact craters superposed on Rembrandt's rim indicates that it is one of the youngest impact basins on Mercury. The basin was imaged as MESSENGER approached Mercury for the mission's second flyby of the innermost planet and was visible even on optical navigation images. However, the high-resolution NAC images acquired as the spacecraft was closer to Mercury revealed unusual features associated with this basin. The basin floor has a set of radiating fractures that bear a similarity to the extensional troughs of Pantheon Fossae, imaged near the center of Caloris basin during MESSENGER's first Mercury flyby.



The walls and floor of the crater on the left side of the basin floor (with a diameter of 60 kilometers, 37 miles) have been cross-cut and offset by a younger lobate scarp. In contrast, the crater near the basin center (diameter of 44 kilometers, 27 miles) exhibits characteristics of a young, fresh crater that has not been altered by scarps or volcanic smooth plains. By examining details such as these for different features within Rembrandt, the relative timing of volcanism, deformation, and cratering within this basin is being revealed.

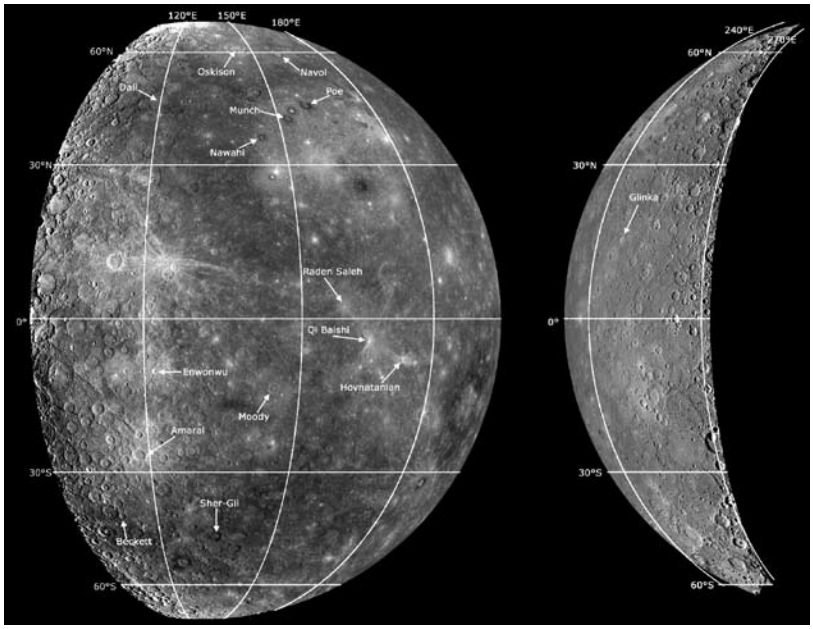


To put the size of Mercury's Rembrandt basin into a familiar context, a NAC mosaic of the basin is overlaid on an Advanced Very High Resolution Radiometer image of the east coast of the United States. With a diameter of 715 kilometers (444 miles), such a feature if formed at this location on Earth would encompass the cities of Washington, D.C., and Boston, Massachusetts, and everything in between.

A Second Set of Crater Names

As MESSENGER reveals portions of Mercury's surface never previously seen in detail, numerous new features are discovered. And those new features need names. The International Astronomical Union (IAU) is the international authority for naming landforms on planets and satellites, and in November 2008 the IAU officially accepted a proposal by the MESSENGER team for 15 new names for craters on Mercury's surface. The IAU has been the arbiter of planetary and satellite nomenclature since its inception in 1919. In keeping with the established naming theme for craters on Mercury, all of the craters are named after famous deceased artists, musicians, or authors. These newly named craters include:

- Amaral, after Tarsila do Amaral of Brazil, considered one of the leading Latin American modernist artists.
- Dalí, after Salvador Dalí, a Spanish painter and leader of the surrealist movement.
- Enwonwu, after sculptor and painter Benedict Chukwukadibia Enwonwu, the most renowned Nigerian artist of the 20th century.
- Glinka, after Mikhail Glinka, a Russian composer considered to be the "father" of genuinely Russian music.
- Hovnatanian, after Hakop Hovnatanian, an Armenian painter known for his portraits.
- Beckett, after Clarice Beckett, recognized as one of Australia's most important modernist artists.
- Moody, after Ronald Moody, a self-taught, Jamaica-born sculptor and painter who found success in mid-20th-century London and Paris.
- Munch, after Edvard Munch, a Norwegian Symbolist painter, printmaker, and draftsman, perhaps most well-known for his painting The Scream.
- Navoi, after Alisher Navoi, a 15th century Uzbek poet, considered by many to be the founder of early Turkic literature.
- Nawahi, after Joseph Nawahi, a self-taught artist, lawyer, educator, publisher, member of the Hawaiian legislature for many years, and principal adviser to Hawaii's Queen Lili'uokalani.
- Oskison, after John Milton Oskison, a Cherokee author who served as editor and editorial writer for the New York Evening Post.



The locations of a second set of 15 named impact craters on Mercury complement the 12 features named in April 2008.

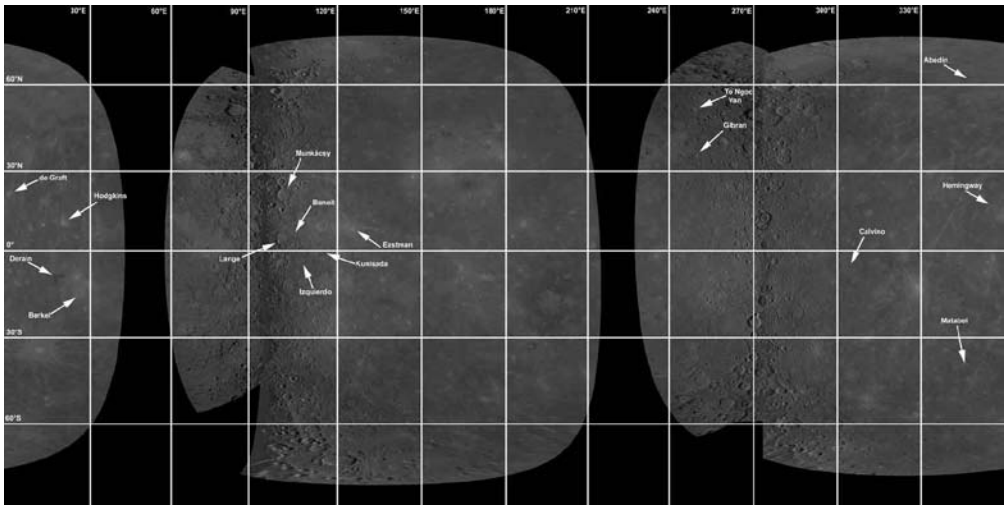
- Poe, after Edgar Allan Poe, American poet, critic, editor, and author, best known for his tales of mystery and the macabre.
- Qi Baishi, after Qi Baishi, a renowned Chinese painter known for his whimsical water colors.
- Raden Saleh, after Raden Saleh, a 19th century Javanese naturalist painter considered to be the first modern artist from what is now Indonesia.
- Sher-Gil, after Amrita Sher-Gil, an eminent Indian painter, today considered an important female painter of 20th-century India.

As the MESSENGER mission continues, more features on Mercury, many yet to even be discovered, will receive names.

And a Third

A third set of features on Mercury were named in July 2009. Several of the craters are from areas seen for the first time at close range by MESSENGER during its second Mercury flyby. The locations of these newly named craters are shown on this MESSENGER mosaic of Mercury. This group of new crater names is:

- Abedin, after Zainul Abedin, a Bangladeshi painter and printmaker who first attracted attention with his sketches of the Bengal famine of 1943.
- Benoit, after Rigaud Benoit, an early member of the Haïtian art movement known as Naive Art, so-called because of its members' limited formal training.
- Berkel, after Sabri Berkel, a Turkish painter and printmaker.
- Calvino, after Italo Calvino, an Italian writer of short stories and novels.
- de Graft, after Joe Coleman De Graft, a prominent Ghanaian writer, playwright, and dramatist who was appointed the first director of the Ghana Drama Studio in 1962.
- Derain, after Andre Derain, a French painter and co-founder of the Fauvism movement with Henri Matisse.
- Eastman, after Charles A. Eastman, a Native American (Sioux) author, physician, and reformer who helped found the Boy Scouts of America.
- Gibran, after Kahlil (Khalil) Gibran, a Lebanese American artist, poet, and writer, best known for his 1923 book *The Prophet*, a series of philosophical essays written in English prose.



The locations of a third set of 16 impact craters on Mercury named in July 2009.

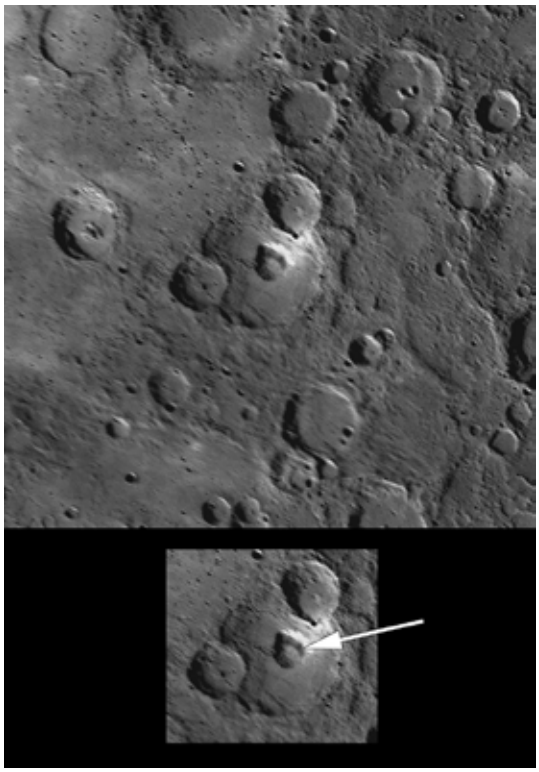
- Hemingway, after Ernest Hemingway, an American writer and journalist who had a significant influence on the development of 20th century fiction.
- Hodgkins, after Frances Hodgkins, a New Zealander painter.
- Izquierdo, after María Izquierdo, a Mexican painter who used the landscape and traditions of Mexico as inspirations for her artwork.
- Kunisada, after Utagawa Kunisada, a Japanese woodblock printmaker considered the most popular, prolific, and financially successful designer of ukiyo-e woodblock prints in 19th century Japan.
- Lange, after Dorothea Lange, an influential American documentary photographer and photojournalist, best known for her depression-era work for the Farm Security Administration.
- Matabei, after Iwasa Matabei, a Japanese artist who specialized in genre scenes of historical events and illustrations of classical Chinese and Japanese literature, as well as portraits.
- Munkácsy, after Mihály Munkácsy, a Hungarian painter who lived in Paris and earned international reputation with his genre pictures and large-scale biblical paintings.
- To Ngoc Van, a master in Vietnamese oil painting whose painting style was influenced by the French impressionist, Gauguin.

More Evidence for Volcanism

The newly named crater Gibran, located at the center of this image, contains a large, nearly circular pit crater, identified with the white arrow. Multiple examples of pit craters have been observed on Mercury on the floors of impact craters, leading to the name pit-floor craters for the impact structures that host these features. Unlike impact craters, pit craters are rimless, often irregularly shaped, steep-sided, and display no associated ejecta or lava flows. These pit craters are thought to be evidence of shallow magmatic activity and may have formed when retreating magma caused an unsupported area of the surface to collapse, creating a pit. Pit-floor craters may provide an indication of internal igneous processes where other evidence of volcanic processes is absent or ambiguous. The discovery of multiple pit-floor craters augments a growing body of evidence that volcanic and magmatic activity has been a widespread process in the geologic evolution of Mercury's crust.

Similar evidence for past volcanic activity is found in Lermontov, a crater first observed by Mariner 10 and seen more recently by MESSENGER during its second flyby. The crater floor is somewhat brighter than the exterior surface and is smooth with several irregularly shaped depressions. Such features, similar to those found on the floor of the crater Praxiteles, may be evidence of past explosive volcanic activity on the crater floor. Lermontov appears reddish in enhanced-color views, suggesting that it has a different composition from the surrounding surface. Lermontov is named for Mikhail Yurevich Lermontov, a nineteenth-century Russian poet and painter who died from a gunshot suffered in a duel.

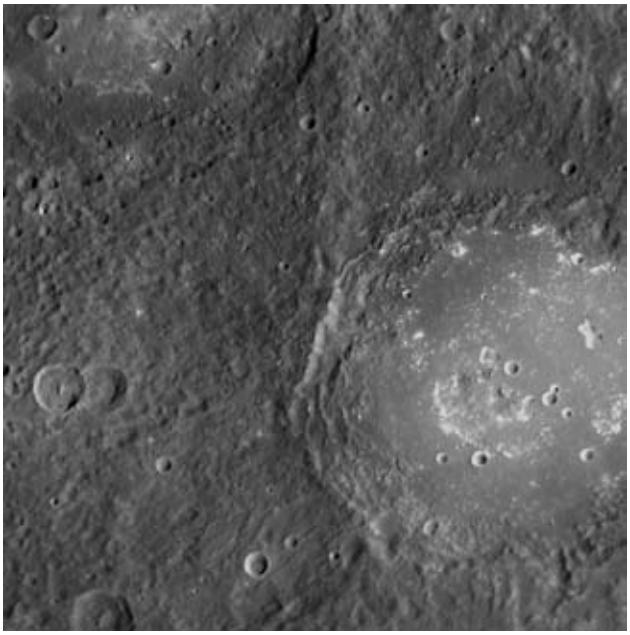
As the Science Team continues to study the detailed images taken by MESSENGER, more and more features are brought to light as the Mercury survey continues. Craters are seen to overlie older craters, and more evidence for volcanic flooding of crater floors and rims continues to be found.



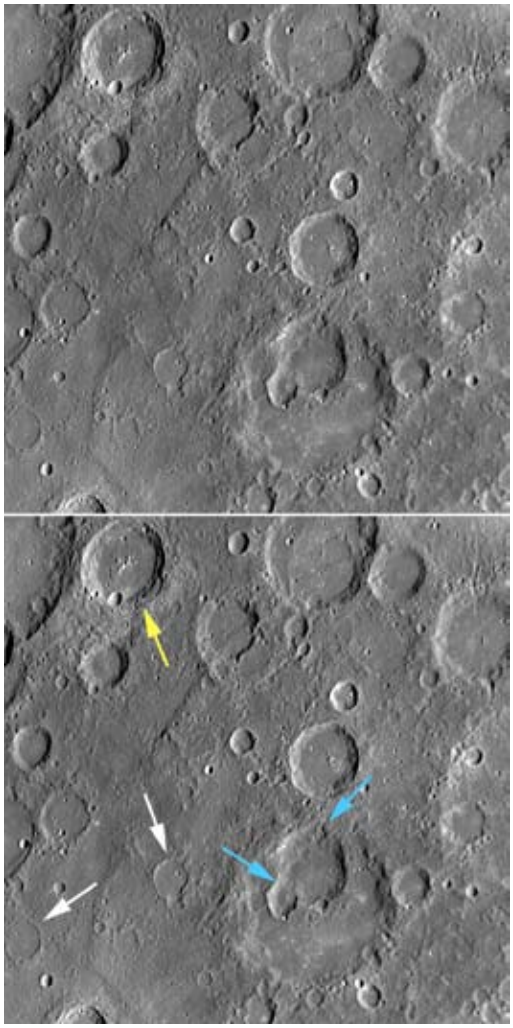
The crater Gibran.

Measuring the Depths of Mercury's Impact Craters

During the first MESSENGER flyby of Mercury, MLA was within range only over the nightside of Mercury, and the surface within view of MLA had not been imaged by Mariner 10, so the ranging results could be correlated only with Earth-based, radar-derived maps of the surface. For the second flyby, topographic measurements were made across territory that was photographed in high resolution by the MDIS NAC as well as other areas that had been imaged during the first flyby. The sample of craters whose topography was sampled during the flyby show great variations in relief, presumably due to differences in volcanic filling.



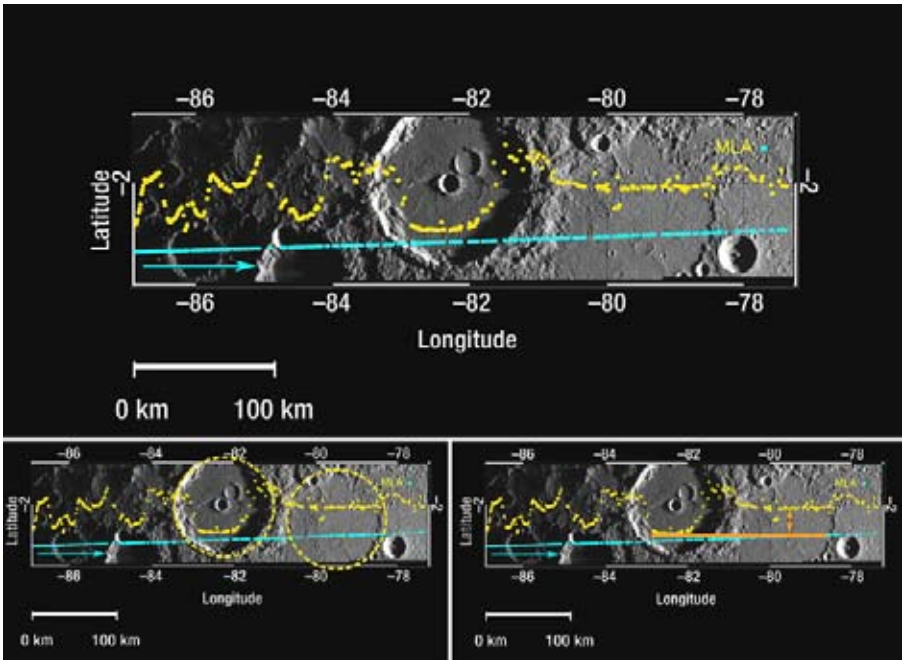
The Lermontov crater was first observed by Mariner 10 and seen more recently by MESSENGER during its second flyby of Mercury.



