MESSENGER’s Flybys of Mercury: Three Glimpses into the Workings of a Complex Exospheric System

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Mercury Atmospheric and Surface Composition Spectrometer (MASCS)

Small Cassegrain telescope with an aperture that simultaneously feeds two parts:

- Ultraviolet and Visible Spectrometer (UVVS)
- Visible and InfraRed Spectrograph (VIRS)

UVVS is a scanning grating, Ebert-Fastie monochromator with three PMTs:

- 115-190 nm (FUV-PMT)
- 160-320 nm (MUV-PMT)
- 250-600 nm (VIS-PMT)

UVVS has two slits:

- Atmospheric slit (1 x 0.04)
- Surface slit (0.05 x 0.04)
**Processes at Work in Mercury’s Exosphere**

### Source Processes

**Low-Energy Processes**
- Photon-Stimulated Desorption and Thermal Evaporation

**High-Energy Processes**
- Ion Sputtering
- Meteoroid Vaporization

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**Atom Trajectories**
- Atoms released with low energy generally return to the surface
- Some atoms will be photoionized and be removed via the magnetic field
- Different atoms are accelerated in the anti-sunward direction to varying degrees; those most strongly accelerated can form an extended tail
- These more energetic atoms are airborne long enough to be affected by solar radiation pressure

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**Notes:**
- Atoms released with higher energy can make it to higher altitudes
Tail Observations
Mercury Flyby 1

Extended Tail
Na

Anti-Sunward Direction

Spacecraft Trajectory
Sodium Tail Observations

First Flyby

- small northern enhancement relative to south – could be observational effect
Sodium Tail Observations

- M1 and M2: Mercury orbit geometry (TA ~ 285, 293)
  - Na radiances comparable ([Na(M1)]/[Na(M2)] ~ 1.2)
- M2 tail asymmetry less compelling (incomplete sampling in the north)
Calcium Tail Observations

- Densities peak toward equatorial plane for $R > 2R_M$
- Short ionization lifetime ($\sim 1700$ sec) suggests significant loss of neutrals
- High energy ($\sim 4-5$ eV) release process required to populate the tail
Magnesium Tail Observations

- Long ionization lifetime ($\sim 2.1 \times 10^5$ sec) + low radiation pressure consistent with a relatively isotropic distribution
- Moderate energy ($\sim 2$ eV) release process required to populate the tail
Comparison of Different Species

**Sodium**

![Sodium Radiance](image)

**Calcium**

![Calcium Radiance](image)

**Magnesium**

![Magnesium Radiance](image)
Variations in the observed distributions tell us about the relative strength of the various processes involved.
Sodium Tail Observations

- M3: ~ 20x reduction in radiance at 2R_M relative to M1 and M2 partly the result of orbit geometry (TA for M3 ~ 331; TA ~ 285, 293 for M1, M2)

First Flyby

Second Flyby

Third Flyby
Sodium Tail Observations

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Clues also come from these “seasonal” variations with time so it is important to have both spatial AND temporal coverage.
Summary of Neutral Tail Observations

- Tail observations probe surface material escape
  - Strong radiation pressure permits escape of low-energy Na
  - High-energy source processes are required to deliver Ca and Mg to $R > 2R_M$
    - High-energy tails of solar-wind sputtering and meteoroid impact vaporization
    - Release of oxide followed by photodissociation possibly a source
    - Recent laboratory work suggests that electron stimulated desorption (ESD) may be a source for the tail

- Distinct distributions of Na, Ca, and Mg result from differing source and loss processes
  - Long ionization lifetimes ($\sim 2.0 \times 10^4$ sec) and varying radiation pressure drive Na tail density and structure
  - Short ionization lifetime ($\sim 1.7 \times 10^3$ sec) requires very energetic source for Ca to reach the tail
  - Very long Mg ionization lifetime ($\sim 2.1 \times 10^5$ sec) and very low radiation pressure contribute to a relatively isotropic distribution
Detection of Ca\textsuperscript{+} in the Tail Region
Polar Observations
Mercury Flyby 3

Extended Tail
Na, Ca, Ca^+, Mg

Anti-Sunward Direction

Spacecraft Trajectory

Polar Regions
Na, Ca, Ca^+, Mg

Anti-Sunward Direction

Spacecraft Trajectory
Sodium

\[
\log_{10}[\text{Radiance (rayleighs)}]
\]
Sodium

\[
\log_{10}[ \text{Radiance (rayleighs)} ]
\]

Mercury Radii

Radiance (rayleighs)

Altitude (km)

North Pole
South Pole
Sodium

\[ \log_{10}[ \text{Radiance (rayleighs)} ] \]

