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The spring constant and the sensitivity of the microwave power sensor are designed for a specific dynamic range of power, which, if exceeded, can lead to membrane stiction against the waveguide. The membrane is designed to have negligible influence on the microwave power flow in the coplanar waveguide through accurate impedance matching to the characteristic impedance of the waveguide. The main advantages of this type of power sensor over others (such as thermistor- and diode-based sensors) is that it does not dissipate the microwave power, can be designed for a variety of dynamic ranges, and offers greater linearity. The limitations of this type of sensor are mostly related to its design and operational complexity.

The sensor shown in Fig. 3 was designed at the National Physical Laboratory, United Kingdom, and fabricated by Microfabica using its EFAB® process. This process allows novel three-dimensional (3D) structures (with heights up to a few hundred micrometers) to be realized, in contrast to conventional MEMS devices, which are often planar and have a height limitation of only a few micrometers due to their fabrication process. Research in the field of 3D MEMS is only just beginning and it is likely to be another decade before other practical applications of 3D MEMS devices emerge.

For background information *see* ACCELEROMETER; BRIDGE CIRCUIT; CAPACITANCE MEASUREMENT; CORIOLIS ACCELERATION; GYROSCOPE; MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS); MICROSENSOR; MICROWAVE POWER MEASUREMENT; PRESSURE MEASUREMENT; Q (ELECTRICITY) in the McGraw-Hill Encyclopedia of Science & Technology.

Shakil A. Awan

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MESSENGER mission

On January 14, 2008, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (*MESSENGER*) spacecraft flew by the planet Mercury. No other space probe had visited Mercury since *Mariner 10* flew by the innermost planet three times in 1974–1975. All the instruments in *MESSENGER*'s payload operated successfully during the 55-hour period centered on closest approach at 201.4 km (125.1 mi) above the planet's surface. About 21% of Mercury's surface (**Fig. 1**) was imaged at close range for the first time, and observations were made of Mercury's exosphere, magnetosphere, and surface. *MESSENGER* is scheduled to fly past Mercury two more times (October 2008 and September 2009) before becoming the first spacecraft to orbit Mercury in March 2011.

Objectives. The mission is focused on answering six key questions about Mercury:

1. What planetary formational processes led to the high ratio of metal to silicate in Mercury?
2. What is the geological history of Mercury?
3. What are the nature and origin of Mercury's magnetic field?
4. What are the structure and state of Mercury's core?
5. What are the radar-reflective materials at Mercury's poles?
6. What are the important volatile species and their sources and sinks on and near Mercury?

These questions are addressable by observations that can be made from an orbiting spacecraft, and their answers bear not only on the planet Mercury but more generally on the comparative formation and evolution of all of the terrestrial planets.

Instruments. The *MESSENGER* payload consists of seven instruments plus radio science. The instruments (**Fig. 2**) include the Mercury Dual Imaging System (MDIS), which has a wide-angle camera with 11 filter channels and a higher-resolution, monochrome narrow-angle camera; the Gamma-Ray and Neutron Spectrometer (GRNS), which incorporates two sensors, a Gamma-Ray Spectrometer (GRS) and a Neutron Spectrometer (NS); the X-Ray Spectrometer (XRS); the Magnetometer (MAG); the Mercury Laser Altimeter (MLA); the Mercury Atmospheric and Surface Composition Spectrometer (MASCS), which consists of a moving-grating Ultraviolet-Visible Spectrometer (UVVS) and a Visible-Infrared Spectrograph (VIRS); and the Energetic Particle and Plasma Spectrometer (EPPS), which consists of an Energetic Particle Spectrometer (EPS) and a Fast Imaging Plasma Spectrometer (FIPS). The instruments communicate to the spacecraft through fully redundant Data Processing Units (DPUs).

Spacecraft. The *MESSENGER* spacecraft body is 1.42 m (4.7 ft) tall, 1.85 m (6.1 ft) wide, and 1.27 m (4.2 ft) deep, and constructed of a lightweight graphite-epoxy composite. The front-mounted ceramic-fabric sunshade, 2.5 m (8.2 ft) tall and 2 m (6.6 ft) across, is mounted on a titanium-tube structure (**Fig. 3**).

Power system. Power is provided by two rotatable solar arrays that extend about 6 m (20 ft) from end to end across the spacecraft. The two 2.6-m^2 (28-ft^2) panels are one-third gallium arsenide solar cells and two-thirds solar reflectors (mirrors), included to moderate thermal input. The arrays are used to charge a 22-cell, 23-A-h nickel-hydrogen battery that provides spacecraft electrical power during eclipses. The power-system electronics regulate the power output of the system; they provided about 390 W near Earth's distance from the Sun and will provide 640 W in Mercury orbit.