The craters in this NAC image display a variety of interesting characteristics. Visible in the lower half of this image (blue arrows) are several overlapping impact craters. These craters have degraded walls, making it somewhat difficult to distinguish the boundaries between them. Several other craters in this image (white arrows) have only their rims visible, suggesting that they were flooded with volcanic lava. In contrast, the crater indicated by the yellow arrow preserves a set of central peaks (a common feature found in other craters), suggesting that it has been less altered than its flooded and degraded neighbors and likely formed more recently.

Global Topography: The Other Side

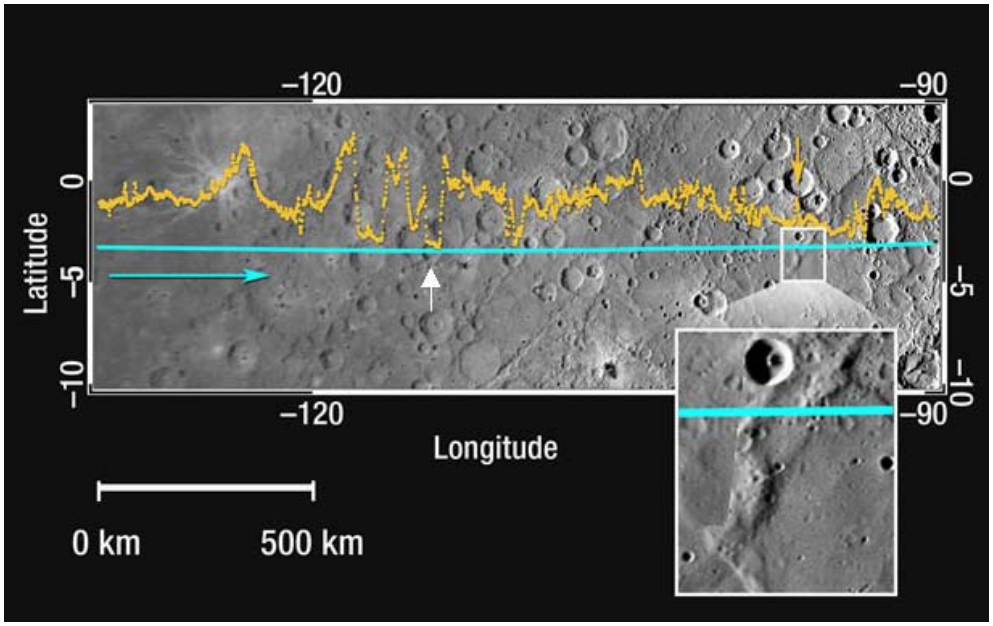
The MLA acquired a topographic profile of the opposite side of Mercury to that sampled by flyby 1. This hemisphere has about 70% of the range in topography sampled by MLA during the first Mercury flyby, and so this part of the equatorial hemisphere is less rugged than that sampled last January. Sampled topography includes a prominent wrinkle ridge and crater floors exhibiting a range of floor tilts.



This figure shows a 400-kilometer-long (250-mile-long) section of the MLA profile from MESSENGER's second Mercury flyby superposed on a high-resolution NAC departure mosaic acquired during the same encounter. The blue dots indicate the spacecraft ground track, and the yellow dots show the altimetry data points; the blue arrow shows the spacecraft's direction of travel. Near the center of this profile, the MLA track crosses two craters of comparable size but different depths (outlined by yellow circles in the lower left figure). The deeper crater in the center of the track is Machaut crater, while the unnamed crater to Machaut's east is considerably shallower. The lower right figure compares the depths of the two craters, indicating the difference measured by MLA with orange arrows. From the NAC mosaic it is apparent that the shallower crater has been filled, probably by volcanic material. By making such measurements systematically over the surface, it will be possible to measure the volumes of volcanic material erupted over Mercury's history.

Mercury's Dynamic Space Environment

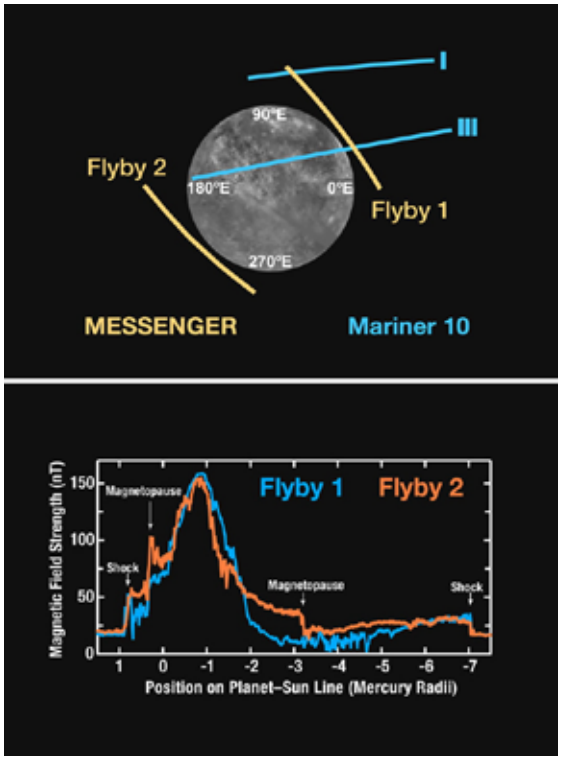
MESSENGER's full suite of particle and fields instruments was used again during the mission's second flyby. The flyby data have provided new science contributions and insights, even as the observations of the first two flybys taken together continue to provide more mysteries. The MESSENGER spacecraft was within Mercury's magnetosphere for about 30 minutes during each flyby, and magnetic field measurements provided more constraints on the internal field while also revealing more of the dynamics produced by its interplay with the magnetic field of the Sun.



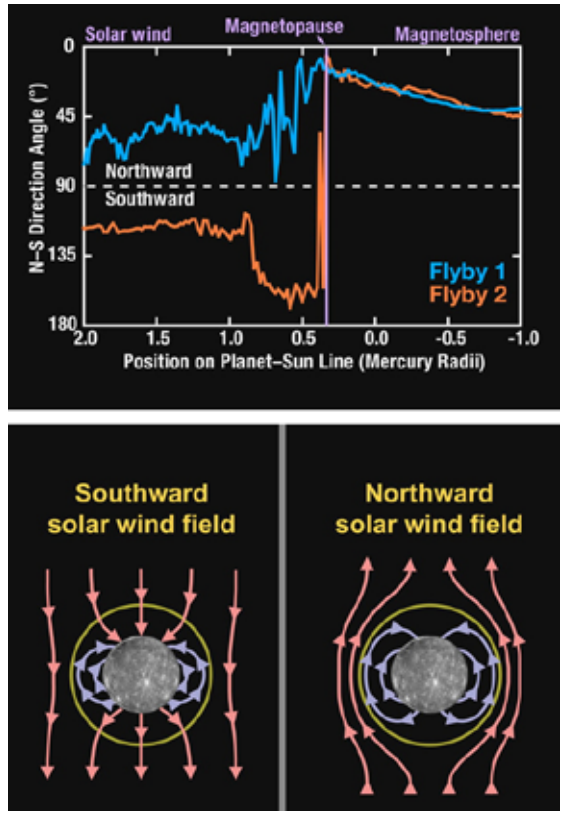
The figure shows about a 1,600 kilometer-long (1,000 mile-long) section of the MLA profile from MESSENGER's second Mercury flyby superimposed on a portion of the NAC approach mosaic from the mission's first Mercury encounter. The blue line indicates the spacecraft ground track, and the yellow dots show the altimetry data points; the blue arrow shows the spacecraft's direction of travel. Near longitude -97° (263°E) there is a wrinkle ridge nearly 1 kilometer high (yellow arrow and white box containing a magnified view) that indicates horizontal shortening of the crust, possibly the result of global contraction associated with the cooling of the interior. In the longitude range -120° to -115° (240°E to 245°E), the instrument sampled several craters of different depths with tilted floors (tilts of -0.5° to -0.2°; example indicated with a white arrow) that may have been the result of deformational processes.

Mercury's Global Magnetic Field

The MESSENGER data from the mission's second Mercury flyby provide the only data to date from the planet's western hemisphere and are therefore key to constraining the geometry of the planet's internal magnetic field. The magnetopause and bow shock crossings occurred where they were expected, so for this comparison the distance scale in the figure below for flyby 1 has been stretched so that these boundaries are coincident. Near closest approach, the flyby 2 data yield a field strength that is only a few percent lower than that obtained from flyby 1 observations. This remarkably close agreement means that the planetary magnetic moment is very nearly centered and is strongly aligned with the rotation axis, to within a tilt of 2°. This result favors models for Mercury's magnetic field generation that predict a magnetic moment aligned with the rotation axis.



MESSENGER Magnetometer observations for January 14, 2008, and October 6, 2008. The top figure shows a view of Mercury from above its north pole and the trajectories along which Magnetometer observations were made by the Mariner 10 (blue) and MESSENGER spacecraft (tan). The bottom figure graphs the magnetic field strengths measured during MESSENGER's first (blue) and second (orange) Mercury flybys, with a striking similarity in the maximum field strength measured during the two encounters. The observations are displayed versus distance along the planet-Sun line; closest approach occurred at about three-fourths of a Mercury radius to the nightside of the planet.



The top figure shows the angle that the magnetic field made with the northward direction for the outbound passes through the magnetopause and bow shock for the mission's first (blue) and second (orange) Mercury flybys. The bottom figure illustrates the profound difference in magnetic connection between Mercury and the solar wind when the magnetic field in the solar wind is southward (left) as for flyby 2 versus northward (right) as for flyby 1. These views from the Sun show a notional cross section of the magnetic lines of force in the dawn-dusk meridian plane.

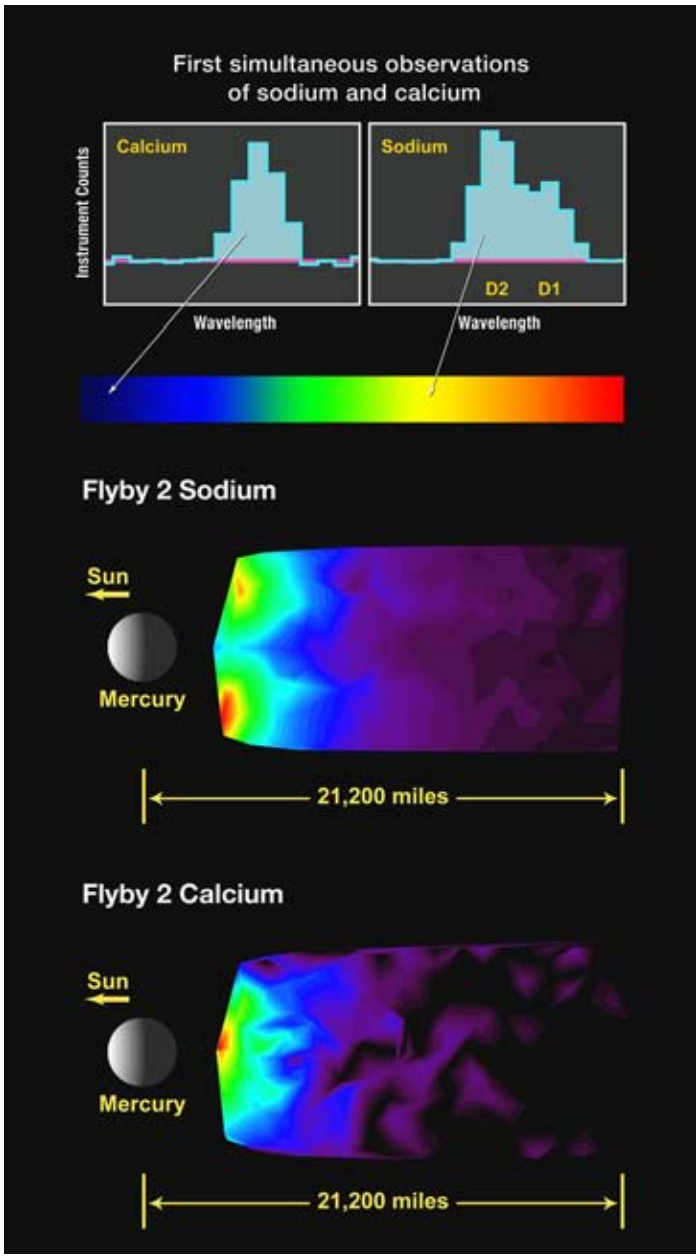
Solar Wind Control of Mercury's Active and Quiet Magnetosphere

Although the Sun has been relatively quiet during and between MESSENGER's first two transits of the planet's magnetosphere, magnetospheric activity varied greatly due to the changed conditions of the interplanetary magnetic field (IMF). Although the strengths of Mercury's internal magnetic field were comparable during the two flybys, the direction of the field outside the magnetosphere, imposed by the solar wind, was opposite: northward for flyby 1 and southward for flyby 2. The two encounters therefore present us with a nearly ideal "controlled" experiment to contrast Mercury's magnetosphere under these two opposite extremes in its interaction with the solar wind. For southward solar wind magnetic fields, the solar wind and planetary magnetic fields are connected over the poles and Mercury's magnetosphere is tightly coupled and strongly driven by the solar wind. By contrast, for northward solar wind magnetic fields, the magnetosphere is "closed" and there is minimal inter-connection between the solar wind and planetary magnetic fields.

The first two flybys demonstrated that Mercury's magnetosphere doesn't need an active Sun to display its own dramatic dynamics. The planet's magnetosphere was much more active during the second flyby due to the difference in the direction of the interplanetary magnetic field.

More Exosphere "Tails"

Ground-based telescopic observations identified calcium (Ca) as a component of Mercury's exosphere, and MESSENGER's first flyby provided an up-close measurement of the spatial structure of the sodium (Na) rail. The second flyby produced the first simultaneous "map" of the Na and Ca tails, both of which vary with solar conditions. In the upper part of the figure below, two histograms represent typical observations in the tail region of Mercury's exosphere for calcium (left) and sodium (right) atoms. Known as "spectral lines," these emissions have been scaled to approximately the same peak level for ease of comparison; however, the sodium emission is much brighter than that of calcium. Each emission occurs at a unique wavelength, with that of sodium in the "yellow" part of the visible spectrum and that of calcium in the "blue" part. The sodium emission is actually two very closely spaced emissions that are usually termed the D lines of sodium. The peaks of the two emissions are just separated (indicated by the D2 and D1 labels) in the figure. These are the same emissions that produce the yellow glow in sodium vapor lamps often used in street lighting. Although both sodium and calcium in Mercury's exosphere have been observed with ground-based telescopes on Earth, this is the first time that measurements of the two species have been obtained simultaneously. Atoms in the exosphere heavier than hydrogen and helium predominantly originate from the surface of Mercury, and a number of processes contribute to their release from the surface material. Differences in the spatial and temporal distributions of the exospheric constituents therefore provide insight into the relative importance of the processes that generate and maintain Mercury's exosphere.



In the upper part of this figure, two histograms represent typical observations in the tail region of Mercury's exosphere from calcium (left) and sodium (right) atoms. The middle and bottom panels show maps of Na and Ca in Mercury's neutral tail; in both panels north is up, and the Sun is to the left. The color scales show relative brightness of emissions.

The middle panel of the figure on the previous page shows the spatial distribution of sodium emission during MESSENGER's second flyby in the tail region of Mercury, which extends away from the planet in the anti-sunward direction. Because the observed emission intensity is related to the number of atoms along the line of sight, images such as this one are a measure of the density of the emitting species. The small-scale structures in these images may be artifacts of the viewing geometry and should not be given too much weight. More important are the broad-scale features that are composed of numerous observations and are therefore a better representation of the overall emission structure. The sodium emission shows two broad peaks that are located close to the planet to the north and south, and there is less emission near the equatorial region.

The bottom panel of the figure on the previous page shows the spatial distribution of calcium emission in the tail region of Mercury during the second flyby. In contrast to the sodium emission, the calcium emission is mostly symmetric about the equatorial region and less bright near polar regions. The spatial variations between the calcium and sodium distributions indicate that the processes controlling these two species are likely different.

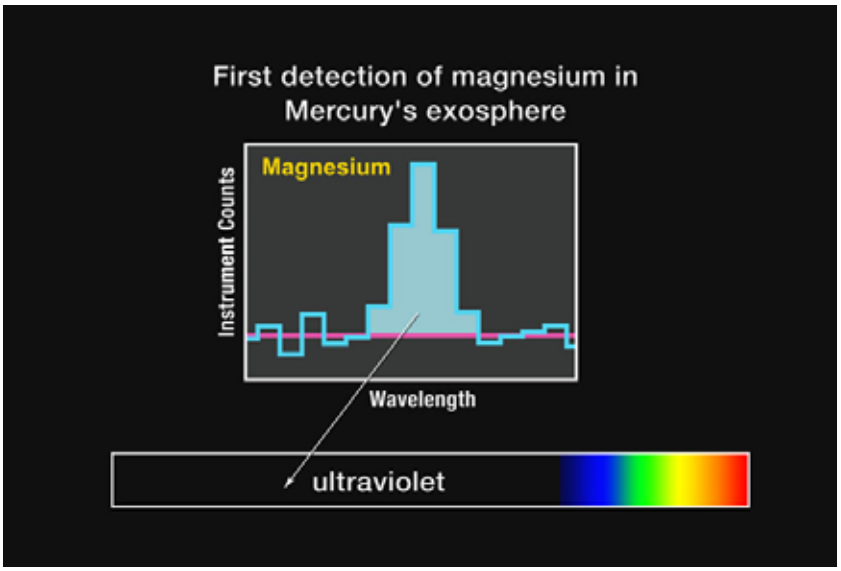
… and a Richer Composition as Well

MESSENGER's MASCS instrument must be "targeted" for spectral regions for specific species in Mercury's exosphere. During the second flyby, such targeting revealed the presence of magnesium (Mg) in the exosphere along with Na and Ca. The histogram in the figure below represents a typical MASCS observation in the tail region of Mercury's exosphere from magnesium atoms. These MASCS measurements mark the first time that magnesium has been detected in Mercury's exosphere. In contrast to emissions from sodium and calcium, magnesium emission occurs at a wavelength that is in the ultraviolet part of the spectrum. Magnesium cannot be observed from ground-based telescopes partly because ultraviolet light is completely obscured by Earth's atmosphere. Because exospheric atoms primarily originate at the surface of Mercury, the detection of magnesium in the exosphere provides evidence that magnesium is an important component of surface material, something that has been expected for years but until now had not been proven. As with calcium and sodium, the distribution of magnesium in Mercury's exosphere is a result of the processes that release the magnesium atoms from the surface and can provide valuable clues to the relative importance of each process.

