MESSENGER at Mercury: Exploring an Enigmatic Planet

Larry R. Nittler
Carnegie Institution of Washington

Night Sky Network Webinar April 18, 2016
Mercury

- Naked-eye planet, but very difficult to observe due to proximity to Sun
Early Observations of Mercury

- Greek astronomer Eudoxus correctly measured Mercury’s synodic period in ~400 BC.
- One early recorded observation (Mesopotamia), Nov. 15, 265 BC.
- Earliest telescopic observations by Galileo and Harriot, 1609.
Early Observations of Mercury

• Discovery of phases by Zupus (1639) proved the Copernican theory that planets orbit the Sun, not the Earth

• Early maps

G. Schiaparelli

P. Lowell

E. Antoniadi
Mercury Is Difficult to Study

...by telescope ...

...or spacecraft.

Only prior visit was by Mariner 10, 1974-1975
Mercury Exploration

Contributions of Mariner 10 flybys:

• Imaged 45% of Mercury’s surface

• Discovered Mercury’s magnetic field and dynamic magnetosphere

• Detected H, He, O in Mercury’s “exosphere”
Mercury Exploration

Contributions of Earth-based astronomy

• Discovery of Mercury’s 3:2 spin-orbit resonance (1965)
  • 3 days in 2 years
• Discovery of sodium (1985), potassium (1986), and calcium (2000) in Mercury’s exosphere

Na emission
Potter et al. 2002
Mercury Exploration

Contributions of Earth-based astronomy

• Discovery of Mercury’s polar deposits (1992)
• Discovery of Mercury’s molten outer core (2007)

Harmon et al. 1999
Mercury: planet of extremes

- Smallest, densest planet
- Closest to Sun
- Highest diurnal variation in temperature
  - $-170 \, ^\circ C$ to $+430 \, ^\circ C$
- Very high Fe:silicate ratio
  - Core $\sim 70\%$ of mass, $80\%$ radius
- Mercury and Earth are the only inner planets with magnetic fields

“end-member of planet formation”
Extrasolar Planetary Context

Mercury

Semi-Major Axis [Astronomical Units (AU)]

Orbital Eccentricity

M_{\sin(i)} [Jupiter Mass]
Extrasolar Planetary Context

Mercury

Mercury-like?
• First spacecraft to orbit Mercury
• 7th NASA Discovery mission
– PI: Sean C. Solomon
Challenge: Surviving at Mercury

Ceramic cloth sunshade

Solar panels 2/3 mirrors
Trajectory allowed orbit insertion
### MESSENGER’s Guiding Science Questions mapped to Measurement Objectives

<table>
<thead>
<tr>
<th>Science Questions</th>
<th>MESSENGER Measurement Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Why is Mercury so dense?</td>
<td>Map the elemental and mineralogical composition of Mercury’s surface</td>
</tr>
<tr>
<td>What is the geological history of Mercury?</td>
<td>Globally image the surface at a resolution of hundreds of meters or better</td>
</tr>
<tr>
<td>What are the nature and origin of Mercury’s magnetic field?</td>
<td>Determine the structure of the planet’s magnetic field</td>
</tr>
<tr>
<td>What are the structure and state of Mercury’s core?</td>
<td>Measure the libration amplitude and gravitational field structure</td>
</tr>
<tr>
<td>What are the radar-reflective materials at Mercury’s poles?</td>
<td>Determine the composition of the radar-reflective materials at Mercury’s poles</td>
</tr>
<tr>
<td>What are the important volatile species and their sources and sinks near Mercury?</td>
<td>Characterize exosphere neutrals and accelerated magnetosphere ions</td>
</tr>
</tbody>
</table>
MESSENGER's Scientific Payload

- Mercury Atmospheric and Surface Composition Spectrometer (MASCS)
- Gamma-Ray Spectrometers (GRNS/GRS)
- Mercury Laser Altimeter (MLA)
- X-ray Spectrometer Solar Assembly (XRS/SAX)
- Mercury Dual Imaging System (MDIS)
- Fast Imaging Plasma Spectrometer (EPPS/FIPS)
- Energetic Particle Spectrometer (EPPS/EPS)
- Neutron Spectrometer (GRNS/NS)
- Data Processing Unit (DPU)
- Magnetometer (MAG) [at end of boom not shown]
Launch, August 2004

Vibration test, December 2003
Getting to Mercury

Earth (August 2005)  Venus (October 2006)
Mercury Flybys (2008-2009)

- >90% of surface imaged

M1 (Jan 2008)
M2 (Oct 2008)
M3 (Sep 2009)
Mercury Flybys (2008-2009)

- >90% of surface imaged

Mission also first spacecraft to use solar sailing!

