Mercury after MESSENGER

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A NASA Discovery Mission
Mercury Is a Planet of Extremes

- Closest to Sun
- Highest uncompressed density
- Highest diurnal variation in temperature
- Only solar system object in 3:2 spin-orbit resonance
- Geological history ended earliest among the terrestrial planets
- Smallest planet with global magnetic field
- Most Earth-like magnetosphere
Mariner 10 mosaic of the Caloris basin.

Contributions of Mariner 10 flybys 1974-1975

- Imaged 45% of Mercury’s surface.
- Discovered Mercury’s magnetic field.
- Detected H, He, O in Mercury’s exosphere.
- Documented time-variable nature of Mercury’s magnetosphere.
“The primary planetary objectives in the exploration of Mercury for the period 1977-1987 are to determine the chemical composition of the planet’s surface on both a global and regional scale, to determine the structure and state of the planet’s interior, and to extend the coverage and improve the resolution of orbital imaging.”

“Secondary planetary objectives of Mercury explorations are (1) further exploration of Mercury’s magnetosphere and internal magnetic field, (2) measuring global heat flow, and (3) conducting gravity and topographic surveys of the planet.”

“Steps should be made to prepare for the investigation of Mercury after definition of an adequate propulsion capability and in advance of availability of the system.”

“COMPLEX…recommends that characterization of Mercury’s magnetic field be a primary objective for exploration of that planet.”

“A Mercury mission is a possible near-term activity, and justification of such a mission should rest on the important role of Mercury in understanding the origin and evolution of all the terrestrial planets.”

Contributions of Earth-based Observations

- Discovery of Mercury’s 3:2 spin-orbit resonance (1965)
- Discovery of Na (1985), K (1986), and Ca (2000) in Mercury’s exosphere
- Discovery of Mercury’s polar deposits (1992)
- Discovery of Mercury’s molten outer core (2007)
“Given the increasingly detailed studies of Mars and Venus, plus the knowledge gained by previous lunar exploration, Mercury stands out among the terrestrial planets as the least understood, although it is a planet rich in potential scientific reward.”

“The planet Mercury holds some special interest because of its remarkably high uncompressed density. A chemical and mineralogical characterization of Mercury’s surface — when combined with an understanding of surface geology and crustal formation — could contribute significantly to understanding the processes that dominated the inner solar system during its formation.”

Mission Milestones

Selection as a Discovery Mission
Phase B (detailed design)
Phase C/D (fabrication, assembly, and test)
Launch
Earth flyby
Venus flybys
Mercury flybys

Mercury orbit

July 1999
January 2000 - June 2001
July 2001 - July 2004
August 2004
August 2005
October 2006, June 2007
January 2008, October 2008,
September 2009
March 2011 - March 2012
What planetary formational processes led to the high metal/silicate ratio in Mercury?
What is the geological history of Mercury?
What are the nature and origin of Mercury's magnetic field?
What are the structure and state of Mercury's core?
What are the radar-reflective materials at Mercury's poles?
What are the important volatile species and their sources and sinks on and near Mercury?
MESSENGER’s objectives have remained unchanged between the 1998 Concept Study Report that was the basis for mission selection and the current mission.

<table>
<thead>
<tr>
<th>Mission Objectives</th>
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<tbody>
<tr>
<td>Map the elemental and mineralogical composition of Mercury’s surface</td>
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<tr>
<td>Image globally the surface at a resolution of hundreds of meters or better</td>
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<td>Determine the structure of the planet's magnetic field</td>
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<td>Measure the libration amplitude and gravitational field structure</td>
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<td>Determine the composition of the radar-reflective materials at Mercury's poles</td>
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<td>Characterize exosphere neutrals and accelerated magnetosphere ions</td>
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MESSENGER
Payload Instruments

- Mercury Atmospheric and Surface Composition Spectrometer (MASCS)
- Gamma-Ray Spectrometer (GRNS/GRS)
- Mercury Laser Altimeter (MLA)
- Fast Imaging Plasma Spectrometer (EPPS/FIPS)
- Energetic Particle Spectrometer (EPPS/EPS)
- Neutron Spectrometer (GRNS/NS)
- Data Processing Unit (DPU)
- X-Ray Spectrometer Mercury Unit (XRS/MXU)
- X-Ray Spectrometer Solar Assembly (XRS/SAX)
- Magnetometer (MAG) [at end of boom - not shown]
“The Inner Planets Panel’s highest-ranked science missions are as follows:

1. *Mercury Science*. The successful implementation of the MESSENGER mission to Mercury, designed for the basic reconnaissance of Mercury’s geology, atmosphere, magnetosphere, and topography, will finally complete our basic knowledge of the planets in the inner solar system. This is a long-standing high priority for exploration, and the panel reaffirms the strong community consensus for support. The panel explicitly reiterates the essential nature of the science objectives as being carried out by MESSENGER and *expects full replacement* in the event of unforeseen implementation problems.”