Mercury: An Old World Seen in New Light

The two flybys of Mercury by MESSENGER in 2008 produced 2,500 images (1,213 on flyby 1 and 1287 on flyby 2) along with a host of other data, e.g., 3,617 MLA range measurements on flyby 1 and 4,388 on flyby 2, for a total data return of over 1.1 gigabytes. With MESSENGER already rewriting the textbooks on the innermost planet of the Solar System, a great deal more is to come, next with the third flyby and then with the orbital phase of the mission.

The sixth and last planetary flyby of MESSENGER (one of Earth, two of Venus, and three of Mercury) is crucial for lining up the trajectory of MESSENGER for orbit insertion

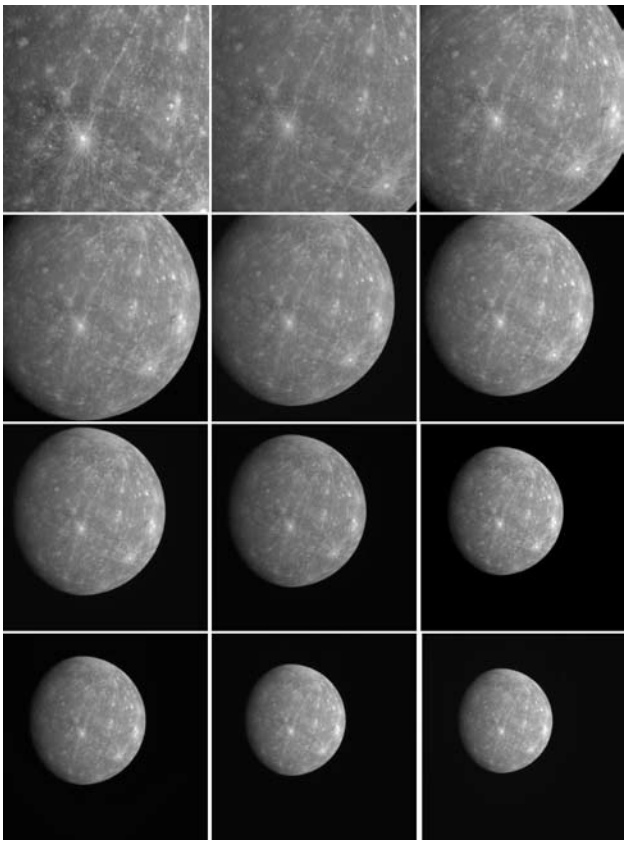


The histogram in this figure represents a typical MASCS observation in the tail region of Mercury's exosphere from magnesium atoms. These MASCS measurements mark the first time that magnesium has been detected in Mercury's exosphere.

in March 2011. Each Mercury flyby has extracted about 2 km/s of speed from MESSENGER as it rapidly circles the Sun to reach near-synchronicity with Mercury's own trajectory. Only by matching speeds sufficiently closely by means of these flybys is MESSENGER's own propulsion system capable of completing the final braking maneuver into orbit in March 2011.

The third flyby is currently scheduled for an altitude of 231.0 km (143.5 miles) at 9:53 p.m. UTC on September 29, 2009 at a distance of 0.3142 AU (29.20 million miles) from the Sun.

Collage of 12 images acquired by MESSENGER during its first two flybys of Mercury in 2008.



These images were taken by MESSENGER as the spacecraft departed Mercury after completing its second flyby on October 6, 2008. During this sequence, images were taken every five minutes. A portion of the same sequence, totaling 198 images in all, has also been made into a movie. MESSENGER will make its third and final flyby of Mercury on September 29, 2009, and will become the first spacecraft ever to orbit Mercury in March 2011.

Why Mercury?

Mercury, Venus, Earth, and Mars are the terrestrial (rocky) planets. Among these, Mercury is an extreme: the smallest, the densest (after correcting for self-compression), the one with the oldest surface, the one with the largest daily variations in surface temperature, and the least explored. Understanding this "end member" among the terrestrial planets is crucial to developing a better understanding of how the planets in our Solar System formed and evolved. To develop this understanding, the MESSENGER mission, spacecraft, and science instruments are focused on answering six key questions.

Key Science Questions

Question 1: Why is Mercury so dense?

Each of the terrestrial planets consists of a dense iron-rich core surrounded by a rocky mantle, composed largely of magnesium and iron silicates. The topmost layer of rock, the crust, formed from minerals with lower melting points than those in the underlying mantle, either during differentiation early in the planet's history or by later volcanic or magmatic activity. The density of each planet provides information about the relative sizes of the iron-rich core and the rocky mantle and crust, since the metallic core is much denser than the rocky components. Mercury's uncompressed density (what its density would be without compaction of its interior by the planet's own gravity) is about 5.3 g/cm^3, by far the highest of all the terrestrial planets. In fact, Mercury's density implies that at least 60% of the planet is a metal-rich core, a figure twice as great as for Earth, Venus, or Mars. To account for about 60% of the planet's mass, the radius of Mercury's core must be approximately 75% of the radius of the entire planet!

There are three major theories to explain why Mercury is so much denser and more metal-rich than Earth, Venus, and Mars. Each theory predicts a different composition for the rocks on Mercury's surface. According to one idea, before Mercury formed, drag by solar nebular gas near the Sun mechanically sorted silicate and metal grains, with the lighter silicate particles preferentially slowed and lost to the Sun; Mercury later formed from material in this region and is consequently enriched in metal. This process doesn't predict any change in the composition of the silicate minerals making up the rocky portion of the planet, just the relative amounts of metal and rock. In another theory, tremendous heat in the early nebula vaporized part of the outer rock layer of proto-Mercury and left the planet strongly depleted in volatile elements. This idea predicts a rock composition poor in easily evaporated elements like sodium and potassium. The third idea is that a giant impact, after proto-Mercury had formed and differentiated, stripped off the primordial crust and upper mantle. This idea predicts that the present-day surface is made of rocks highly depleted in those elements that would have been concentrated in the crust, such as aluminum and calcium.

MESSENGER will determine which of these ideas is correct by measuring the composition of the rocky surface. X-ray, gamma-ray, and neutron spectrometers will measure the elements present in the surface rocks and determine if volatile elements are depleted or if elements that tend to be concentrated in planetary crusts are deficient. A visible-infrared spectrograph will determine which minerals are present and will permit the construction of mineralogical maps of the surface. Analysis of gravity and topography measurements will provide estimates of the thickness of Mercury's crust. To make these challenging, first-ever measurements of Mercury's surface composition and crustal characteristics, these instruments will need to accumulate many observations of the surface. MESSENGER's three Mercury flybys provide opportunities to test the instrument operations, but numerous measurements from an orbit around Mercury are needed to determine accurately the surface composition. Once in orbit, together, these measurements will enable MESSENGER to distinguish among the different proposed origins for Mercury's high density and, by doing so, gain insight into how the planet formed and evolved.

Question 2: What is the geologic history of Mercury?

Prior to MESSENGER, only 45% of Mercury's surface had been seen by spacecraft during the Mariner 10 mission. Combining the Mariner 10 photos with the images from MESSENGER's first and second Mercury flybys, about 90% of the surface of Mercury has been seen in detail. It is now possible for the first time to begin to investigate Mercury's geologic history on a global basis.

Much of Mercury's surface appears cratered and ancient, with a resemblance to the surface of Earth's Moon.

Slightly younger, less cratered plains sit within and between the largest old craters. Many of these plains are volcanic, on the basis of their age relative to nearby large impact features and other indicators of volcanic activity. .

Mercury's tectonic history is unlike that of any other terrestrial planet. On the surface of Mercury, the most prominent features due to tectonic forces are long, rounded, lobate scarps or cliffs, some over a kilometer in height and hundreds of kilometers in length. These giant scarps are believed to have formed as Mercury cooled and the entire planet contracted on a global scale. Understanding the formation of these scarps thus provides the potential to gain insight into the thermal history and interior structure of Mercury.

Once in orbit, MESSENGER will bring a variety of investigations to bear on Mercury's geology in order to determine the sequence of processes that have shaped the surface. The X-ray, gamma-ray, and visible-infrared spectrometers will determine the elemental and mineralogical makeup of rock units composing the surface. The cameras will image Mercury's surface in color and at a typical imaging resolution that surpasses that of most Mariner 10 pictures. Nearly all of the surface will be imaged in stereo to determine the planet's global topographic variations and landforms; the laser altimeter will measure the topography of surface features even more precisely in the northern hemisphere. Comparing the topography with the planet's gravity field, measured by tracking the MESSENGER spacecraft, will allow determinations of local variations in the thickness of Mercury's crust. This large breadth and depth of data returned by MESSENGER will enable the reconstruction of the geologic history of Mercury.

Question 3: What is the nature of Mercury's magnetic field?

Mercury's magnetic field and the resulting magnetosphere, produced by the interaction of Mercury's magnetic field with the solar wind, are unique in many ways. Perhaps one of the most noteworthy observations about Mercury's magnetic field is that the small planet has one. Mercury's magnetic field is similar in its "dipole" shape to Earth's magnetic field, which resembles the field that would be produced if there was a giant bar magnet at the center of the planet. In contrast, Venus, Mars, and the Moon do not show evidence for intrinsic dipolar magnetic fields, but the Moon and Mars have evidence for local magnetic fields centered on different rock deposits.

Earth's magnetosphere is very dynamic and constantly changes in response to activity of the Sun, including the solar wind and solar flares. We see the effects of these dynamics on the ground as they affect power grids and electronics, causing blackouts and interference with radios and telephones. Mercury's magnetosphere was shown by Mariner 10 to experience similar dynamics; understanding those variations will help us understand the interaction of the Sun with planetary magnetospheres in general.

Although Mercury's magnetic field is thought to be a miniature version of Earth's, Mariner 10 didn't measure Mercury's field well enough to characterize it. There was even considerable uncertainty in the strength and source of the magnetic field after Mariner 10. MESSENGER's first two Mercury flybys confirmed that there is a global magnetic field on Mercury, and that the field has a strong dipolar component nearly aligned with the planet's spin axis. Mercury's magnetic field most likely arises from fluid motions in an outer liquid portion of Mercury's metal core. There is debate, however, about the molten fraction of the core as well as on whether the field is driven by compositional or thermal differences. These different ideas for the driving force behind Mercury's magnetic field predict slightly different field geometries, so careful measurements by spacecraft can distinguish among current theories.

MESSENGER's Magnetometer will characterize Mercury's magnetic field in detail from orbit over four Mercury years (each Mercury year equals 88 Earth days) to determine its precise strength and how that strength varies with position and altitude. The effects of the Sun on magnetospheric dynamics will be measured by the Magnetometer and by the Energetic Particle and Plasma Spectrometer. MESSENGER's highly capable instruments and broad orbital coverage will greatly advance our understanding of both the origin of Mercury's magnetic field and the nature of its interaction with the solar wind.

Question 4: What is the structure of Mercury's core?

As discussed in Questions 1 and 3, Mercury has a very large iron-rich core and a global magnetic field; this

information was first gathered by the Mariner 10 flybys. More recently, Earth-based radar observations of Mercury have also determined that at least a portion of the large metal core is still liquid. Having at least a partially molten core means that a very small but detectable variation in the spin rate of Mercury has a larger amplitude because of decoupling between the solid mantle and the liquid core. Knowing that the core has not completely solidified, even as Mercury has cooled over billions of years since its formation, places important constraints on the planet's thermal history, evolution, and core composition.

However, these constraints are limited because of the low precision of current information on Mercury's gravity field from the Mariner 10 flybys and MESSENGER's first two flybys, currently the only gravity measurements available for Mercury. Fundamental questions about Mercury's core remain to be explored, such as its composition. A core of pure iron would be completely solid today, due to the high melting point of iron. However, if other elements, such as sulfur, are also present in Mercury's core, even at only a level of a few percent, the melting point is lowered considerably, allowing Mercury's core to remain at least partially molten. Constraining the composition of the core is intimately tied to understanding what fraction of the core is liquid and what fraction has solidified. Is there just a very thin layer of liquid over a mostly solid core, or is the core completely molten? Addressing questions such as these can also provide insight into the current thermal state of Mercury's interior, which is very valuable information for determining the evolution of the planet.

Using the laser altimeter in orbit, MESSENGER will verify the presence of a liquid outer core by measuring Mercury's libration. Libration is the slow, 88-day wobble of the planet around its rotational axis. The libration of the rocky outer part of the planet will be twice as large if it is floating on a liquid outer core than if it is frozen to a solid core. By radio tracking of the spacecraft in orbit, MESSENGER will also determine the gravity field with much better precision than can be accomplished during flybys. The libration experiment, when combined with improved measurements of the gravity field, will provide information on the size and structure of the core.

Question 5: What are the unusual materials at Mercury's poles?

Mercury's axis of rotation is oriented nearly perpendicular to the planet's orbit, so that in polar regions sunlight strikes the surface at a near-constant grazing angle. Some of the interiors of large craters at the poles are thus permanently shadowed and perpetually very cold. Earth-based radar images of the polar regions show that the floors of large craters are highly reflective at radar wavelengths, unlike the surrounding terrain. Furthermore, the radar-bright regions are consistent in their radar properties with the polar cap of Mars and the icy moons of Jupiter, suggesting that the material concentrated in the shadowed craters is water ice. The idea of water ice being stable on the surface of the planet closest to the Sun is an intriguing suggestion.

The temperature inside these permanently shadowed craters is believed to be low enough to allow water ice to be stable for the majority of the observed deposits. Ice from infalling comets and meteoroids could be cold-trapped in Mercury's polar deposits over billions of years, or water vapor might outgas from the planet's interior and freeze at the poles. A few craters at latitudes as low as 72° N have also been observed to contain radar-bright material in their interiors, and at these warmer latitudes, maintaining stable water ice for longer periods of time may be more difficult; a recent comet impact, in the last few million years, delivering water to Mercury may be required. Alternatively, it has been suggested that the radar-bright deposits are not water ice but rather consist of a different material, such as sulfur. Sulfur would be stable in the cold traps of the permanently shadowed crater interiors, and the source of sulfur could be either meteoritic material or the surface of Mercury itself. It has also been proposed that the naturally occurring silicates that make up the surface of Mercury could produce the observed radar reflections when maintained at the extremely low temperatures present in the permanently shadowed craters.

MESSENGER's three flybys of Mercury pass nearly over the equator, which doesn't allow viewing of Mercury's poles. Once in orbit around Mercury, however, MESSENGER's neutron spectrometer will search for hydrogen in any polar deposits, the detection of which would suggest that the polar deposits are water-rich. The ultraviolet spectrometer and energetic particle

and plasma spectrometer will search for the signatures of hydroxide or sulfur in the tenuous vapor over the deposits. The laser altimeter will provide information about the topography of the permanently shadowed craters. Understanding the composition of Mercury's polar deposits will clarify the inventory and availability of volatile materials in the inner Solar System.

Question 6: What volatiles are important at Mercury?

Mercury is surrounded by an extremely thin envelope of gas. It is so thin that, unlike the atmospheres of Venus, Earth, and Mars, the molecules surrounding Mercury don't collide with each other and instead bounce from place to place on the surface like many rubber balls. This tenuous atmosphere is called an "exosphere."

Seven elements are known to exist in Mercury's exosphere: (1) hydrogen, (2) helium, (3) oxygen, (4) sodium, (5) potassium, (6) calcium, and, as discovered during MESSENGER's second flyby, (7) magnesium. The observed exosphere is not stable on timescales comparable to the age of Mercury, and so there must be sources for each of these elements. High abundances of hydrogen and helium are present in the solar wind, the stream of hot, ionized gas emitted by the Sun. The other elements are likely from material impacting Mercury, such as micrometeoroids or comets, or directly from Mercury's surface rocks. Several different processes may have put these elements into the exosphere, and each process yields a different mix of the elements: vaporization of rocks by impacts, evaporation of elements from the rocks in sunlight, sputtering by solar wind ions, or diffusion from the planet's interior. Strong variability of the composition of Mercury's exosphere has been observed, suggesting the interaction of several of these processes.

MESSENGER will determine the composition of Mercury's exosphere using its ultraviolet spectrometer and Energetic Particle and Plasma Spectrometer. The exosphere composition measured by these instruments will be compared with the composition of surface rocks measured by the X-ray, gamma-ray, and neutron spectrometers. As MESSENGER orbits Mercury, variations in the exosphere's composition will be monitored. The combination of these measurements will elucidate the nature of Mercury's exosphere and the processes that contribute to it.

Learn More

For additional, detailed information about the science questions driving the MESSENGER mission, check out the articles posted at http://messenger.jhuapl.edu/the_mission/publications.html.