Propulsion system. A key characteristic of *MESSENGER* is its initially large mass fraction of propellant and low-mass (81.7-kg or 180-lb) propulsion system that enables a velocity-change capability of 2250 m/s (7380 ft/s). Features include three custom-built titanium tanks that feed a dual-mode propulsion system having one bipropellant (hydrazine and nitrogen tetroxide) thruster for large maneuvers and 16 monopropellant thrusters for small trajectory adjustments and attitude control. This system, with 599 kg (1320 lb) of propellant at launch (54% by mass), is used to perform five large deep-space maneuvers (three accomplished by mid-2008) that, along with the six planetary gravity assists (four performed by mid-2008) and a final large Mercury-orbit-insertion burn, permit the spacecraft to be placed into Mercury orbit. Smaller trajectory-correction maneuvers employ hydrazine burns, and the three-axis-stable flight configuration is maintained through a combination of the monopropellant thrusters, reaction wheels, and solar radiation pressure on the steered solar arrays. The main tanks have no internal propellant management devices other than a vortex suppressor at the outlet, and under zero acceleration between bipropellant maneuvers the fuel and oxidizer are not localized in the tanks. Thrusters therefore rely on an initial low-acceleration "settling" burn, executed with hydrazine in a bladder-containing auxiliary tank, to position fuel and oxidizer at the exit ports of the main tanks before each bipropellant maneuver. This management approach places burdens on burn design and flight

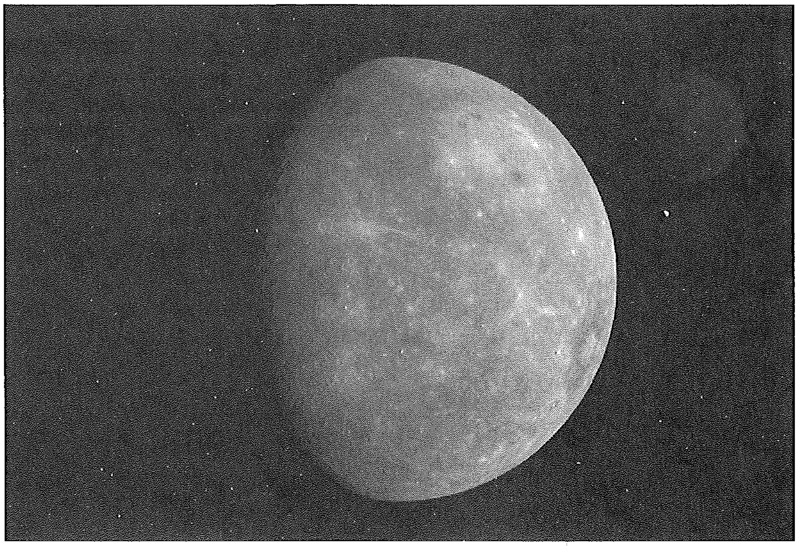

Fig. 1. ***MESSENGER*** **wide-angle camera image of the hemisphere of Mercury seen as the spacecraft departed the planet. The image, at a resolution of approximately 2.5 km/pixel (1.6 mi/pixel), includes all of the Caloris basin (upper right) and 21% of the planet's surface never before seen at close range. (*NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington*)**