Fits to Low-Energy Component
Fits to High-Energy Component
North Pole
South Pole

Altitude (km)
Sodium

Low-Energy Component

e-folding Distances
\sim 200 \text{ km}

PSD
Core of Ion Sputtering
Sodium

High-Energy Component

e-folding Distances
\(~ 490 \text{ km}~

High-Energy Tail of Ion Sputtering
Meteoroid-Impact Vaporization

![Graph showing radiance vs. altitude with fits to low-energy and high-energy components.](image-url)
Calcium

\[ \log_{10}[\text{Radiance (rayleighs)}] \]

- Mercury Radii
- Radiance (rayleighs)
- Altitude (km)

Graphs showing radiance data with respect to Mercury Radii and Altitude.
Calcium

\[ \log_{10}[ \text{Radiance (rayleighs)} ] \]

- Mercury Radii
- Radiance (rayleighs)
- Altitude (km)

Fits to Data

North Pole
South Pole
Calcium

- e-folding Distances
  ~ 1750 km

- Ion Sputtering
- Meteoroid-Impact
- Vaporization

![Graph showing radiance (rayleighs) vs. altitude (km) with data points and curves for North and South Pole, and a fit to the data.](image-url)
Magnesium

\[
\log_{10}[ \text{Radiance (rayleighs)} ]
\]

![Graph showing radiance data for Mercury radii and altitude, with log scale for radiance and linear scale for altitude. The graph includes data for the North and South Poles.]
Magnesium
Magnesium

e-folding Distance
~ 2150 km

Ion Sputtering
Meteoroid-Impact
Vaporization
Magnesium
Magnesium

Additional Source at Altitude

Photodissociation of MgO?
Magnesium

Additional Source at Altitude
Photodissociation of MgO?

Resonance Process
Magnesium Surface Composition Variability
Magnesium

Surface Composition Variability

![Graph showing variability in magnesium radiances across different altitudes. The graph compares data from the North Pole (blue line) and the South Pole (red line), with a green line indicating the fit to the data.](image-url)
Magnesium

Surface Composition Variability

![Graph showing the variability of Magnesium surface composition with altitude.]
“Fantail” Observations
Complicated Geometry
Complicated Geometry
Complicated Geometry
Calcium

M1, M2, and M3 distributions show persistent dawn – dusk asymmetry
M2 distribution isotropic within uncertainties
M3 distribution peaked north of the equator on the dawn side

Both M2 and M3 distributions show enhancements over the equator
Surprises From the MASCS Observations
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• Mg distribution isotropic about the planet-Sun line in the northern hemisphere for M2 but peaked toward northern dawn for M3 (and into the dayside?)
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- Complex Mg altitude profile above north pole near the terminator
- Mg distribution isotropic about the planet-Sun line in the northern hemisphere for M2 but peaked toward northern dawn for M3 (and into the dayside?)
- Distributions of chemically similar refractory species Ca and Mg are distinct from each other and from the distribution of the volatile species Na
Additional Observations
Mercury Flyby 2

Anti-Sunward Direction

Near Dawn Terminator Na, Ca, Mg

Spacecraft Trajectory
- Ca and Mg increases proportional to illuminated column
- \([\text{Na}]/[\text{Ca}]\) and \([\text{Na}]/[\text{Mg}]\) ratios increase toward the terminator
- Consistent with the idea that Na results from both high- and low-energy source processes while Ca and Mg result from high-energy processes
Mariner 10 Observations

Figure from Hunten et al. (1988)

Figure from Broadfoot et al. (1976)
What are the origins of the "cold" and "warm" components?
Mariner 10 Observations

What are the origins of the “cold” and “warm” components?

What is the origin of the “bump”?
MASCS Flyby Hydrogen Observations

First Flyby

Second Flyby
MASCS Flyby Hydrogen Observations

First Flyby

Second Flyby
MASCS Flyby Hydrogen Observations

First Flyby

Second Flyby
Miscellaneous Bits o’ Info
We looked for K and O in M1.

Small g-values $+$ short time $=$ didn’t see
Miscellaneous Bits o’ Info

We looked for K and O in M1.

Small g-values + short time = didn’t see

We looked for Fe and Al in M3.

Better g-values but…

Short time + smaller abundances = didn’t see
Overall Conclusion

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Observations point to a greater degree of interaction among the exosphere, surface, and space environment than expected
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LOTS of surprises to come!
Parting Thought

To understand Mercury fully we must have measurements of the surface, the exosphere, AND the space environment.
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In other words, there’s good reason that MESSENGER has one of the longest names of any planetary mission.

MErcury Surface, Space ENvironment, GEmochemistry, and Ranging