Mercury's Visitors

Mariner 10

Most of what we know about Mercury today comes from Mariner 10's three flyby visits in 1974 and 1975, plus MESSENGER's first two flybys in January and October 2008. The Mariner 10 flybys weren't the NASA mission's only historic moments; Mariner 10 was also the first spacecraft to use the gravitational pull of one planet (Venus) to reach another and the first to study two planets up close.

Carrying two TV cameras with filter wheels, an infrared radiometer, a plasma experiment, a magnetometer, a charged-particle detector, extreme-ultraviolet spectrometers, and a radio science experiment, Mariner 10 was launched toward Venus by an Atlas Centaur 34 on November 3, 1973. After flying past Venus on February 5, 1974 – and snapping the first close-up images of the planet's upper clouds – the spacecraft headed for Mercury in an orbit around the Sun. That trajectory brought it past Mercury three times – on March 29 and September 21, 1974, and March 16, 1975 – each affording views of the same side, and while the planet was at aphelion, its farthest point from the Sun.

The spacecraft's closest passes – respectively occurring at 703 km, 48,069 km, and 327 km – gave it different vantages on approach and departure. Mariner 10 mapped 45% of Mercury's surface at a scale of approximately 1 km, revealing a landscape battered with impact craters and a fascinating mix of smooth and rough terrain. It discovered a global magnetic field and a thin atmosphere, and confirmed that Mercury, thanks to a large, iron-rich core, has the highest uncompressed density of any planet.

Mariner 10's reconnaissance whetted scientists' appetites to learn more about the innermost planet, and its results helped form the questions MESSENGER is now answering three decades later.

Mariner 10 liftoff in 1973 (top) and MESSENGER liftoff in 2004 (bottom).

Future Missions

At the end of the next decade, MESSENGER will have company in its study of Mercury. The BepiColombo mission, a collaboration between the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA), will place a pair of spacecraft in orbit around Mercury, one to map the planet and the other to study the magnetosphere. The mission is named for the late Italian mathematician and engineer Guiseppe (Bepi) Colombo, who suggested to NASA the flight path that allowed Mariner 10 to fly by Mercury three times. The two spacecraft are scheduled for launch in 2014 and for arrival at Mercury in 2020.

Other Links

The Web and your local library (or bookstore) offer several sources of information on the Mariner 10 mission, Mercury, and the MESSENGER mission, including:

The Voyage of Mariner 10: Mission to Venus and Mercury, by James A. Dunne and Eric Burgess, Jet Propulsion Laboratory, SP-424, 1978 – http://history.nasa.gov/SP-424/sp424.htm

Mariner 10 Archive Project (Mark Robinson, Arizona State University) – http://ser.sese.asu.edu/merc.html

The SP-423 Atlas of Mercury On Line (NASA history website) – http://history.nasa.gov/SP-423/mariner.htm

Flight to Mercury, by Bruce Murray and Eric Burgess, Columbia University Press, 1977 (ISBN 0-231-03996-4)

Mercury, by Faith Vilas, Clark Chapman, and Mildred Shapley Matthews, University of Arizona Press, 1988 (ISBN 0-8165-1085-7)

Exploring Mercury, by Robert Strom and Ann Sprague, Springer-Praxis Books, 2003 (ISBN 1-85233-731-1)

The MESSENGER Mission to Mercury, by D. L. Domingue and C. T. Russell, Springer, 2007.

Mission Overview

Cruise Trajectory

The MESSENGER mission takes advantage of an ingenious trajectory design, lightweight materials, and miniaturization of electronics, all developed in the three decades since Mariner 10 flew past Mercury in 1974 and 1975. The compact orbiter, fortified against the searing conditions near the Sun, will investigate key questions about Mercury's characteristics and environment with a set of seven scientific instruments.

On a 7.9-billion-km journey that includes more than 15 loops around the Sun, the spacecraft's trajectory includes one pass by Earth, two by Venus, and three by Mercury, before a propulsive burn will ease it into orbit around its target planet. The Earth flyby in August 2005, along with the Venus flybys in October 2006 and June 2007 and the first two Mercury flybys in January 2008 and October 2008, used the pull of each planet's gravity to guide MESSENGER toward Mercury's orbit. The remaining Mercury flyby in September 2009 will further adjust MESSENGER's trajectory while also providing opportunities for the spacecraft to gather important science observations in advance of the mission's orbital phase.

The combined effect of the six gravity assists from three planets and five deterministic deep-space maneuvers (DSMs) – using the bipropellant Large Velocity Adjust (LVA) engine of the spacecraft and the influence of the Sun – accelerates the spacecraft from an average speed around the Sun of 30 km/s (the Earth's average speed around the Sun) to 48 km/s (Mercury's average speed around the Sun).

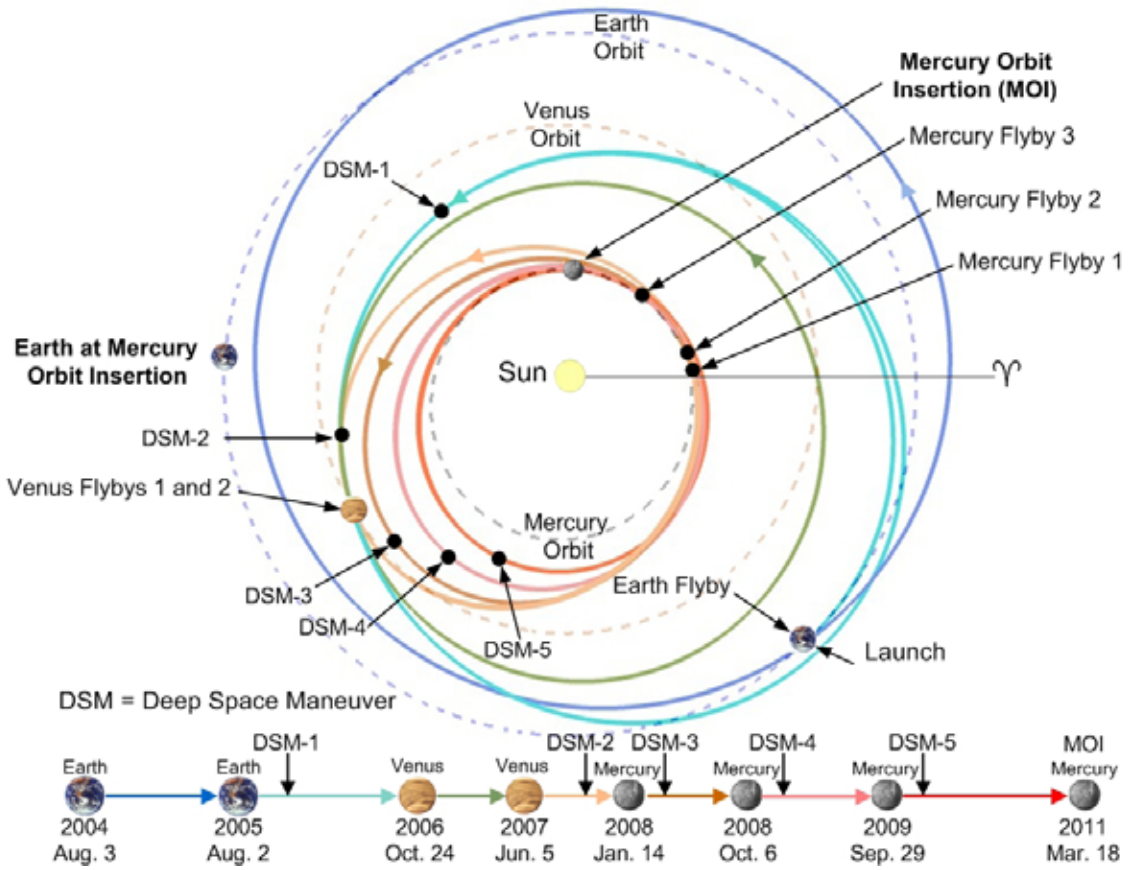
The cruise phase of the mission concludes in March 2011, when the spacecraft will execute the Mercury orbit insertion (MOI) maneuver, slowing the spacecraft and allowing it to be captured into orbit around Mercury.

Getting a Boost

For a gravity assist, a spacecraft flies close to a planet and trades with the planet's orbital momentum around the Sun. Depending on the relative difference in mass between the planet and the spacecraft, as well as the distance between the two, this exchange of momentum can impart a substantial change in spacecraft speed. Since the spacecraft's mass is negligible compared with that of the planet, this process has a negligible effect on the planet's orbit around the Sun. But the spacecraft receives a great boost on the way to its next destination.

Gravity-assist maneuvers can be used to speed a spacecraft up or slow a spacecraft down. Closest approach distance, direction, and the velocity of a spacecraft relative to the planet's velocity all affect the acceleration magnitude and direction change of the spacecraft's trajectory. The greatest change in a spacecraft's speed and direction occurs when a slow-moving spacecraft approaches just above the surface or cloud tops of a massive planet. The least change in a spacecraft's speed and direction occurs when a fast-moving spacecraft approaches a small planet from a great distance.

Earth to Mercury



MESSENGER cruise trajectory from the Earth to Mercury with annotation of critical flyby and maneuver events. View looks down from the ecliptic north pole.

Multiple Flybys

Mariner 10 flew past Venus to reach Mercury, but the idea of multiple Venus/Mercury flybys to help a spacecraft "catch" Mercury and begin orbiting the planet came years later, when Chen-wan Yen of NASA's Jet Propulsion Laboratory developed the concept in the mid-1980s. MESSENGER adopted this mission design approach; without these flybys, MESSENGER would move so fast past Mercury (about 10 km/s) that no existing propulsion system could slow it down sufficiently for it to be captured into orbit.

Launch

MESSENGER launched from complex 17B at Cape Canaveral Air Force Station, Fla., on a three-stage Boeing Delta II expendable launch vehicle on August 3, 2004. The Delta II 7925-H (heavy lift) model was the largest allowed for NASA Discovery missions. It features a liquid-fueled first stage with nine strap-on solid boosters, a second-stage liquid-fueled engine, and a third-stage solid-fuel rocket. With MESSENGER secured in a 9.5-m fairing on top, the launch vehicle was about 40 m tall.

The launch vehicle imparted an excess launch energy per mass (usually denoted by C_3 and equal to the excess over what is required for Earth escape) of approximately 16.4 km^2/s^2 to the spacecraft, setting up the spacecraft for a return pass by the Earth approximately one year from launch.

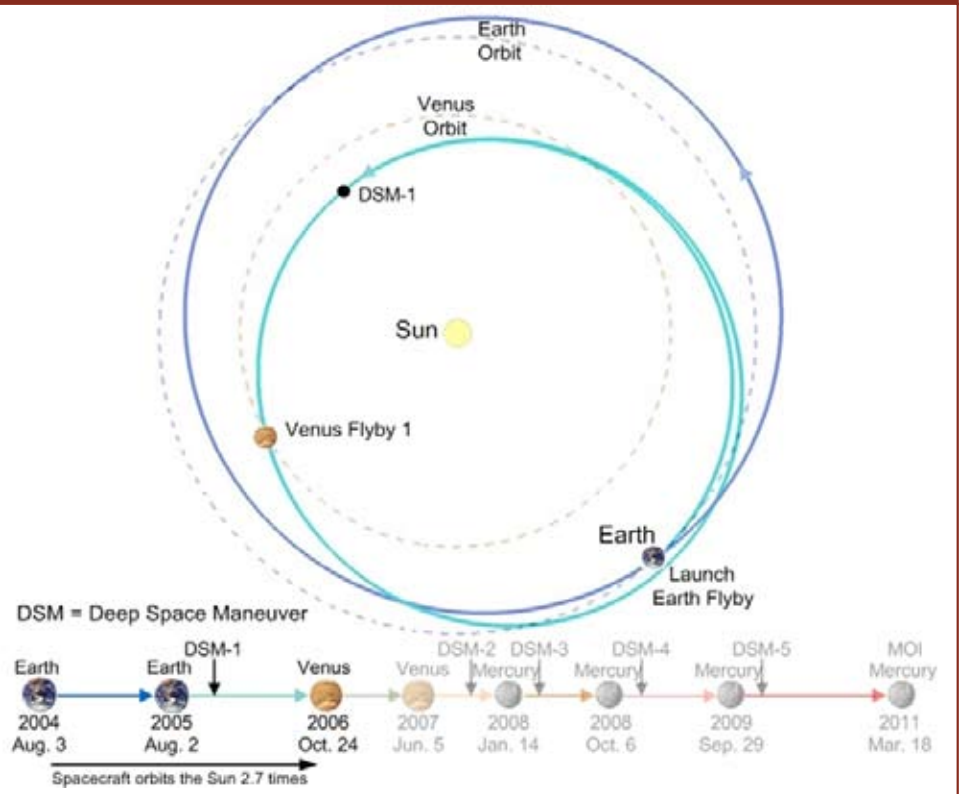
MESSENGER launch from Cape Canaveral Air Force Station, Fla., on August 3, 2004, at 2:15 a.m. EDT.

Team members in the MESSENGER Mission Operations Center at APL watch the spacecraft launch from Cape Canaveral. The team began operating the spacecraft less than an hour later, after MESSENGER separated from the launch vehicle.

Earth Flyby Highlights

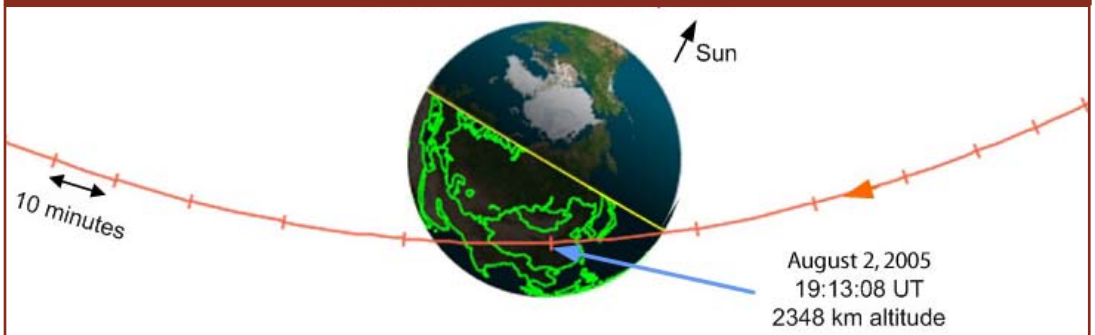
MESSENGER swung by its home planet on August 2, 2005, for a gravity assist that propelled it deeper into the inner Solar System. MESSENGER's systems performed flawlessly as the spacecraft swooped around Earth, coming to a closest approach point of about 2,347 km over central Mongolia at 3:13 p.m. EDT. The spacecraft used the tug of Earth's gravity to change its trajectory significantly, bringing its average orbital distance nearly 29 million km closer to the Sun and sending it toward Venus for gravity assists in 2006 and 2007.

Earth to Venus



North ecliptic pole view of the trajectory between Earth and the first Venus flyby. Dashed lines depict the orbits of Earth and Venus. Timeline fading helps emphasize primary events.

Earth Flyby



View of the Earth flyby trajectory from above northern Asia. Major country borders are outlined in green on Earth's nightside. The yellow line marks the position of the day/night or dawn/dusk terminator.

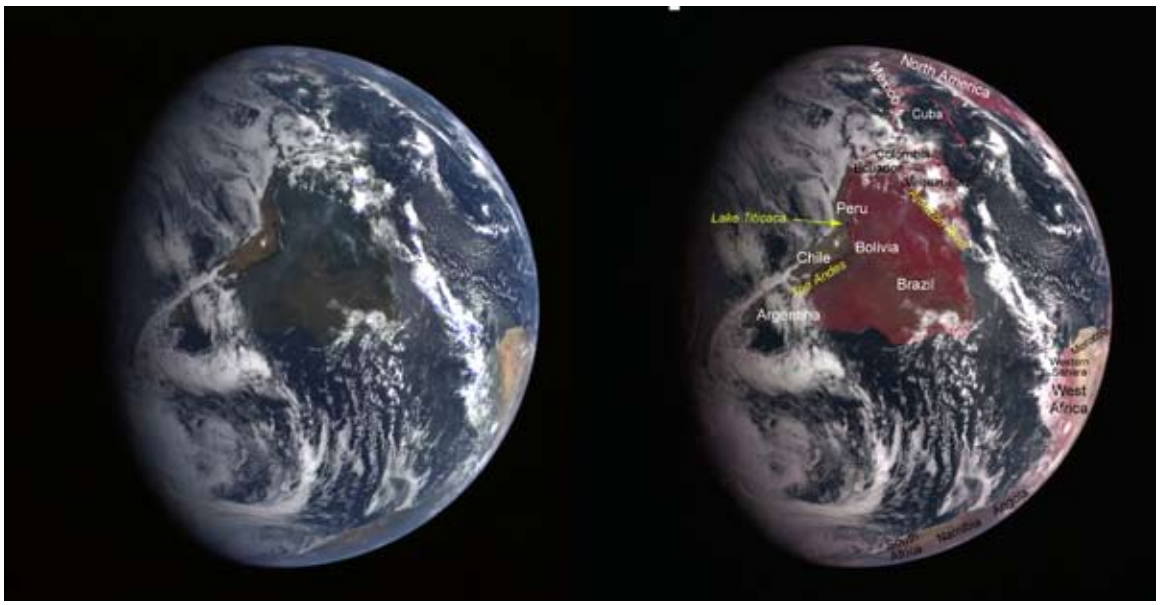
MESSENGER's main camera snapped several approach shots of Earth and the Moon, including a series of color images that science team members strung into a "movie" documenting MESSENGER's departure. On approach, the Mercury Atmospheric and Surface Composition Spectrometer (MASCS) also made several scans of the Moon in conjunction with the camera observations, and during the flyby the particle and magnetic field instruments spent several hours making measurements in Earth's magnetosphere.