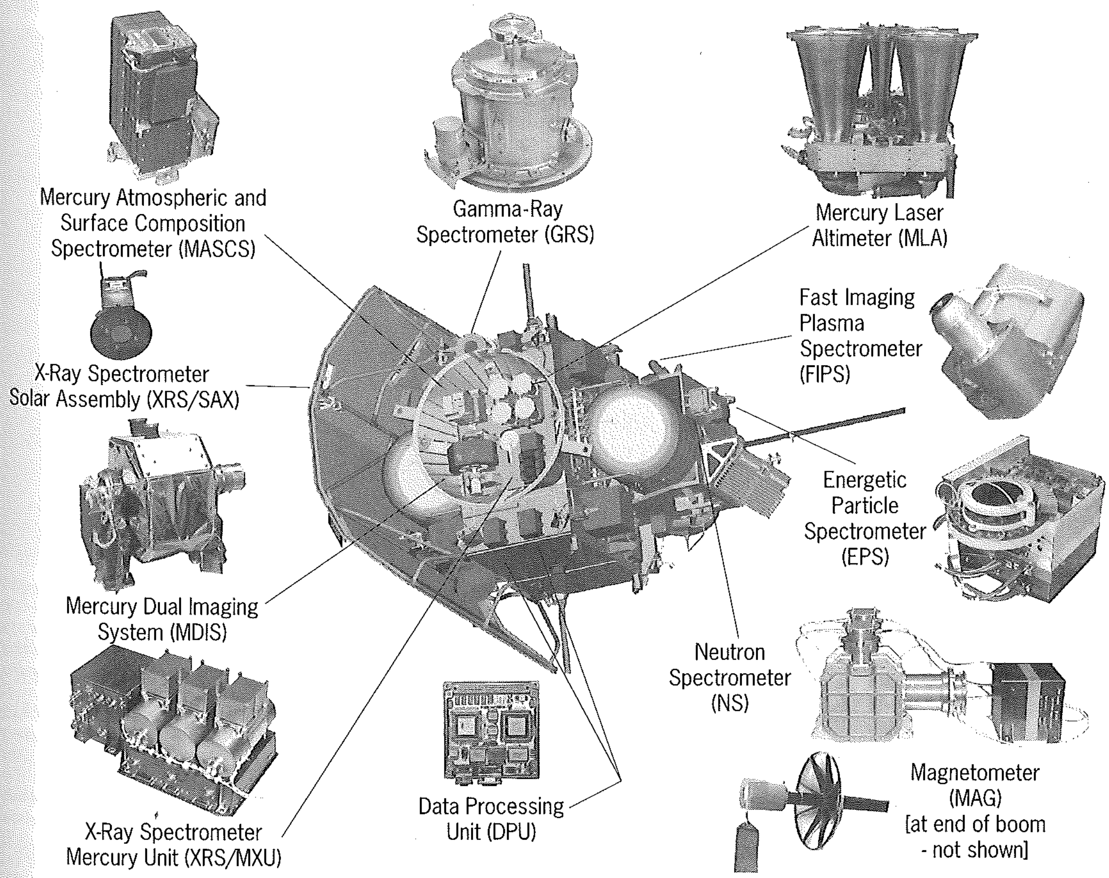

Fig. 2. Montage of the *MESSENGER* instruments showing images of flight units and their locations on the spacecraft. (*NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington*)

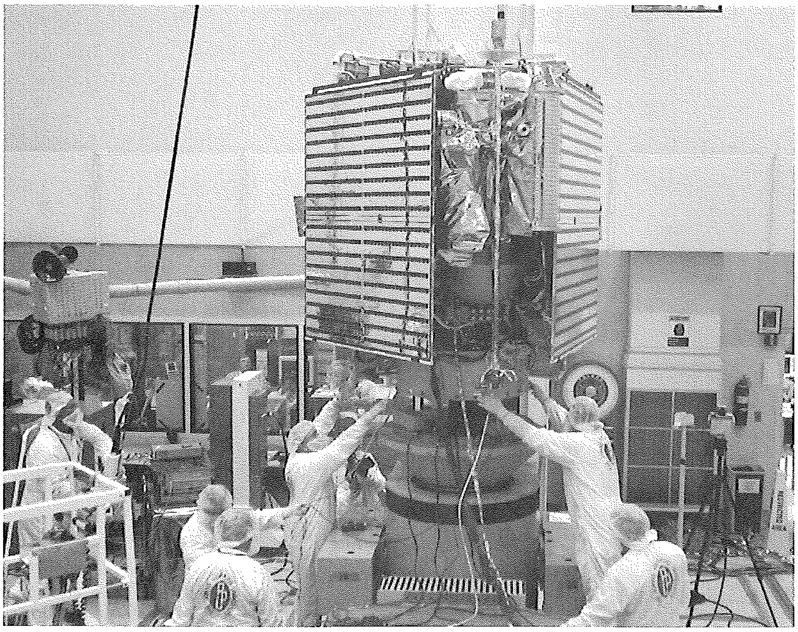

Fig. 3. Completed *MESSENGER* spacecraft being prepared for vibration testing at the Johns Hopkins University Applied Physics Laboratory prior to shipment to Cape Canaveral and subsequent launch. (*NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington*)

software but helped to minimize mass and hardware cost.

Avionics. A redundant processor performs all main spacecraft functions, while other processors use rule-based engines to provide for spacecraft health and safety. Command and data handling, guidance and control, and fault-protection functions are implemented in (redundant) Integrated Electronics Modules (IEMs). As with all *MESSENGER* systems, significant development and manufacturing design effort went into minimizing the mass of these systems while retaining a high level of robustness for the mission. The system is built around RAD6000 processors and includes redundant solid-state recorders with 8 gigabits of memory, implemented with a VxWorks-based, file-system protocol. The RAD6000 processor is based on the IBM reduced instruction set computer (RISC) single-chip central processing unit (CPU) and is radiation-hardened to function reliably in Mercury's environment over the long duration of the mission. VxWorks, one of the real-time operating systems that run on these units, is "UNIX-like" and can be used in a multitasking environment. The telecommunications system runs at X-band and employs redundant transponders, solid-state power amplifiers, and a suite of antennas that includes two phased-array antennas, the first electronically steered antennas designed for use in deep space.

