FIRST ROCK FROM THE SUN: 50 YEARS OF MERCURY EXPLORATION. Sean C. Solomon[1], Larry R. Nittler[2], Brian J. Anderson[3], and Paul K. Byrne[4], [1]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA (solomon@ldeo.columbia.edu), [2]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA, [3]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA, [4]Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695, USA.

Introduction. Among the solar system's inner planets, Mercury is the smallest and closest to the Sun. Its bulk density corrected for the effect of internal compression is the highest among the planets, implying that Mercury's mass fraction of iron is much greater than those of Earth, Venus, or Mars. Its orbit is the most eccentric of the planets, and the planet is the only known solar system object locked in a 3:2 spin–orbit resonance, in which three sidereal days equal two Mercury years. These attributes were all known 50 years ago, before spacecraft exploration of the innermost planet.

Mariner 10. NASA's Mariner 10 was the first spacecraft to visit Mercury. Launched in November 1973 on a trajectory with a gravity-assist flyby of Venus, Mariner 10 flew by Mercury in March 1974. After a propulsive maneuver transferred the spacecraft to an orbit with a period twice that of Mercury, two more successful flybys followed. Mariner 10 carried an imaging system, two magnetometers, an infrared radiometer, two ultraviolet spectrometers, two plasma detectors, two charged-particle telescopes, and a radio science experiment [1].

Because of Mercury's spin–orbit resonance, the same hemisphere of the planet was sunlit during each of the three flybys. The spacecraft thus acquired images of only ~45% of the surface, but that fraction was sufficient to document the generally high areal density of impact craters, characterize the largest tectonic features on the planet, and discern the major types of morphological units on the surface. Our understanding of the Moon from the Apollo missions shaped efforts to synthesize Mercury's geological history [2] and raised the question of whether Mercury's smooth plains were emplaced as volcanic material or ejecta from large impacts [3]. Mariner 10 also discovered Mercury's global magnetic field, detected bursts of energetic charged particles inside Mercury's magnetosphere, and measured the abundances of neutral hydrogen and helium in Mercury's exosphere [1].

MESSENGER. After Mariner 10, it was widely recognized that the next logical step in the exploration of Mercury would be an orbiter [4], but nearly a quarter century would pass before such a mission was selected for flight by a space agency. Key steps in the U.S. were the discovery of trajectories involving multiple gravity-assist flybys of Venus and Mercury that permitted insertion of a spacecraft into orbit about Mercury with a chemical propulsion system [5] and the establishment of NASA's Discovery Program of planetary spacecraft missions led by a scientific investigator and limited in total mission cost, development time, and launch vehicle requirements. Missions to Mercury were among the earliest to receive funding for concept studies under that program [6], and at least two Mercury missions were proposed in response to each of the program's announcements of opportunity in 1994, 1996, and 1998. The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission [7] was proposed to the Discovery Program in 1996 and 1998, and on the basis of the second proposal NASA selected the mission for flight in July 1999.

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

Launched in 2004, MESSENGER followed an interplanetary cruise phase that lasted 6.6 years and included one flyby of Earth, two of Venus, and three of Mercury. During the Mercury flybys, MESSENGER mapped nearly the entire planet in color, imaged most of the areas unseen by Mariner 10, measured the composition of Mercury's exosphere and neutral tail, and conducted initial characterizations of the structure and dynamics of Mercury's magnetosphere. In March 2011, MESSENGER was inserted into an eccentric orbit about Mercury with a high northern periapsis. Over the primary orbital mission phase and two extended missions, MESSENGER acquired a variety of global imaging data sets, mapped the composition of surface materials, determined the planet's magnetic and gravity fields, measured global topography, assayed the composition and distribution of Mercury's neutral atmosphere and charged-particle environment, and documented the structure of Mercury's magnetosphere and its dynamic response to changes in the solar wind and interplanetary magnetic field [7].

MESSENGER observations markedly changed our view of Mercury. Surface materials are much more chemically reduced than those of the Moon or other inner planets and contain unexpectedly high abundances of volatile elements [8,9], and the discovery of pyroclastic deposits [10] and a new landform, called hollows [11], point to volatiles at depth. Mercury's interior structure is characterized by a larger core and thinner silicate shell and mantle than earlier thought [12,13]. The planetary magnetic field is that of an axially aligned dipole, but one offset from the planet center by ~20% of the planetary radius, and crustal magnetic anomalies of ancient origin were discovered from low-altitude measurements [14]. Plains volcanism was widespread on Mercury and probably dominated the emplacement of the planet's crust, but effusive activity largely ended by ~3.5 Ga [10,15–17]. Tectonic features accommodated substantially more crustal shortening than previously recognized, resolving a long-standing discrepancy between photogeological observations and predictions of thermal history models [18,19].

Mercury's polar deposits consist predominantly of water ice, exposed at the surface in the highest-latitude regions of permanent shadow but covered in other permanently shadowed regions by a dark, insulating layer of other volatile materials, likely complex organic deposits, stable to variable but higher temperatures than water ice [20]. The three most dominant species in Mercury's exosphere – Na, Ca, and Mg – display different distributions with altitude and local time, indicating a different mix of source and transport processes for each [21,22]; and exospheric Mg is enhanced over a high-Mg region [23] identified from geochemical remote sensing [8,24]. Mercury's magnetosphere, much smaller than but broadly similar in structure to Earth's, acts effectively to energize solar wind plasma and channel it to the planetary surface, and magnetic reconnection between the planetary and interplanetary magnetic fields at Mercury occurs with an intensity an order of magnitude greater than at Earth [25,26].

BepiColombo. The BepiColombo dual orbiter mission of the European Space Agency (ESA) and Japan Exploration Space Agency (JAXA), with roots also extending back to the 1990s, was approved as an ESA mission in 2000, and the ESA–JAXA partnership was finalized in 2003 [27,28]. The two probes were launched, together with a Mercury Transfer Module that hosts a solar electric propulsion system, in October 2018 and will follow a cruise trajectory involving one flyby of Earth, two of Venus, and six of Mercury. The package will be gravitationally captured by Mercury in December 2025, after which the two spacecraft – a Mercury Planetary Orbiter (MPO) and the Mio magnetospheric orbiter – will be inserted into distinct coplanar polar orbits with equatorial periapses.

The two spacecraft carry a total of 16 instruments, with 11 on the MPO and five on Mio [27,28]. The MPO carries imaging, geochemical and exospheric remote sensing, and particle spectrometers, a laser altimeter, a magnetometer, an accelerometer, and a radio science package. Mio is equipped with a plasma particle experiment and plasma wave instrument, a spectral imager, a dust monitor, and another magnetometer. The MPO will also test gravitational theory and make precise measurements of the temporal variation of the gravitational constant. The orbital mission phase will last one Earth year, and there will be an option for a one-year extended mission [27,28].

Conclusion. Although the spacecraft exploration of Mercury long lagged that of the Venus and Mars, with the completion of the MESSENGER mission in 2015 and the launch of the BepiColombo mission last year our understanding of the distinctive innermost planet is now in the midst of a scientific renaissance.

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