The close flyby of Earth and the Moon allowed MESSENGER to give its two Mercury Dual Imaging System (MDIS) cameras a thorough workout. The images helped the team understand fully how the cameras operate in flight in comparison with test results obtained in the laboratory before launch. Images were taken in full color and at different resolutions, and the cameras passed their tests.

Not only were these pictures useful for carefully calibrating the imagers for the spacecraft's Mercury encounters, they also offered a unique view of Earth. Through clear skies over much of South America, features such as the Amazon, the Andes, and Lake Titicaca are visible, as are huge swaths of rain forest.

The pictures from MESSENGER's flyby of Earth include "natural" color and infrared views of North and South America; a peek at the Galápagos Islands through a break in the clouds; and the movie of the rotating Earth, taken as MESSENGER sped away from its home planet.

Twins Image

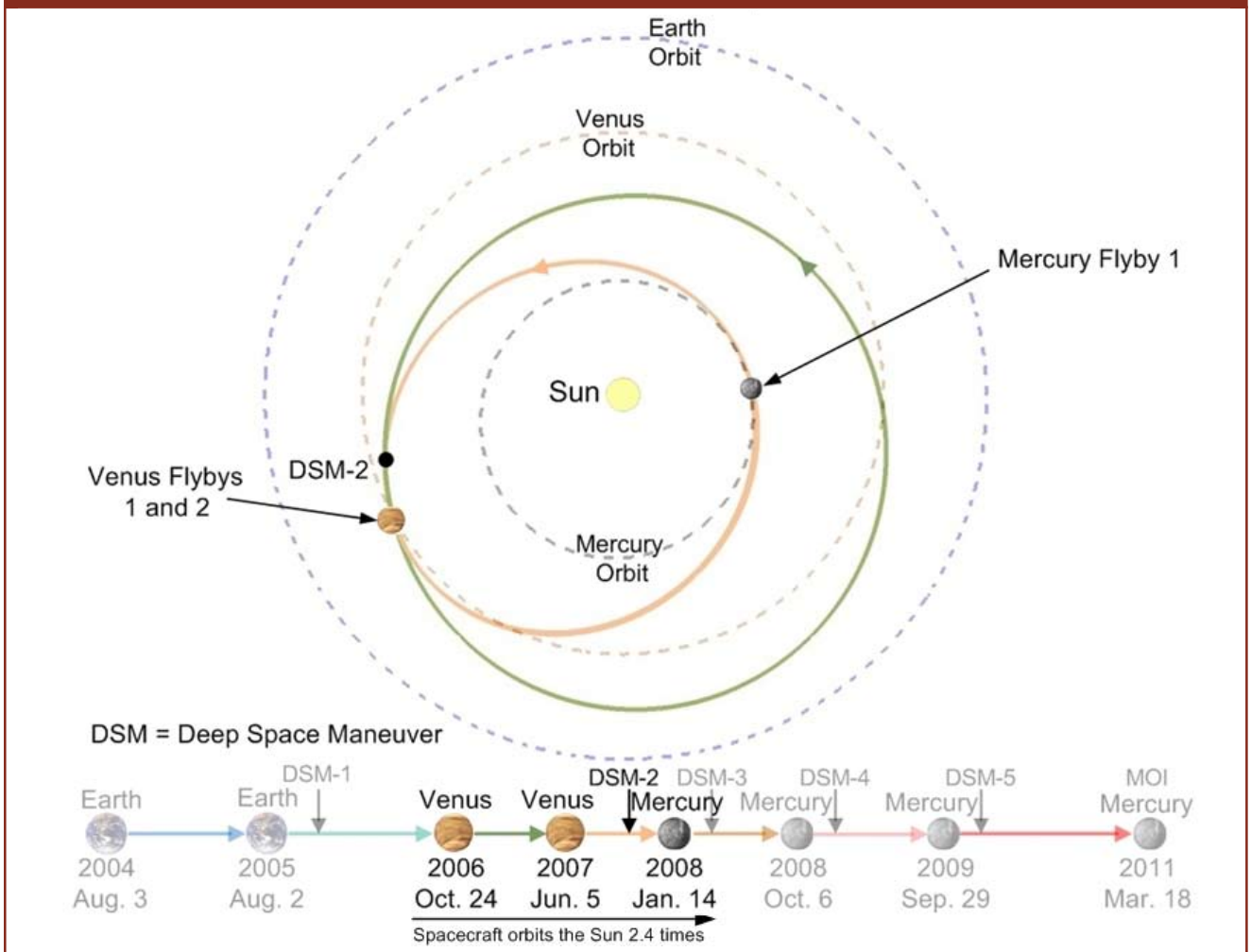


Using various combinations of filters in the optical path, MESSENGER's camera can obtain a mix of red, green, and blue (RGB) light in various proportions to create a full spectrum of colors. Infrared images are visualized by substituting one of the RGB components. On the left is a "normal" color image of the Earth. On the right, the red component is the 750-nm (infrared) band, and green and blue are formed from the 630-nm and the 560-nm bands. Despite the substitution of only one band, the results are dramatically different. Continental areas are mostly red due to the high reflectance of vegetation in the near-infrared. Short-wavelength light (blue) is easily scattered in Earth's atmosphere, producing our blue skies, but also obscuring the surface from MESSENGER's viewpoint. Infrared light is not easily scattered, so images of the Earth remain sharp. The red coloring in the center of the image is a reflection of the Brazilian rain forests and other vegetation in South America.

Venus Gravity Assists

MESSENGER has flown by Venus twice using the tug of the planet's gravity to change its trajectory, to shrink the spacecraft's orbit around the Sun, and to bring it closer to Mercury.

Venus to Mercury

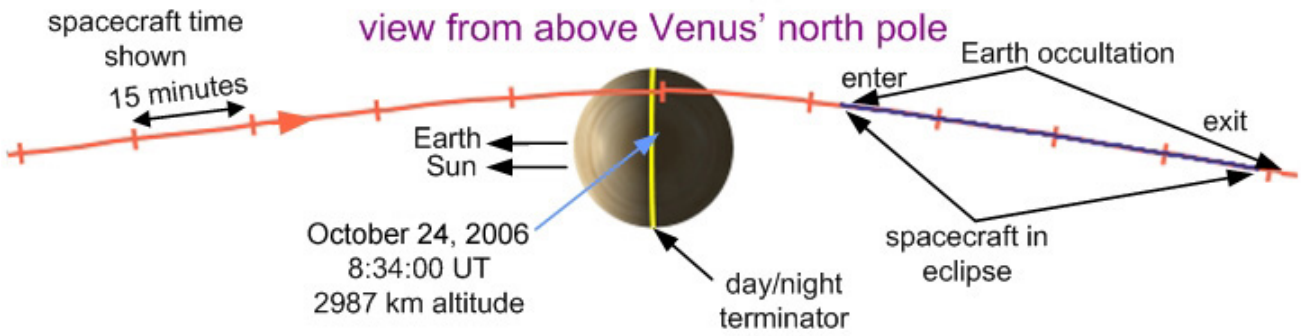


North ecliptic pole view of the trajectory between the first Venus flyby and the first Mercury flyby. Dashed lines depict the orbits of Earth, Venus, and Mercury. Timeline fading helps emphasize primary events.

During the first Venus flyby on October 24, 2006, the spacecraft came within 2,987 km of the surface of Venus. Shortly before the encounter, MESSENGER entered superior solar conjunction, where it was on the opposite side of the Sun from Earth and during which reliable communication between MESSENGER and mission operators was not possible. In addition, during the flyby the spacecraft experienced the mission's first and longest eclipse of the Sun by a planet. During the eclipse, which lasted approximately 56 minutes, the spacecraft's solar arrays were in the shadow of Venus and MESSENGER operated on battery power.

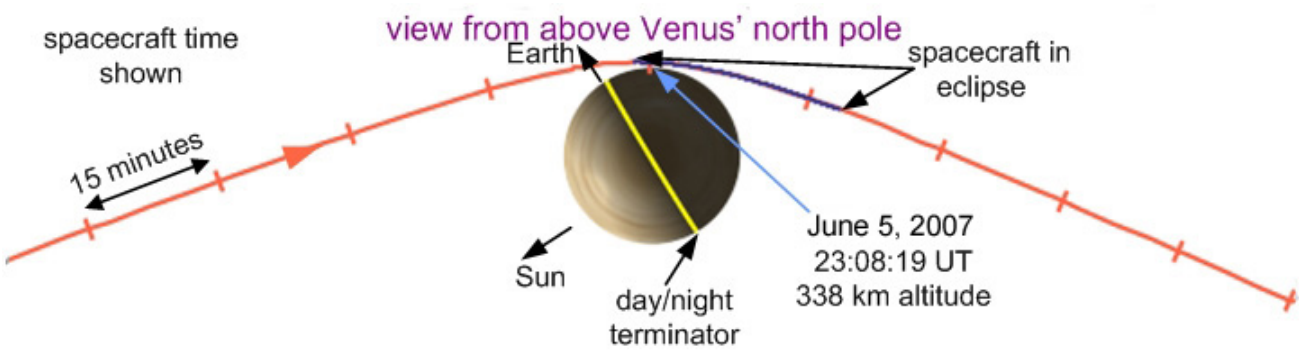
MESSENGER swung by Venus for the second time on June 5, 2007, speeding over the planet's cloud tops at a relative velocity of more than 48,000 km/hour and passing within 338 km of its surface near the boundary between the lowland plains of Rusalka Planitia and the rifted uplands of Aphrodite Terra. The maneuver sharpened the spacecraft's aim toward the first encounter with Mercury and presented a special opportunity to calibrate several of its science instruments and learn something new about Earth's nearest neighbor.

Venus Flyby 1



View of the first Venus flyby trajectory from above the planet's northern pole. The yellow line marks the position of the day/night or dawn/dusk terminator. Closest approach time listed is in local spacecraft time, not accounting for the one-way light time for the signals to reach the Earth.

Venus Flyby 2



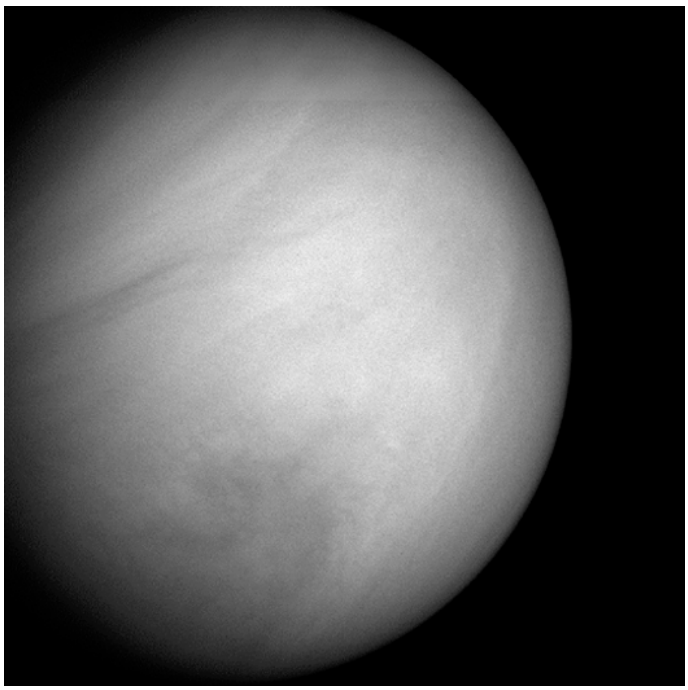
View of the second Venus flyby trajectory from above the planet's northern pole. The yellow line marks the position of the day/night or dawn/dusk terminator. Closest approach time listed is in local spacecraft time, not accounting for the one-way light time for the signals to reach the Earth.

All of the MESSENGER instruments operated during the flyby. The camera system imaged the nightside in near-infrared bands and obtained color and higher-resolution monochrome mosaics of both the approaching and departing hemispheres. The Ultraviolet and Visible Spectrometer on the MASCS instrument obtained profiles of atmospheric species on the day and nightsides as well as observations of the exospheric tail on departure.

The MASCS Visible and Infrared Spectrograph observed the Venus dayside near closest approach to gather compositional information on the upper atmosphere and clouds, and the Mercury Laser Altimeter (MLA) carried out passive radiometry at 1,064 nm and attempted to range to the Venus upper atmosphere and clouds for several minutes near closest approach. The Gamma-Ray and Neutron Spectrometer (GRNS) instrument observed gamma-rays and neutrons from Venus' atmosphere, providing information for planning the upcoming Mercury flybys and for calibration from a source of known composition.

The European Space Agency's Venus Express mission was operating at the time of the flyby, permitting the simultaneous observation of the planet from two independent spacecraft, a situation of particular value for characterization of the particle-and-field environment at Venus. MESSENGER's Energetic Particle and Plasma Spectrometer (EPPS) observed charged particle acceleration at the Venus bow shock and elsewhere, and the Magnetometer (MAG) measured the upstream interplanetary magnetic field (IMF), bow shock signatures, and pick-up ion waves as a reference for energetic particle and plasma observations by both spacecraft. The encounter also enabled two-point measurements of IMF penetration into the Venus ionosphere, primary plasma boundaries, and the near-tail region.

Venus 2 Approach



Approach image taken through the 630-nm filter (stretched). Global circulation patterns in the clouds are clearly visible.

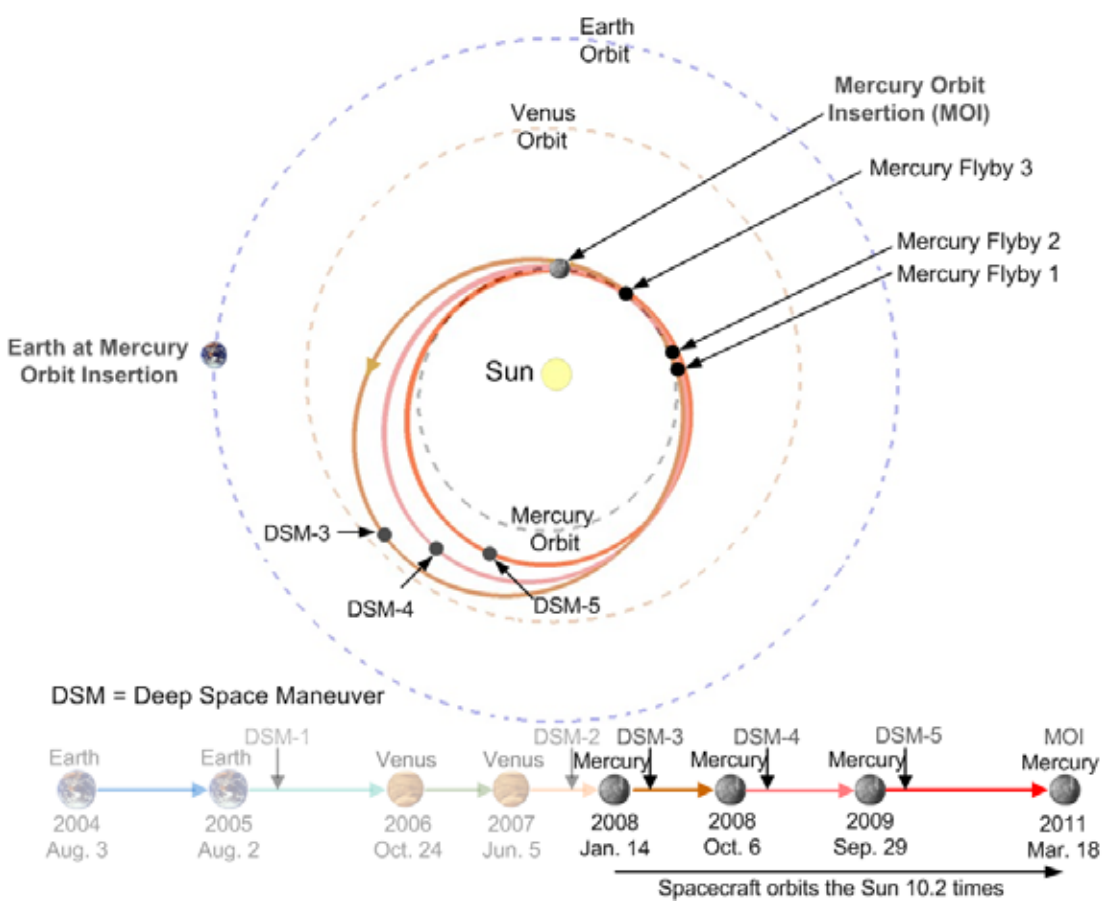
Interplanetary Golf

The MESSENGER spacecraft flew within 3.7 km of the targeted aim point during the approach to the second Venus encounter, the interplanetary equivalent of hitting a hole-in-one.

Flying by Mercury

On January 14, 2008, at 19:04:39 UTC (2:04:39 p.m. EST) the MESSENGER spacecraft executed its first Mercury flyby, passing over the uncharted surface of the planet at an altitude of 201.4 km, an even more accurate aim than for the second Venus flyby. The primary purpose of this activity was to shrink the orbital period of the spacecraft around the Sun by 11 days, bringing MESSENGER's orbit closer to Mercury's orbit. On October 6th, 2008, at 08:40:22 UTC (4:40:22 EDT) the MESSENGER spacecraft executed its second Mercury flyby, passing above the surface at an altitude of 199.4 km, within a phenomenal 600 meters of the planned flyby altitude! Although the flyby enabled direct observation of additional previously unobserved planetary surface features, the primary purpose of the flyby was to shrink the orbital period of the spacecraft around the sun by an additional 16 days and increase the ecliptic inclination of the spacecraft by 0.1 degrees, further matching the orbit of Mercury around the Sun. The last Mercury flyby will make the final adjustments to the heliocentric orbit of the spacecraft, ultimately enabling MESSENGER to enter Mercury orbit in mid March 2011.