MESSENGER Trajectory

Mercury Orbit Insertion (MOI)
$\Delta V = 0.867 \text{ km/s}$

Mercury Flyby 3
Mercury Flyby 2
Mercury Flyby 1
(200 km altitude - all 3 flybys)

DSM = Deep Space Maneuver

Earth at Mercury Orbit Insertion

Venus Flybys 1 and 2
(3368 and 300 km altitude)

Earth Flyby
(2364 km altitude)

Launch
$C_3 = 16.4 \text{ km}^2/\text{s}^2$

8/03/04 8/02/05 10/24/06 6/6/07 1/14/08 10/6/08 9/30/09 3/18/11
MESSENGER
Flyby 1 and 2 Geometries

View from above Mercury’s north pole

spacecraft time shown

5 minutes

spacecraft in eclipse

day/night terminator

smooth area was not imaged by Mariner 10

Sun

January 14, 2008
19:04:39 UTC
201.4 km (125.1 mi) altitude

Earth

View from above Mercury’s north pole

spacecraft time shown

5 minutes

spacecraft in eclipse

day/night terminator

smooth area was not imaged by Mariner 10

Sun

October 6, 2008
08:40:22 UTC
199.4 km (123.9 mi) altitude
All instruments operated successfully

Flyby 1 returned 1213 images, nearly 500 MB of data

Flyby 2 returned 1287 images, 650 MB of data

WAC image taken 90 minutes after M2 closest approach (~5 km/pixel).
Some Mercury Firsts

- Closest spacecraft approach
- First spacecraft observations of neutral tail
- First plasma ion measurements
- First laser altimetry
- First 11-color imaging
- First high-resolution surface spectroscopy by spacecraft
- First UV spectroscopy of surface

NAC image of rayed crater 80 km in diameter (530 m/pixel).
Mercury Orbit Insertion: 18 March 2011

hp = 200 km

337° Mercury true anomaly (near start of orbital phase)

247° Mercury true anomaly (maximum eclipse)

φ = Periapsis latitude

ha = Apoapsis altitude

hp = Periapsis altitude

i = Orbital inclination

P = Orbital period

P = 12 hours

ha = 15,193 km

φ = 60° N
MESSENGER
Global Color, M1 and M2
**Equatorial Color Mosaic, M2**

- Orange-rimmed craters
- Tectonic deformation
- Smooth plains
- Low-reflectance (blue) material

**Scale:** Mosaic 1950 km wide
Orbital Color Imaging

Resolution(BV3a_ColorAl010)

(μ = 1.029, σ = 0.312)
MESSENGER
High-resolution NAC Images
Orbital Monochrome Imaging

Resolution(BV3a_BasemapConstant68)

(μ = 0.211, σ = 0.069)
Targeted Hi-res Imaging

Pantheon Fossae, Caloris basin
• Mercury is spectrally similar to lunar highlands (without FeO band).
• Spatial variations in spectra are resolvable and reflect differences in maturity and composition.

Sample of M1 spectra
Variations in the observed distributions constrain the combination of source processes involved.
Plasma Ion Composition

[Zurbuchen et al., 2008]
Smooth inversions of MESSENGER and M10 observations, after correcting for external fields and accounting for noise contributions, yield harmonic fields.

Field is dominantly dipolar (~215 nT $R_M^3$, ~2° tilt), with substantial higher-order structure.