Mission timeline. The seventh competed Discovery Program mission flown by the National Aeronautics and Space Administration (NASA), *MESSENGER* was launched on August 3, 2004 (**Fig. 4**). The spacecraft subsequently executed gravity-assist maneuvers at Earth (August 2, 2005) and twice at Venus (October 24, 2006, and June 5, 2007).

Prior to insertion into orbit about Mercury in 2011, *MESSENGER* will have traveled 7.9×10^9 km (4.9×10^9 mi) in 15 revolutions around the Sun. The Mercury orbital phase of the mission as currently planned will last one Earth year (equivalent to just over four Mercury years or two Mercury solar days).

Mercury flyby observations. During *MESSENGER*'s first flyby of Mercury, MDIS obtained 1213 images of the surface as well as an additional 104 images for optical navigation and the production of approach and departure movies. The Caloris basin—the largest, best-preserved impact basin on Mercury—was imaged in its entirety for the first time. A number of large monochrome mosaics were taken at a range of resolutions, some suitable for stereogrammetry, and a series of color frames was acquired for photometric analysis. MASCS obtained the first high-resolution spectral reflectance measurements (at ultraviolet to near-infrared wavelengths) of surface composition, conducted night-side and day-side limb scans of species in Mercury's tenuous atmosphere, and mapped the structure of Mercury's cometlike tail of neutral sodium atoms that extends from the planet in the direction opposite that of the Sun. MAG measured Mercury's intrinsic magnetic field near the equator and documented the major plasma boundaries of Mercury's magnetosphere. (Mercury's intrinsic magnetic field is of internal origin, the product of either a magnetic dynamo within the fluid outer core or a permanently magnetized upper crustal layer, in contrast to fields of external origin, such as those generated by currents in the magnetosphere.) EPPS made the first measurements of low-energy ions in Mercury's magnetosphere and its heliospheric environment. MLA carried out the first laser altimetric profile of the planet, and GRNS and XRS provided a first look at surface elemental composition. The radio science experiment reduced uncertainties in the long-wavelength components (that is, lowest spherical harmonics) of Mercury's gravity field.

Surface observations. Although Mercury's surface is densely populated with impact-craters, *MESSENGER* images have revealed substantial new information on the geological history of the planet. From temporal constraints on the emplacement of smooth plains indicated by superposition relationships and measurements of impact-crater density, MDIS images provided evidence for widespread volcanism on Mercury, and candidate sites for volcanic centers were identified. MDIS also revealed newly imaged lobate scarps and other tectonic landforms

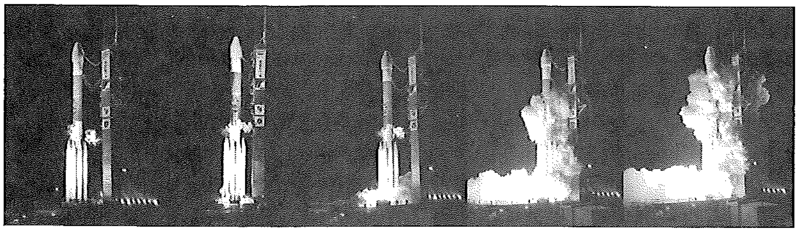

Fig. 4. Launch of *MESSENGER* from Cape Canaveral Air Force Station Space Launch Complex 17B on a Delta II 7925H-9.5 at 06:15:56.537 UTC on August 3, 2004. (*NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington*)

supportive of the hypothesis that Mercury contracted globally in response to interior cooling and growth of a solid inner core (**Fig. 5**). From the density of fault structures now recognized, the magnitude of global contraction is at least one-third greater than appreciated from *Mariner 10* observations. Reflectance spectra of Mercury show no evidence for ferrous iron (FeO) in surface silicates, and the Neutron Spectrometer sensor on GRNS indicates an upper bound of 6% on the surface elemental abundance of iron. The reflectance and color imaging observations support earlier inferences that Mercury's surface material consists dominantly of iron-poor, calcium-magnesium silicates with an admixture of spectrally neutral opaque minerals. The Caloris basin, one of the few areas of Mercury that experienced horizontal extensional faulting, has at its center a radial pattern of extensional troughs unlike anything seen elsewhere on the planet (**Fig. 6**). MLA demonstrated that the equatorial topography of Mercury has at least 5 km (3 mi) of relief.