Mercury Flybys

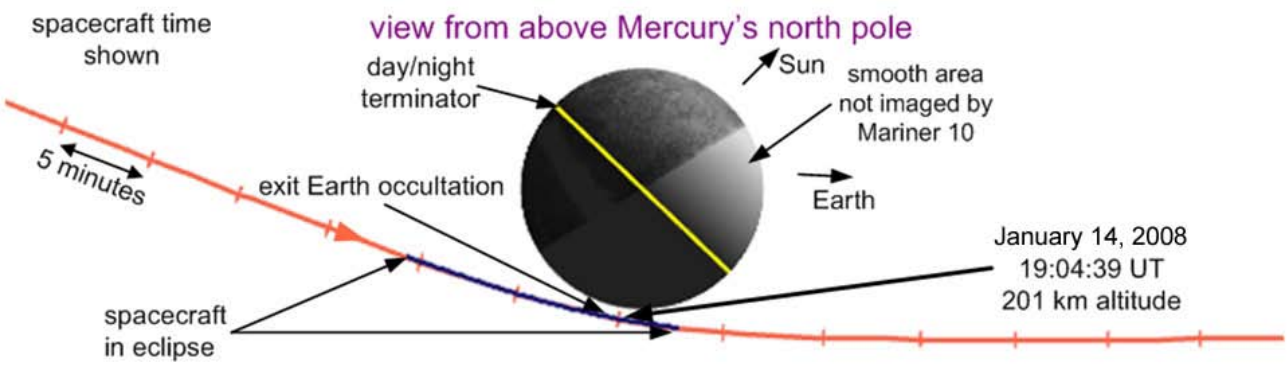


North ecliptic pole view of the trajectory between the first Mercury flyby and Mercury orbit insertion. Dashed lines depict the orbits of Earth, Venus, and Mercury. Timeline fading helps emphasize primary events.

In conjunction with these flyby activities, pre-determined course-correction maneuvers – deep-space maneuvers (DSMs) using the main Large Velocity Adjust (LVA) engine – are scheduled approximately two months after each flyby to adjust further the spacecraft trajectory in preparation for the eventual capture into orbit around Mercury.

During the first flyby the spacecraft departed looking back toward the sunlit views of the planet. Soon after reaching minimum altitude, MESSENGER's instruments viewed approximately 20% of the surface of Mercury not seen by Mariner 10.

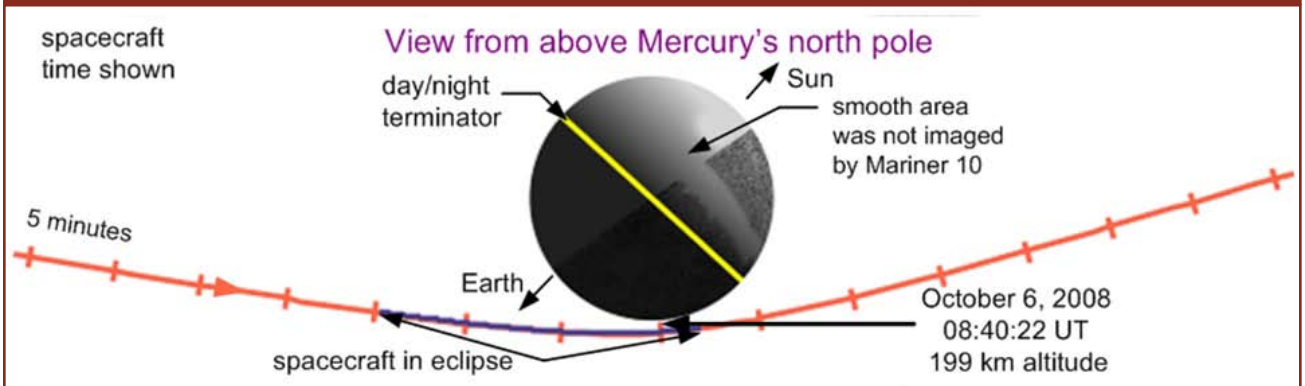
Mercury Flyby 1



View of the first Mercury flyby trajectory from above the planet's northern pole. The yellow line marks the position of the day/night or dawn/dusk terminator. Closest approach time listed is in local spacecraft time, not accounting for the one-way light time for the signals to reach the Earth.

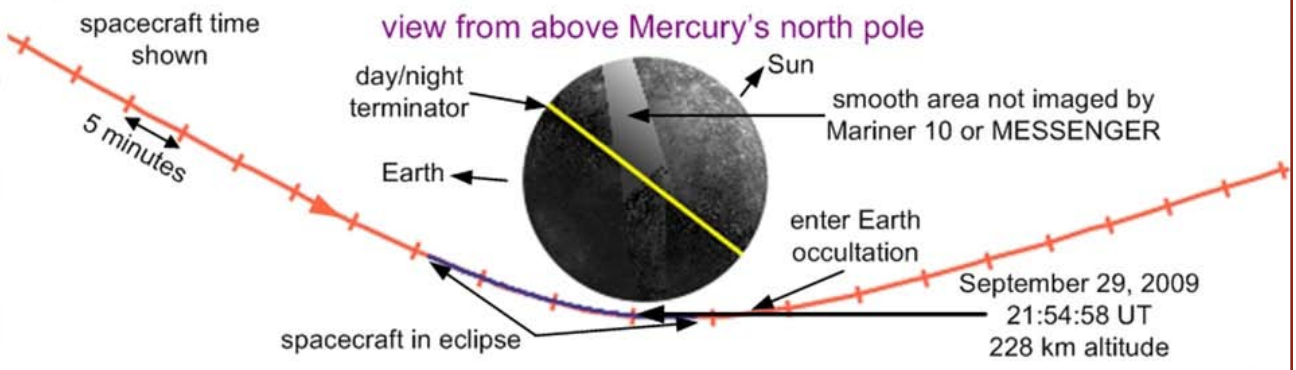
After the three flybys of Mercury, MESSENGER will have mapped nearly 90% of the entire planet in color, imaged most of the areas not seen by Mariner 10, and taken measurements of the composition of the surface, atmosphere, and magnetosphere. In contrast to the orbital phase of the mission, the closest approach points during the flybys occur near the planet's equator. These approaches provide special vantages to gather high-resolution images of the low- to mid-latitude regions of the planet as well as low-latitude measurements of the magnetic and gravitational fields.

Mercury Flyby 2



View of the second Mercury flyby trajectory from above the planet's northern pole. The yellow line marks the position of the day/night or dawn/dusk terminator. Closest approach time listed is in local spacecraft time, not accounting for the one-way light time for the signals to reach the Earth.

Mercury Flyby 3



View of the third Mercury flyby trajectory from above the planet's northern pole. The yellow line marks the position of the day/night or dawn/dusk terminator. Closest approach time listed is in local spacecraft time, not accounting for the one-way light time for the signals to reach the Earth.

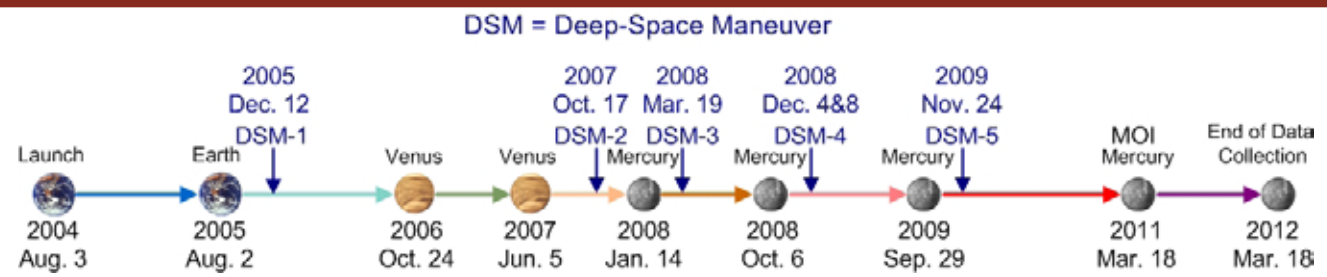
Terra Incognita

During its three flybys of Mercury in 1974–1975, the Mariner 10 spacecraft imaged approximately 45% of the visible surface. Although radar and visible images of portions of the planet not viewed by Mariner 10 have been made from Earth-based observatories, MESSENGER's first two Mercury flybys revealed about 20% and 30%, respectively, of the planet never before seen in detail from spacecraft at a resolution of approximately 1.5 km or better.

MESSENGER's Deep-Space Maneuvers

In conjunction with the six planetary flybys, MESSENGER's complex 6.6-year cruise trajectory includes more than 40 anticipated trajectory-correction maneuvers (TCMs). These TCMs include five deterministic deep-space maneuvers (DSMs), which use the spacecraft's bipropellant Large Velocity Adjust (LVA) engine. In addition to imparting a combined spacecraft change in velocity of more than 1 km/s, the DSMs are the primary method used to target the spacecraft before each planetary flyby (except the second Venus flyby). Smaller velocity adjustment maneuvers that use the propulsion system's monopropellant thrusters fine-tune the trajectory between the main DSMs and the gravity-assist flybys of the planets.

Deep-Space Maneuvers



Timeline of deterministic deep-space maneuvers for the MESSENGER spacecraft over the entire cruise phase of the mission. Additional statistical "fine-tune" maneuvers are not listed.

On December 12, 2005, MESSENGER successfully fired its bipropellant LVA engine for the first time, completing the first of the five critical deep-space maneuvers (DSM-1). The maneuver, just over 8 minutes long, changed MESSENGER's speed by approximately 316 m/s, placing the spacecraft on target for the first Venus flyby on October 24, 2006.

This maneuver was the first to rely solely on the LVA, the largest and most efficient engine of the propulsion system. Maneuvers performed with the LVA use about 30% less total propellant mass – both fuel and oxidizer – than the other thrusters, which use monopropellant fuel only. Approximately 100 kg of bipropellant (both fuel and oxidizer), about 18% of the total onboard propellant, was used to complete DSM-1.

On October 17, 2007, MESSENGER completed its second critical DSM – 250 million km from Earth – successfully firing the LVA again to change the spacecraft's trajectory and target it for its historic flyby of Mercury on January 14, 2008.

The maneuver, just over 5 minutes long, consumed approximately 70 kg of bipropellant (both fuel and oxidizer), changing the velocity of the spacecraft by approximately 226 m/s.

On March 19, 2008, MESSENGER completed its third critical DSM, successfully firing the LVA once again to change the spacecraft's trajectory and target it for the second flyby of Mercury on October 6, 2008. The shortest deterministic maneuver for the mission on the LVA, just over 2.5 minutes long, consumed approximately 21 kg of bipropellant (both fuel and oxidizer), changing the velocity of the spacecraft by approximately 72 m/s.

On December 4 and 8, MESSENGER completed its fourth critical DSM, successfully firing the LVA twice to adjust the spacecraft's trajectory and target it for the third flyby of Mercury on September 29, 2009. This maneuver was purposely split into two parts to provide engineers a practice opportunity for the cruise-ending Mercury Orbit Insertion maneuver. Combined, this DSM consumed about 68 kg of bipropellant over a total firing time of 6.5 minutes, changing the spacecraft velocity by 222 m/s and then by 25 m/s, respectively, for each part of the maneuver.

MESSENGER's Large Gas Tank

To support the five DSMs and final Mercury orbit-insertion maneuver, the propulsion system was designed to impart more than 2.2 km/s of velocity change to the spacecraft over the life of the mission. To contain this amount of energy and still be able to launch the spacecraft, over 54% of the spacecraft's launch mass was liquid propellant – fuel and oxidizer.

Solar System Sailing

Using the orientation of the spacecraft solar panels as sails, engineers have been able to harness the radiation pressure generated by the spacecraft's close proximity to the Sun to correct the spacecraft trajectory. This technique has eliminated the need to execute small trajectory correction maneuvers since December 19, 2007, conserving propellant and enabling the phenomenal flyby targeting accuracies experienced for the first two Mercury encounters.

Science Orbit: Working at Mercury

For one year MESSENGER will operate in a highly elliptical (egg-shaped) orbit around Mercury, starting at 200 km above the surface at the closest point (periapsis) and 15,193 km at the farthest (apoapsis). The plane of the orbit will be inclined about 82.5° to Mercury's equator, and the low point in the orbit comes initially at 60° N latitude. MESSENGER will orbit Mercury twice every 24 hours.

Orbit insertion occurs in March 2011. Using 30% of its initial propellant load, MESSENGER will fire its Large Velocity Adjust (LVA) engine and slow down by approximately 860 m/s, coming to a virtual stop relative to Mercury. This braking maneuver will be executed in two parts: the first maneuver (lasting about 14 minutes) places the spacecraft in a stable orbit and the second maneuver, a much shorter "cleanup" maneuver, is executed a few days later near the orbit's lowest point.

The 12-month orbital mission covers two Mercury solar days; one Mercury solar day, from noon to noon, is equal to 176 Earth days. MESSENGER will obtain global mapping data from the different instruments during the first day and focus on targeted science investigations during the second.

While MESSENGER circles Mercury, the planet's gravity, the Sun's gravity, and radiation pressure from the Sun will slowly and slightly change the spacecraft's orbit. Once every Mercury year (or 88 Earth days) MESSENGER will carry out a pair of maneuvers to reset the orbit to its original size and shape.

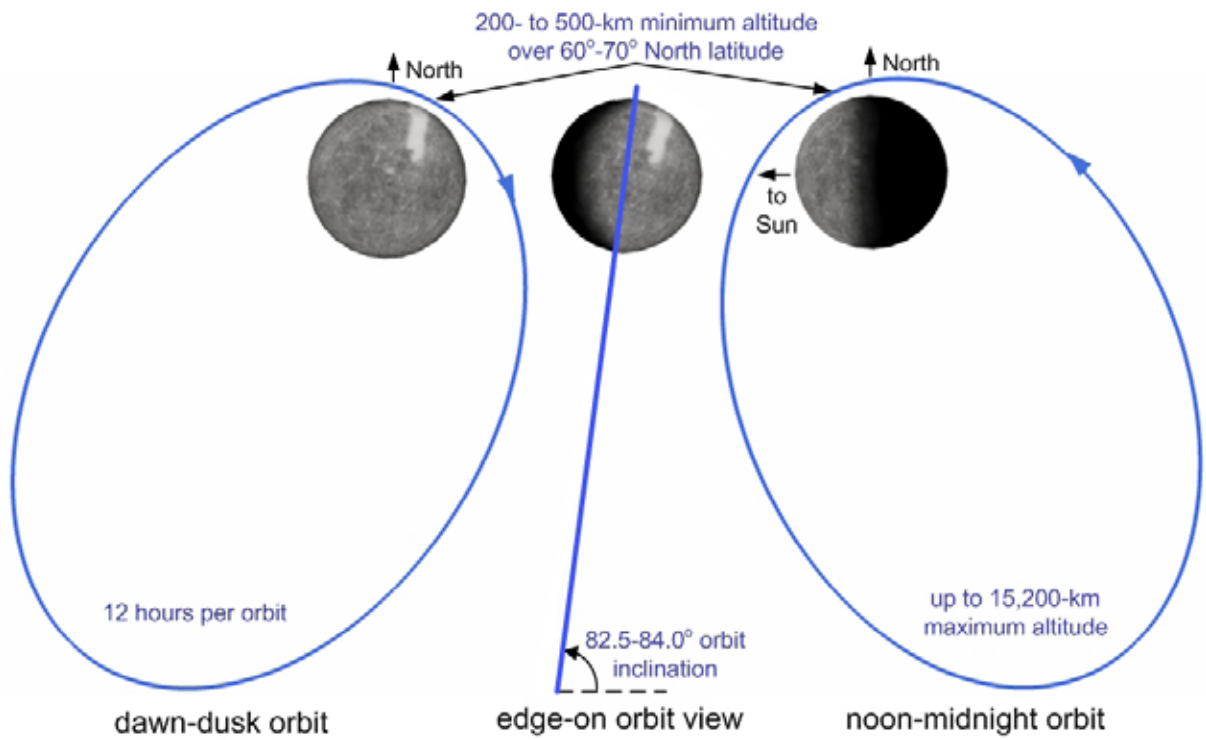
Mission Operations

MESSENGER's mission operations are conducted from the Space Science Mission Operations Center (SSMOC) at the Johns Hopkins University Applied Physics Laboratory (APL) in Laurel, Md., where the spacecraft was designed and built. Flight controllers and mission analysts monitor and operate the spacecraft, working closely with the multi-institutional science team, the mission design team at APL, the systems engineering team at APL, and the navigation team at KinetX, Inc., based in Simi Valley, Calif. Mission operators, engineers, and scientists work together to plan, design, and test commands for MESSENGER's science instruments and spacecraft subsystems. Working with the mission design and navigation teams, the operators build, test, and send the commands that fire MESSENGER's propulsion system to refine its path to and around Mercury.

Like all NASA interplanetary missions, MESSENGER relies on the agency's Deep Space Network (DSN) of antenna stations to track and communicate with the spacecraft. The stations are located in California's Mojave Desert; near Madrid, Spain; and near Canberra, Australia. All three complexes communicate directly with the control center at NASA's Jet Propulsion Laboratory, Pasadena, Calif., which in turn communicates with the MESSENGER SSMOC. Typical DSN coverage for MESSENGER includes three 8-hour contacts per week during the cruise phase, with daily contacts around critical events such as maneuvers, and seven to twelve sessions per week during the orbital phase.

The Science Operations Center (SOC), also located at APL, works with the mission operations team to plan instrument activities and to validate, distribute, manage, and archive MESSENGER's science data.

Spacecraft Orbit at Mercury



MESSENGER's operational orbit at Mercury.