[Uno et al., 2009]
Observations of Reconnection

- Measured large $B_n = 13$ nT at MP, ratio $B_n/B_t = 13\%$ (Earth 1%).
- Reconnection leads to formation of flux ropes and plasmoids in the magnetotail.
- A flux transfer event was observed at the M2 outbound magnetopause crossing.
BepiColombo Cruise Configuration

- MTM: Mercury Transfer Module
- MPO: Mercury Planetary Orbiter
- MMO: Mercury Magnetospheric Orbiter
- Sunshield
MESSENGER
BepiColombo Objectives

• Origin and evolution of a planet close to its parent star

• Mercury as a planet - form, interior, structure, geology, composition and craters

• Mercury's exosphere composition and dynamics

• Mercury's magnetized envelope (magnetosphere): structure and dynamics

• Origin of Mercury's magnetic field

• Test of Einstein's theory of general relativity
Mercury Planetary Orbiter (MPO)
- Polar orbit optimized for study of the planet
- 400 X 1500 km
- 2.3-hr period

Mercury Magnetospheric Orbiter (MMO)
- Polar orbit optimized for study of the magnetosphere
- 400 X 12,000 km
- 9.2-hr period
**MESSENGER**
BepiColombo Responsibilities

- **ESA:**
  - Mission design,
  - MPO spacecraft,
  - Mercury Transfer Module, integration and test, launch,
  - Overall cruise operations,
  - MPO operations at Mercury

- **JAXA:**
  - MMO spacecraft and its operations
  - National funding:
    - 10 European and 1 Russian instruments on the MPO
    - 4 Japanese and 1 European instruments on the MMO
## MESSENGER
MPO Payload Resources

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass [kg]</th>
<th>Power (allocated) [W]</th>
<th>Power (Orbit Average) [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BELA (altimeter)</td>
<td>12</td>
<td>49</td>
<td>49</td>
</tr>
<tr>
<td>ISA (accelerometer)</td>
<td>5.3</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>MPO/MAG</td>
<td>1.8</td>
<td>5</td>
<td>4.6</td>
</tr>
<tr>
<td>MERTIS (mid-IR)</td>
<td>3.3</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>MIXS (XRS)</td>
<td>7.3</td>
<td>12</td>
<td>18</td>
</tr>
<tr>
<td>MGNS (GRS, NS)</td>
<td>5.2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>MORE (radio sci)</td>
<td>3.5</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>PHEBUS (UV)</td>
<td>6.6</td>
<td>4</td>
<td>5.4</td>
</tr>
<tr>
<td>SERENA (particles)</td>
<td>5.4</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>SIMBIO-SYS (imaging)</td>
<td>8.3</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>SIXS (solar X-rays)</td>
<td>1.3</td>
<td>2</td>
<td>2.7</td>
</tr>
<tr>
<td>TOTAL</td>
<td>60</td>
<td>164</td>
<td>182</td>
</tr>
</tbody>
</table>
**MGF (2 sub-units)**
Magnetic Field Investigation studies magnetic field from the planet, magnetosphere, and interplanetary solar wind.

**MPPE (7 sub-units)**
Mercury Plasma Particle Experiment studies plasma and neutral particles from the planet, magnetosphere, and interplanetary solar wind.

**PWI (7 sub-units)**
Plasma Wave Investigation studies electric field, electromagnetic waves, and radio waves from magnetosphere and solar wind.

**MSASI**
Mercury Sodium Atmosphere Spectral Imager studies the thin sodium atmosphere.

**MDM**
Mercury Dust Monitor studies dust from the planet and interplanetary and interstellar space.
MESSENGER will complete its nominal mission in 2012; an extended mission could enable additional observations until 2013 or perhaps longer.

BepiColombo is scheduled to launch in 2014, to arrive at Mercury in 2020, and to operate from orbit for at least one year.

After three Mercury orbiters have completed operations, the next mission to Mercury should be substantially different, e.g., a lander or a sample return mission.
Determination of Mercury’s surface composition, one of the highest-priority goals of orbiter missions, may prove challenging (limited spectral features, large integration times needed for elemental remote sensing).

- Ground-truth information would provide key constraints on planetary formation hypotheses and could be leveraged by orbital mapping.

- A lander or sample return would be needed.
Determining the composition of Mercury’s polar deposits is another high-priority objective.

Remote sensing will be challenged for spacecraft orbits having periapses far from a pole.

Alander mission to a polar crater floor, with some ability to probe the subsurface (e.g., drill or arm), would offer a substantial advance on this question.

Arecibo radar image of north polar deposits [Harmon et al., 2001].
Challenges to Surface Operations

- Power (3-month night)
- Temperature (600°C diurnal cycle at equator)
- Communication (orbiter link needed?)

Credit: Michael Carroll