M1 (Jan 2008)
M2 (Oct 2008)
M3 (Sep 2009)
Mercury Orbit Insertion (March 18, 2011)

- 200- to 500-km minimum altitude over 60°-70° North latitude
- North to Sun
- 12 hours per orbit
- 82.5-84.0° orbit inclination
- Edge-on orbit view
- Dawn-dusk orbit
- Noon-midnight orbit
- Up to 15,200-km maximum altitude
Mercury Orbit Insertion (March 18, 2011)

4104 orbits completed before impact April 30, 2015
Feb 2013: MESSENGER imaging coverage reached 100%
Illumination Matters

MARINER 10

MESSENGER
Formation of Mercury

- Terrestrial planets shared common formation process: *accretion*

  Dust -> Rocks -> Planetesimals -> Planets

- Why does Mercury have such a large Fe core?
(pre-MESSENGER) Mercury Formation Models

- Accretion at high-T? (Lewis 1973)
- Evaporation by hot Sun? (Cameron 1985)
- Giant impact stripping? (Wetherill, Benz 1988)
- Metal-silicate segregation (Weidenschilling 1978)
Composition is key

- Surface elemental composition depends on starting materials and history
- MESSENGER had 3 instruments for measuring surface composition
  - X-ray Spectrometer (XRS)
  - Gamma-ray Spectrometer (GRS)
  - Neutron Spectrometer (NS)
Volatile Elements on Mercury

Moon depleted in volatile K (Peplowski et al., 2011, 2012)
Volatile Elements on Mercury

Mercury not volatile-depleted (similar to Mars, Earth)

(Peplowski et al., 2011, 2012)
Volatile Elements on Mercury

Mercury not volatile-depleted (similar to Mars, Earth)

Also rich in volatiles Na and Cl!
• X-ray Spectrometer data indicate Mercury Mg-rich, Al-Ca-poor, relative to Earth and Moon surface.
• X-ray Spectrometer data indicate Mercury Mg-rich, Al-Ca-poor, relative to Earth and Moon surface
Major elements on Mercury

Mg/Si

Al/Si

Weider et al. EPSL, 2015
High Sulfur, Low Fe

- S much higher; Fe much lower than other terrestrial planet crusts
  - Earth’s Crust: ~300 ppm S, 5 wt% Fe
- Indicates formation under much less oxidizing conditions than other planets
Carbon on Mercury!

Mercury very dark; darkest materials excavated from deep in crust

Low-altitude neutron measurements, spectra most consistent with graphite
- average ~1 wt% graphite at surface
- Buried remnant of Mercury’s first crust

Mercury is a volatile-enriched, chemically reduced planet

- Rules out many pre-MESSENGER formation models involving very high temperatures
  - High-temperature accretion
  - Evaporation of larger mantle by bright early Sun
  - Stripping of larger mantle by giant impact?? [still viable, but no reliable geochemical predictions]

- Mercury made of different mix of materials than other terrestrial planets
Geologic History: Widespread Volcanism

Northern Plains

Murchie et al. [2008]

Head et al. [2011]
New Landform: “Hollows”

• Bright deposits within impact craters show fresh-appearing, rimless depressions, commonly with halos.

• Formation from recent volatile loss?

[Blewett et al., 2011]
Tectonics

- Mercury covered with “lobate scarps” (cliffs)
- Due to contraction of planet as it cooled
- Detailed analysis of MESSENGER data indicates much more contraction than previous work (Byrne et al. 2014)
Mercury Geophysics

- Radio Science combined with topography (left, from laser altimetry) to infer gravity map (below)
- Use to constrain interior structure

Zuber et al. Science [2012]

Smith et al. Science [2012]
Internal Structure

- Model of interior based on gravity field
  - Based on millions of internal structure models (Smith et al. 2012, Hauck et al. 2013)
  - Top of liquid core at $r=2020 \pm 30$ km [$R_{\text{planet}}=2440$ km]

- High density (FeS) layer at base of mantle not required but consistent with data and may be expected for highly reduced planet
Magnetic field is dipolar and of the same sense as that of the Earth, but displaced northward from the planet center by 480 km.

Large offset is unprecedented in the solar system and puts constraints of the generation mechanism.

Anderson et al. [2011]
Remanent Crustal Magnetism

- At low altitude (<60 km), saw magnetic field variations from surface – preserved in crust
- Thermal preservation of magnetization over ~4 Gyr!

Johnson et al. 2015
Mercury’s Magnetosphere

- Interaction of Mercury’s weak magnetic field with solar magnetic field leads to complex and dynamic “magnetosphere”
  - Playground for space plasma physicists

Slavin et al. [2009]
Mercury’s Exosphere

- Na, Ca, Mg most abundant species
- Asymmetries in distributions: different source mechanisms
  - Na uniformly distributed
  - Ca shows dawn enhancement
  - Both show seasonal variability

Vervack et al., 2011, Killen et al., 2012, Burger et al., 2012, 2014; Merkel et al., 2012
• Deposits with radar characteristics of water ice discovered in polar craters by ground-based astronomy in 1992.
• Imaging of polar regions confirms that radar-bright deposits occur in permanently shadowed regions.
• Thermal modeling indicates ice/organic stability where deposits located.
• Neutron emissions sensitive to hydrogen
• Decrease at Mercury’s North pole quantitatively matches expectation if deposits are water ice

Lawrence et al., Neumann et al., Paige et al. Science [2013]
• Deep MESSENGER imaging also reveals brightness variations in deposits (Chabot et al., 2014)
End of mission

- First use of helium as spacecraft propellant!
The rayed crater Debussy has a diameter of 80 kilometers (50 miles). This image is about 1 kilometers (0.6 miles) across.
Acknowledgements

• MESSENGER Science Team, Engineers and Mission Controllers
MESSENGER at Mercury

• MESSENGER was an extraordinarily successful mission

• Despite its small size, Mercury is a weird and wonderful world.
  - Different in fundamental ways from other terrestrial planets
  - May provide valuable information for extrasolar planets