The Spacecraft

After Mariner 10's visits to Mercury, the space science and engineering communities yearned for a longer and more detailed look at the innermost planet – but that closer look, ideally from orbit, presented formidable technical obstacles. A Mercury orbiter would have to be tough, with enough protection to withstand searing sunlight and roasting heat bouncing back from the planet below. The spacecraft would need to be lightweight, since most of its mass would be fuel to fire its rockets to slow the spacecraft down enough to be captured by Mercury's gravity. And the probe would have to be sufficiently compact to be launched on a conventional and cost-effective rocket.

Designed and built by the Johns Hopkins University Applied Physics Laboratory (APL) – with contributions from research institutions and companies around the world – the MESSENGER spacecraft tackles each of these challenges. A ceramic-fabric sunshade, heat radiators, and a mission design that limits time over the planet's hottest regions protect MESSENGER without expensive and impractical cooling systems. The spacecraft's graphite composite structure – strong, lightweight, and heat tolerant – is integrated with a low-mass propulsion system that efficiently stores and distributes the approximately 600 kg of propellant that accounts for 54% of the total launch weight.

To fit behind the 2.5-m by 2-m sunshade, the wiring, electronics, systems, and instruments are packed into a small frame that could fit inside a large sport utility vehicle. And the entire spacecraft is light enough to launch on a Delta II 7925-H ("heavy") rocket, the largest launch vehicle allowed under NASA's Discovery Program of lower-cost space science missions.

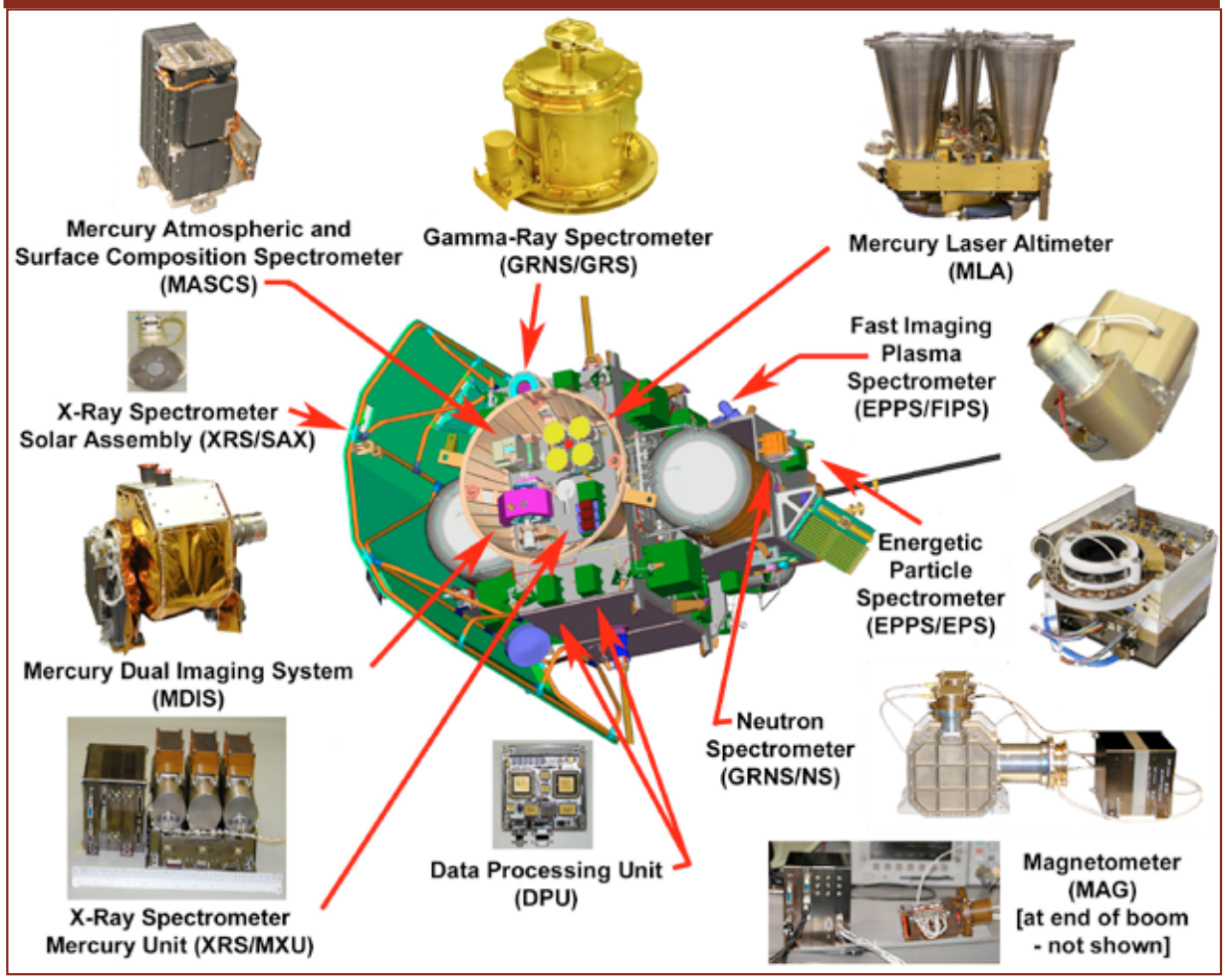
MESSENGER spacecraft during integration and testing. The sunshade is visible on the left with the spacecraft undergoing testing in thermal-vacuum conditions at NASA's Goddard Space Flight Center. On the right, the solar panels and Magnetometer boom are in their position for flight during work at APL.

Science Payload

MESSENGER carries seven scientific instruments and a radio science experiment to accomplish an ambitious objective: return the first data from Mercury orbit. The miniaturized payload – designed to work in the extreme environment near the Sun – will image all of Mercury for the first time, as well as gather data on the composition and structure of Mercury's crust, its geologic history, the nature of its active magnetosphere and thin atmosphere, and the makeup of its core and the materials near its poles.

The instruments include the Mercury Dual Imaging System (MDIS), the Gamma-Ray and Neutron Spectrometer (GRNS), the X-Ray Spectrometer (XRS), the Magnetometer (MAG), the Mercury Laser Altimeter (MLA), the Mercury Atmospheric and Surface Composition Spectrometer (MASCS), and the Energetic Particle and Plasma Spectrometer (EPPS). The instruments communicate to the spacecraft through fully redundant Data Processing Units (DPUs).

Spacecraft Instruments



The process of selecting the scientific instrumentation for a mission is typically a balance between answering as many science questions as possible and fitting within the available mission resources for mass, power, mechanical accommodation, schedule, and cost. In the case of MESSENGER, the mass and mechanical accommodation issues were very significant constraints. Payload mass was limited to 50 kg because of the propellant mass needed for orbit insertion. The instrument mechanical accommodation was difficult because of the unique thermal constraints faced during the mission; instruments had to be mounted where Mercury would be in view but the Sun would not, and they had to be maintained within an acceptable temperature range in a very harsh environment. Instrument details follow.

In each case the mass includes mounting hardware and thermal control components, and the power is the nominal average power consumption per orbit; actual values vary with instrument operational mode.

Mercury Dual Imaging System

Mass: 8.0 kg
Power: 7.6 W
Development: The Johns Hopkins University Applied Physics Laboratory

The multi-spectral MDIS has wide- and narrow-angle cameras (the "WAC" and "NAC," respectively) – both based on charge-coupled devices (CCDs) similar to those found in digital cameras – to map the rugged landforms and spectral variations on Mercury's surface in monochrome, color, and stereo. The imager pivots, giving it the ability to capture images from a wide area without having to re-point the spacecraft.

The wide-angle camera has a 10.5° by 10.5° field of view and can observe Mercury through 11 different filters and monochrome across the wavelength range 395 to 1,040 nm (visible through near-infrared light). Multi-spectral imaging will help scientists investigate the diversity of rock types that form Mercury's surface. The narrow-angle camera can take black-and-white images at high resolution through its 1.5° by 1.5° field of view, allowing extremely detailed analysis of features as small as 18 m across.

Gamma-Ray and Neutron Spectrometer

GRNS packages separate gamma-ray and neutron spectrometers to collect complementary data on elements that form Mercury's crust.

Gamma-Ray Spectrometer
Mass: 9.2 kg
Power: 6.6 W
Development: The Johns Hopkins University Applied Physics Laboratory, Patriot Engineering, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory

GRS measures gamma rays emitted by the nuclei of atoms on Mercury's surface that are struck by cosmic rays. Each element has a signature emission, and the instrument will look for geologically important elements such as hydrogen, magnesium, silicon, oxygen, iron, titanium, sodium, and calcium. It may also detect naturally radioactive elements such as potassium, thorium, and uranium.

Neutron Spectrometer
Mass: 3.9 kg
Power: 6.0 W
Development: The Johns Hopkins University Applied Physics Laboratory, Patriot Engineering, Los Alamos National Laboratory

NS maps variations in the fast, thermal, and epithermal neutrons that Mercury's surface emits when struck by cosmic rays. "Fast" neutrons shoot directly into space; others collide with neighboring atoms in the crust before escaping. If a neutron collides with a light atom (like hydrogen), it will lose energy and be detected as a slow (or thermal) neutron. Scientists can look at the ratio of thermal to epithermal (slightly faster) neutrons across Mercury's

surface to estimate the amount of hydrogen – possibly locked up in water molecules – and other elements.

X-Ray Spectrometer

Mass: 3.4 kg
Power: 6.9 W
Development: The Johns Hopkins University Applied Physics Laboratory

XRS maps the elements in the top millimeter of Mercury's crust using three gas-filled detectors (MXU) pointing at the planet, one silicon solid-state detector pointing at the Sun (SAX), and the associated electronics (MEX). The planet-pointing detectors measure fluorescence, the X-ray emissions coming from Mercury's surface after solar X-rays hit the planet. The Sun-pointing detector tracks the X-rays bombarding the planet.

XRS detects emissions from elements in the 1–10 keV range – specifically, magnesium, aluminum, silicon, sulfur, calcium, titanium, and iron. Two detectors have thin absorption filters that help distinguish among the lower-energy X-ray lines of magnesium, aluminum, and silicon.

Beryllium-copper honeycomb collimators give XRS a 12° field of view, which is narrow enough to eliminate X-rays from the star background even when MESSENGER is at its farthest orbital distance from Mercury. The small, thermally protected, solar-flux monitor is mounted on MESSENGER's sunshade.

Hot Space, Cool Instrument

To help it measure surface gamma rays from long distances, MESSENGER uses the most sensitive detector available – a high-purity germanium semiconductor crystal. But while MESSENGER moves through one of the Solar System's hottest environments, the crystal must operate at cryogenic temperatures. Instrument designers addressed this challenge by suspending the detector on thin Kevlar strings inside a high-tech thermos bottle, with a small, powerful refrigerator (called a cryocooler) that keeps temperatures at a frosty –183° C, or about –300° F.

Magnetometer

Mass (including boom): 4.4 kg
Power: 4.2 W
Development: NASA Goddard Space Flight Center and the Johns Hopkins University Applied Physics Laboratory

A three-axis, ring-core fluxgate detector, MAG characterizes Mercury's magnetic field in detail, helping scientists determine the field's precise strength and how it varies with position and altitude. Obtaining this information is a critical step toward determining the source of Mercury's magnetic field.

The MAG sensor is mounted on a 3.6-m-long boom that keeps it away from the spacecraft's own magnetic field. The sensor also has its own sunshade to protect it from the Sun when the spacecraft is tilted to allow for viewing by the other instruments. While in orbit at Mercury the instrument will collect magnetic field samples at 50-ms to 1-s intervals; the rapid sampling will take place near Mercury's magnetospheric boundaries.

Mercury Laser Altimeter

Mass: 7.4 kg
Peak Power: 16.4 W
Development: NASA Goddard Space Flight Center

MLA maps Mercury's landforms and other surface characteristics using an infrared laser transmitter and a receiver that measures the round-trip time of individual laser pulses. The data will also be used to track the planet's slight, forced libration – a wobble about its spin axis – which will tell researchers about the state of Mercury's core.

MLA data combined with Radio Science Doppler ranging will be used to map the planet's gravitational field. MLA can view the planet from up to 1,500 km away with an accuracy of 30 cm. The laser's transmitter, operating at a wavelength of 1,064 nm, will deliver eight pulses per second. The receiver consists of four sapphire lenses mounted on beryllium structures, a photon-counting detector, a time-interval unit, and processing electronics.

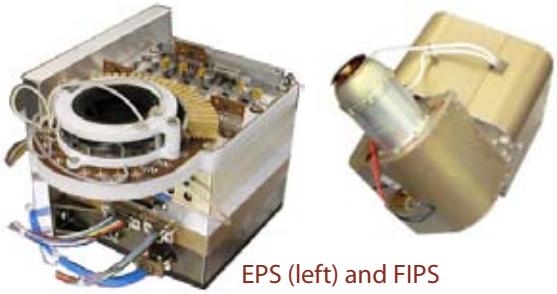
Mercury Atmospheric and Surface Composition Spectrometer

Mass: 3.1 kg
Peak Power: 6.7 W
Development: Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder

Combining an ultraviolet spectrometer and infrared spectrograph, MASCS will measure the abundance of atmospheric gases around Mercury and detect minerals in its surface materials.

The *Ultraviolet and Visible Spectrometer* (UVVS) will determine the composition and structure of Mercury's exosphere – the extremely low-density atmosphere – and study its neutral gas emissions. It will also search for and measure ionized atmospheric species. Together these measurements will help researchers understand the processes that generate and maintain the atmosphere, the connection between surface and atmospheric composition, the dynamics of volatile materials on and near Mercury, and the nature of the radar-reflective materials near the planet's poles. The instrument has 25-km resolution at the planet's limb.

Perched atop the ultraviolet spectrometer, the *Visible and Infrared Spectrograph* (VIRS) will measure the reflected visible and near-infrared light at wavelengths diagnostic of iron- and titanium-bearing silicate materials on the surface, such as pyroxene, olivine, and ilmenite. The sensor's best resolution is 3 km at Mercury's surface.



EPS (left) and FIPS (right)

Energetic Particle and Plasma Spectrometer

Mass: 3.1 kg
Peak Power: 7.8 W
Development: The Johns Hopkins University Applied Physics Laboratory and University of Michigan, Ann Arbor

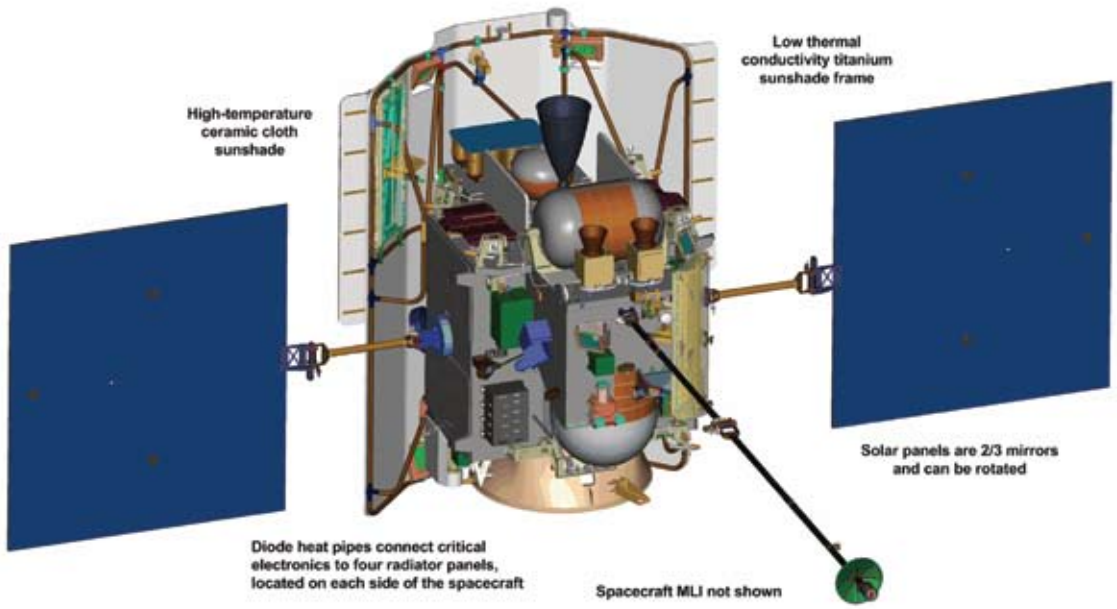
EPPS will measure the mix and characteristics of charged particles in and around Mercury's magnetosphere using an Energetic Particle Spectrometer (EPS) and a Fast Imaging Plasma Spectrometer (FIPS). The unit is equipped with time-of-flight and energy-measurement technology to determine simultaneously particle velocities and elemental species.

From its vantage point near the top deck of the spacecraft, EPS will observe ions and electrons accelerated in the magnetosphere. EPS has a 160° by 12° field of view for measuring the energy spectra and pitch-angle distribution of these ions and electrons. Mounted on the side of the spacecraft, FIPS will observe low-energy ions coming from Mercury's surface and sparse atmosphere, ionized atoms picked up by the solar wind, and other solar-wind components. FIPS provides nearly full hemispheric coverage.

Radio Science Experiment

Radio Science observations – gathered by tracking the spacecraft through its communications system – will precisely measure MESSENGER's speed and distance from Earth. From this information, scientists and engineers will watch for changes in MESSENGER's movements at Mercury to measure the planet's gravity field, and to support the laser altimeter investigation to determine the size and condition of Mercury's core. NASA's Goddard Space Flight Center leads the Radio Science investigation.

Spacecraft Systems and Components



MESSENGER spacecraft in flight configuration, rear view

Thermal Design

While orbiting Mercury, MESSENGER will "feel" significantly hotter than spacecraft that orbit Earth. This is because Mercury's elongated orbit swings the planet to within 46 million km of the Sun, or about two-thirds closer to the Sun than Earth. As a result, the Sun shines up to 11 times brighter at Mercury than we see from our own planet.