Space environment observations. MESSENGER also confirmed that Mercury's internal magnetic field is primarily dipolar, inventoried the heavy ions that fill the magnetosphere, and detected two current-sheet boundaries on the outbound leg of its trajectory. A current sheet is a surface that separates regions of differing magnetic field orientation or intensity. One of the current sheets was located at Mercury's magnetopause (the boundary to the region of space dominated by Mercury's magnetic field rather than that of the solar wind field), as expected, while the other, about 1000 km (600 mi) closer to the planet, may mark the edge of a boundary layer for planetary ions that have been ionized and accelerated by the solar wind or possibly signals that solar wind protons have much greater access to Mercury's magnetosphere than is the case at Earth. MASCS mapped a north-south asymmetry in the sodium tail and determined the ratio of sodium to calcium near the tail and also near the dawn terminator.

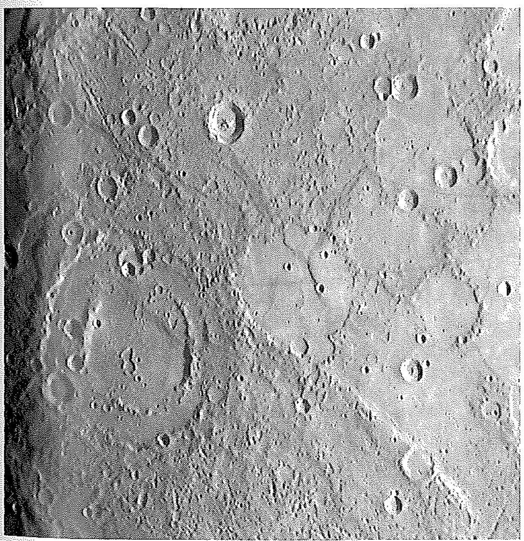

Fig. 5. *MESSENGER* narrow-angle camera image, about 500 km (300 mi) across, illustrating the interplay of cratering, volcanism, and deformation on Mercury. A peak-ring basin (left) has been nearly filled with smooth plains material. The basin was later disrupted by the formation of a prominent scarp or cliff, the surface expression of a major thrust fault, which runs alongside part of the basin's northern rim and may have led to the uplift seen across a portion of the basin floor. A smaller crater in the lower right of the image has also been deformed by the scarp, showing that the fault system was active after both impact features had formed. Smooth plains material abutting and ponding against the lower, northeastern edge of the scarp suggests that volcanism continued in this area after this fault system ceased to be active. (*NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington*)

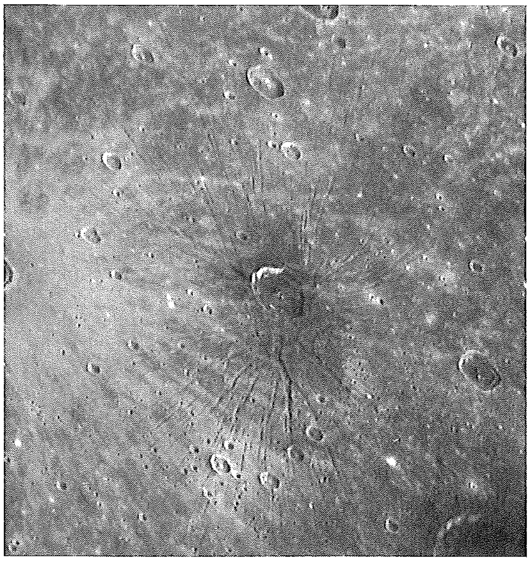

Fig. 6. *MESSENGER* narrow-angle camera image of Pantheon Fossae, a set of more than 100 narrow troughs that radiate outward from the 41-km-diameter (25-mi) Apollodorus crater and occupy the central region of the interior floor of the 1550-km-diameter (960-mi) Caloris basin. (*NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington*)

Administration. The Johns Hopkins University Applied Physics Laboratory built and operates the *MESSENGER* spacecraft and manages the mission for NASA.

For background information *see* MAGNETOSPHERE; MERCURY; OPERATING SYSTEM; PLANET; SPACE COMMUNICATIONS; SPACE POWER SYSTEMS; SPACE PROBE; SPACE TECHNOLOGY; SPACECRAFT PROPULSION in the McGraw-Hill Encyclopedia of Science & Technology.

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Metal-free hydrogen activation and catalysis

Hydrogen (H_2) is the simplest diatomic molecule. Despite this simplicity, H_2 plays a very significant role in today's economy and is destined to become even more important in the future. Hydrogenation—the chemical addition of H_2 across double or triple