MESSENGER's first line of thermal defense is a heat-resistant and highly reflective sunshade, fixed on a titanium frame to the front of the spacecraft. Measuring about 2.5 m tall and 2 m across as viewed head-on, the thin shade has front and back layers of Nextel ceramic cloth – the same material that protects sections of the space shuttle – surrounding several inner layers of Kapton plastic insulation. While temperatures on the front of the shade could reach 370° C when Mercury is closest to the Sun, behind it the spacecraft will operate at room temperature, around 20° C.

As the second line of defense against this challenging environment, the science orbit is designed to limit MESSENGER's exposure to the heat re-radiating from the surface of Mercury. (MESSENGER will only spend about 25 minutes of each 12-hour orbit crossing Mercury's broiling surface at low altitude.) Multilayered insulation covers most of the surfaces of the spacecraft to protect against incident thermal radiation and insulate against internal heat loss, and radiators connected to diode ("one-way") heat pipes are installed on the sides of the spacecraft to carry heat away from the spacecraft body. The combination of the sunshade, unique orbital design, thermal blanketing, and heat-radiation system allows the spacecraft to operate without special high-temperature electronics.

Power

Two single-sided solar panels are the spacecraft's main source of electric power. To run MESSENGER's systems and charge its 23-ampere-hour nickel-hydrogen battery, the panels, each about 1.5 m by 1.75 m in extent, will support between 440 and 475 W of spacecraft load power during the cruise phase and 650 W during the orbit at Mercury. The panels themselves produce more than 2 kW of power near Mercury, but to prevent stress on MESSENGER's electronics and keep operating temperatures within acceptable limits, onboard power processors convert only what the spacecraft was designed to consume in orbit.

The custom-developed panels are two-thirds mirrors (called optical solar reflectors) and one-third triple-junction solar cells, which convert 28% of the sunlight hitting them into electricity. Each panel has two rows of mirrors for every row of cells; the small mirrors reflect the Sun's energy and keep the panel cooler. The panels also rotate, so the operations team tilts the panels away from the Sun, positioning them to get the required power while maintaining a normal surface operating temperature of about 150° C.

Propulsion

MESSENGER's dual-mode propulsion system includes a 660-N bipropellant thruster for large maneuvers and 16 hydrazine-propellant thrusters for smaller trajectory adjustments and attitude control. The Large Velocity Adjust (LVA) thruster requires a combination of hydrazine fuel and nitrogen tetroxide oxidizer. Fuel and oxidizer are stored in custom-designed, lightweight titanium tanks integrated into the spacecraft's composite frame. Helium pressurizes the system and pushes the fuel and oxidizer through to the engines.

At launch the spacecraft carried just under 600 kg of propellant, and it will use nearly 30% of it during the maneuver that inserts the spacecraft into orbit around Mercury. The hydrazine thrusters play several important roles: four 22-N thrusters are used for small course corrections and help steady MESSENGER during large engine burns. The dozen 4.4-N thrusters are also used for small course corrections and also help steady the spacecraft during all propulsive maneuvers. These smallest thrusters can also serve as a backup for the reaction wheels that maintain the spacecraft's orientation during normal cruise and orbital operations.

Communications

MESSENGER's X-band coherent communications system includes two high-gain, electronically steered, phased-array antennas – the first ever used on a deep-space mission; two medium-gain fanbeam antennas; and four low-gain antennas. The circularly polarized phased arrays – developed by APL and located with the fanbeam antennas on the front and back of the spacecraft – are the main link for sending science data back to Earth. For better reliability in the high-temperature environment the antennas are fixed; they "point" electronically across a 45° field of regard without moving parts.

High-gain antennas send radio signals through a narrower, more concentrated beam than medium- or low-gain antennas and are used to send large amounts of data over the same distance as a lower-gain antenna. The fanbeam antennas, also located on MESSENGER's front and back sides, are used for lower-rate data transmissions to the Earth as well as nominal command transmissions from the Earth, such as operating commands, status data, or emergency communications. The four low-gain antennas provide hemispheric fields of view from the top, bottom, front, and back of the spacecraft, providing primarily an emergency bi-directional communications link with the Earth in the event attitude knowledge is lost. MESSENGER's downlink rate ranges from 9.9 bits per second to 104 kilobits per second; operators can send commands at 7.8 to 500 bits per second. Transmission rates vary according to onboard communications system configuration, spacecraft distance from the Earth, and ground-station antenna size.

Command and Data Handling

MESSENGER's "brain" is its Integrated Electronics Module (IEM), a space- and weight-saving device that combines the spacecraft's core avionics into a single box. The spacecraft carries a pair of identical IEMs for backup purposes; both house a 25-MHz main processor and 10-MHz fault-protection processor. All four are radiation-hardened RAD6000 processors, based on predecessors of the PowerPC chip found in some models of home computers. The computers, slow by current home-computer standards, are state of the art for the radiation tolerance required on the MESSENGER mission.

Programmed to monitor the condition of MESSENGER's key systems, both fault-protection processors are turned on at all times and protect the spacecraft by turning off components and/or switching to backup components when necessary. The main processor runs the command and data handling software for data transfer and file storage, as well as the guidance and control software used to navigate and point the spacecraft. Each IEM also includes a solid-state data recorder, power converters, and the interfaces between the processors and MESSENGER's instruments and systems.

Intricate flight software executes MESSENGER's Command and Data Handling system. MESSENGER receives operating commands from Earth and can perform them in real time or store them for later execution. Most of the frequent, critical operations (such as propulsive maneuvers) are programmed into the flight computer's memory and timed to run automatically.

For data, MESSENGER carries two solid-state recorders (one backup) able to store up to 1 gigabyte each. The main processor collects, compresses, and stores images and other data from the subsystems and instruments onto the recorder; the software sorts the data into files in a manner similar to how files are stored on a PC. The main processor selects the files with highest priority to transmit to Earth, or mission operators can download data files in any order the team chooses.

In orbit around Mercury, data downlink rates will vary predominantly with spacecraft-to-Earth distance. Thus when orbiting Mercury, MESSENGER will store most of its data when it's farther from Earth, typically sending only information on its condition and the highest-priority images and measurements during contacts through NASA's Deep Space Network. The spacecraft will send most of the recorded data when Mercury's path around the Sun brings it closer to Earth.

Guidance and Control

MESSENGER is well protected against the heat, but it must always know its orientation relative to Mercury, Earth, and the Sun and be "smart" enough to keep its sunshade pointed at the Sun. Attitude determination – knowing in which direction MESSENGER is facing – is performed using star-tracking cameras, digital Sun sensors, and an inertial measurement unit (IMU, which contains gyroscopes and accelerometers). Attitude control for the three-axis stabilized craft is accomplished using four internal reaction wheels and, when necessary, MESSENGER's small thrusters.

The IMU accurately determines the spacecraft's rotation rate, and MESSENGER tracks its own orientation by checking the location of stars and the Sun. Star-tracking cameras on MESSENGER's top deck store a complete map of the heavens; once a second, one of the cameras takes a wide-angle picture of space, compares the locations of stars to its onboard map, and then calculates the spacecraft's orientation. The guidance and control software also automatically rotates the solar panels to the commanded Sun-relative orientation, as the spacecraft body rotates, ensuring that the panels produce sufficient power while maintaining safe temperatures.

The suite of Sun sensors back up the star trackers, continuously measuring MESSENGER's angle to the Sun. If the flight software detects that the Sun is "moving" out of a designated safe zone, it can initiate an automatic turn to ensure that the shade faces the Sun. Ground controllers can then analyze the situation while the spacecraft turns its antennas to Earth and awaits instructions – an operating condition known as "safe" mode.

Hardware Suppliers

Spacecraft Hardware Suppliers

Antenna Waveguide: Continental Microwave, Exeter, N.H.
Battery (with APL): Eagle Picher Technologies, Joplin, Mo.
Heat Pipes: ATK (formally Swales Aerospace), Beltsville, Md.
Sun Shade Material (with APL): 3M Ceramic Textiles, St. Paul, Minn.
Inertial Measurement Unit: Northrop Grumman, Woodland Hills, Calif.
Integrated Electronics Module (with APL): BAE Systems, Manassas, Va.
Launch Vehicle: Boeing, Huntington Beach, Calif.
Precision Oscillator: Datum Timing Test and Measurement, Beverly, Mass.
Propulsion: Aerojet, Sacramento, Calif.
Reaction Wheels: Teldix GmbH, Heidelberg, Germany
Semiconductors: TriQuint, Dallas, Tex.
Solar Array Drives: Moog, Inc., East Aurora, N.Y.
Solar Arrays: Northrop Grumman Space Technology, Redondo Beach, Calif.
Solid-State Power Amplifier Converters: EMS Technologies, Montreal, Quebec, Canada
Star Trackers: Galileo Avionica, Florence, Italy
Structure: ATK Composite Optics, Inc., San Diego, Calif.
Sun Sensors: Adcole Corporation, Marlborough, Mass.
Transponder: General Dynamics, Scottsdale, Ariz.

Instrument Hardware Suppliers

MDIS:
Integrator: APL, Laurel, Md.
SSG, Inc. (NAC telescope), Wilmington, Mass.
Atmel (CCD), San Jose, Calif.
CDA Intercorp (filter wheel motor for WAC), Deerfield, Fla.
Starsys Research (pivot motor), Boulder, Colo.
Optimax (WAC lenses), Chicago, Ill.
Northrop Grumman Poly Scientific (twist capsule), Blacksburg, Va.
Optical Coating Laboratory, Inc. (heat filters), Santa Rosa, Calif.

GRNS:
Integrator: APL, Laurel, Md.
Ricor (cooler), En Harod Ihud, Israel
Patriot Engineering (design, analysis, and subassembly of sensors), Chagrin Falls, Ohio.
Hamamatsu Corp. (photomultipliers), Bridgewater, N.J.
Lawrence Berkeley National Laboratory (GRS), Berkeley, Calif.
Lawrence Livermore National Laboratory (GRS), Livermore, Calif.
Space Science Laboratory, University of California, Berkeley, (GRS), Berkeley, Calif.

XRS:
Integrator: APL, Laurel, Md.
Amptek (components), Bedford, Mass.
Metorex (X-ray sensor tubes), Espoo, Finland

MAG:
Integrator and digital electronics: APL, Laurel, Md.
Goddard Space Flight Center (sensor and analog electronics), Greenbelt, Md.

MLA:
Integrator: Goddard Space Flight Center, Greenbelt, Md.

MASCS:
Integrator: LASP, University of Colorado, Boulder, Colo.

EPPS:
Integrator, common electronics, and EPS subassembly: APL, Laurel, Md.
University of Michigan (FIPS subassembly), Ann Arbor, Mich.
Amptek (components), Bedford, Mass.
Luxel (microchannel plate), Friday Harbor, Wash.
Micron Semiconductor (solid-state detectors), Lancing, Sussex, UK

The MESSENGER Science Team

The MESSENGER Science Team consists of experts in all fields of planetary science, brought together by their ability to complete the science investigations conducted by MESSENGER. The team is divided into four discipline groups: (1) Geochemistry, (2) Geology, (3) Geophysics, and (4) Atmosphere and Magnetosphere, with each team member given responsibility for implementation of a particular part of the mission's science plan.

Principal Investigator: Sean C. Solomon, Director of the Department of Terrestrial Magnetism at the Carnegie Institution of Washington
Project Scientist: Ralph L. McNutt, Jr., Johns Hopkins University Applied Physics Laboratory (APL)
Deputy Project Scientist: Brian J. Anderson, APL

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Robert W. Gaskell
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Thomas R. Watters
Smithsonian Institution National Air and Space Museum

Maria T. Zuber
Massachusetts Institute of Technology

Thomas H. Zurburchen
University of Michigan

† *deceased*

Program/Project Management

Sean C. Solomon of the Carnegie Institution of Washington (CIW) leads the MESSENGER mission as the Principal Investigator. The Johns Hopkins University Applied Physics Laboratory (APL), Laurel, Md., manages the MESSENGER mission for NASA's Science Mission Directorate, Washington, D.C.

At NASA Headquarters, Edward J. Weiler is the Associate Administrator for NASA's Science Mission Directorate. James L. Green is the Director of that directorate's Planetary Science Division. Anthony Carro is the MESSENGER Program Executive, and Marilyn M. Lindstrom is the MESSENGER Program Scientist. The NASA Discovery Program is managed out of the Marshall Space Flight Center, where Dennon J. Clardy is the Discovery Program Manager, and James E. Lee is the MESSENGER Mission Manager.

At APL, Peter D. Bedini is the MESSENGER Project Manager, Ralph L. McNutt, Jr., is Project Scientist, Eric J. Finnegan is the Mission Systems Engineer, and Andrew B. Calloway is the Mission Operations Manager.

NASA Discovery Program

MESSENGER is the seventh mission in NASA's Discovery Program of lower-cost, highly focused, planetary science investigations. Created in 1992, Discovery challenges teams of scientists and engineers to find innovative and imaginative ways to uncover the mysteries of the Solar System within limited, cost-capped budgets and schedules.

Other Discovery Missions

NEAR (Near Earth Asteroid Rendezvous) marked the Discovery Program's first launch, in February 1996. The NEAR Shoemaker spacecraft became the first to orbit an asteroid when it reached 433 Eros in February 2000. After collecting 10 times the data initially expected during a year around Eros, in February 2001, NEAR Shoemaker became the first spacecraft to land on an asteroid and collect data from its surface.

Mars Pathfinder launched December 1996 and landed on Mars in July 1997. The mission demonstrated several tools and techniques for future Mars missions – such as entering, descending, and landing with airbags to deliver a robotic rover – while captivating the world with color pictures from the red planet.

Lunar Prospector orbited Earth's Moon for 18 months after launching in January 1998. The mission's data enabled scientists to create detailed maps of the gravity, magnetic properties, and chemical makeup of the Moon's entire surface.

Stardust, launched in February 1999, collected samples of comet dust and provided the closest look yet at a comet nucleus when it sailed through the coma of Wild 2 in January 2004. It returned the cometary dust to Earth in January 2006.

Genesis, launched in August 2001, collected solar wind particles and returned them to Earth in September 2004. The samples are improving our understanding of the isotopic composition of the Sun, information that will help to identify what the young Solar System was like.

CONTOUR (Comet Nucleus Tour) was designed to fly past and study at least two very different comets as they visited the inner Solar System. The spacecraft was lost six weeks after launch, during a critical rocket-firing maneuver in August 2002 to boost it from Earth's orbit onto a comet-chasing path around the Sun.

Deep Impact, launched in January 2005, was the first experiment to probe beneath the surface of a comet, attempting to reveal never-before-seen materials that would provide clues to the internal composition and structure of a comet. In July 2005, a variety of instruments, both onboard the spacecraft and at ground-based and space-based observatories around the world, observed the impact with the comet and examined the resulting debris and interior material.

Dawn, launched in September 2007 toward Vesta and Ceres, two of the largest main-belt asteroids in our Solar System, will provide key data on asteroid properties by orbiting and observing these minor planets.

Kepler, launched in March 2009, is monitoring 100,000 stars similar to our Sun for four years, using new technology to search the galaxy for Earth-size (or smaller) planets for the first time.

The **GRAIL** (Gravity Recovery and Interior Laboratory) mission, scheduled to launch in 2011, will fly twin spacecraft in tandem orbits around the Moon for several months to measure its gravity field in unprecedented detail. The mission also will answer longstanding questions about Earth's Moon and provide scientists a better understanding of how Earth and other rocky planets in the Solar System formed.

Discovery also includes Missions of Opportunity – not complete Discovery missions, but pieces of a larger NASA or non-NASA mission or creative reuses of spacecraft that have completed their prime missions. Those selected to date for flight include:

- The **ASPERA-3** (Analyzer of Space Plasma and Energetic Atoms) instrument is studying the interaction between the solar wind and the Martian atmosphere from the European Space Agency's Mars Express spacecraft, which began orbiting Mars in December 2003.
- The **M3** (Moon Mineralogy Mapper), pronounced M-cubed, is one of eleven instruments that flew onboard Chandrayaan-1, which launched in October 2008. Chandrayaan-1, India's first deep space mission, was a project of the Indian Space Research Organisation (ISRO). The goals of the mission included expanding scientific knowledge of the Moon, upgrading India's technological capability, and providing challenging opportunities for planetary research for the younger generation.
- The **EPOXI** mission combines two science investigations – the Extrasolar Planet Observation and Characterization (EPOCh) and the Deep Impact Extended Investigation (DIXI). Both investigations are using the Deep Impact spacecraft, which finished its prime mission in 2005. EPOCh is using the Deep Impact spacecraft to observe several nearby bright stars for transits by orbiting planets, and DIXI involves a flyby of comet Hartley 2 in October 2010.
- **NExT** (New Exploration of Tempel 1) will reuse NASA's Stardust spacecraft to revisit comet Tempel 1, the cometary target of Deep Impact. This investigation will provide the first look at the changes to a comet nucleus produced after its close approach to the Sun. NExT is scheduled to fly by Tempel 1 in February 2011.
- **STROFIO** (Start from a ROtating FIeld mass spectrOmeter) is a mass spectrometer that is part of the SERENA (Search Exospheric Refilling and Emitted Natural Abundances) instrument package selected to fly on the European Space Agency's BepiColombo Mercury Planetary Orbiter spacecraft, scheduled to launch in 2014. The SERENA instrument has two neutral particle analyzers (STROFIO and ELENA) and two ion spectrometers (MICA and PICAM). STROFIO, from the Greek word "strofi" (to rotate), will determine the composition of Mercury's exosphere.

For more on the Discovery Program, visit http://discovery.nasa.gov.