Measurement of Dust Environment around Mercury by MDM (Mercury Dust Monitor) on Board MMO Bepi Colombo

SHO SASAKI (NAOJ)
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# BepiColombo MMO Payload

## Mercury Dust Monitor (MDM) Group

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<tbody>
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</table>
**Dust particles in the solar system**

- **A) Interstellar dust**
- **B) Cometary dust trail (trail)**
- **C) β meteoroids**
- **D) Hermean dust**
- **E) Interplanetary dust**

**Cruising Phase**
# Scientific Objectives

<table>
<thead>
<tr>
<th>Dust Types</th>
<th>Scientific Interests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dust flux within the Inner Solar System</td>
<td>Confirm the flux and size distribution as a function of the heliocentric distance (0.31-0.47 AU). In-situ measurement to constrain zodiacal dust cloud distribution model.</td>
</tr>
<tr>
<td>Cometary Dust</td>
<td>Possible encounters with the cometary dust trails and highly eccentric trajectories.</td>
</tr>
<tr>
<td>Beta Meteoroids</td>
<td>Direct flux measurement in the vicinity of Mercury (0.31-0.47 AU) help to understand mechanism and location.</td>
</tr>
<tr>
<td>Interstellar Dust</td>
<td>Possible detection of large interstellar dust (&gt;=1 micron) coming into close to the sun.</td>
</tr>
</tbody>
</table>
| Dust to Mercury (V orbit = 47.5 km/s, V rel > 6 km/s) | +Investigation of temporal and directional variations of dust influx throughout Mercurian orbit to identify the key meteoroid sources.  
+Assessment of meteoroid impact contribution to the formation of the tenuous Na atmosphere.  
+Constraint to space weathering effect on the Mercurian surface.  
+Estimate external mass accretion rate to the Mercurian surface |
| Dust from Mercury (V esc. = 4.25 km/s)           | +Search for Mercurian dust ejection (e.g., temporal dust cloud?) by meteoroid impacts, similar to the Jovian satellites.  
+Possible interaction with the magnetic field, similar to the Jovian satellite dust stream. |
### Historical dust mission of inner solar system

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>distance range (AU)</th>
<th>spin axis direction</th>
<th>sensor orientation (deg.)</th>
<th>mass threshold (g)</th>
<th>sensitive area (m²)</th>
<th>solid angle (sr)</th>
<th>dynamic range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helios 1/2</td>
<td>0.3–1</td>
<td>N</td>
<td>65, 134</td>
<td>9 ⋅ 10⁻¹₅</td>
<td>0.012</td>
<td>1.23</td>
<td>10⁴</td>
</tr>
<tr>
<td>Galileo</td>
<td>0.7–5.4</td>
<td>S, E</td>
<td>120</td>
<td>4 ⋅ 10⁻¹₅</td>
<td>0.1</td>
<td>1.4</td>
<td>10⁶</td>
</tr>
<tr>
<td>Pioneer 9</td>
<td>0.75–0.99</td>
<td>N</td>
<td>90</td>
<td>2 ⋅ 10⁻¹³</td>
<td>0.0074</td>
<td>2.9</td>
<td>200</td>
</tr>
<tr>
<td>Pioneer 8</td>
<td>0.97–1.09</td>
<td>N</td>
<td>90</td>
<td>2 ⋅ 10⁻¹³</td>
<td>0.0094</td>
<td>2.9</td>
<td>200</td>
</tr>
<tr>
<td>HEOS 2</td>
<td>1</td>
<td>var.</td>
<td>0</td>
<td>2 ⋅ 10⁻¹⁶</td>
<td>0.01</td>
<td>1.03</td>
<td>10⁴</td>
</tr>
<tr>
<td>Hiten</td>
<td>1</td>
<td>N</td>
<td>90</td>
<td>2 ⋅ 10⁻¹⁵</td>
<td>0.01</td>
<td>1.5</td>
<td>3 ⋅ 10⁴</td>
</tr>
<tr>
<td>Ulysses</td>
<td>1–5.4</td>
<td>E</td>
<td>85</td>
<td>4 ⋅ 10⁻¹⁵</td>
<td>0.1</td>
<td>1.4</td>
<td>10⁶</td>
</tr>
<tr>
<td>Pioneer 10</td>
<td>1–18</td>
<td>E</td>
<td>180</td>
<td>8 ⋅ 10⁻¹⁰</td>
<td>0.26(1)</td>
<td>2.8</td>
<td>1</td>
</tr>
<tr>
<td>Pioneer 11</td>
<td>1–10</td>
<td>E</td>
<td>180</td>
<td>6 ⋅ 10⁻⁹</td>
<td>0.56(1)</td>
<td>2.8</td>
<td>1</td>
</tr>
</tbody>
</table>

*This work* 0.31–0.47 N 90 10⁻¹⁴ 0.0064 2 10⁴
Dust flux around Mercury's orbit
from Mann et al. 2003

Flux (impact/m²s⁻¹)

- $m \geq 10^{-14}$ g
- $m \geq 10^{-12}$ g
- $m \geq 10^{-10}$ g

Helios data
- ▲ $m \geq 10^{-14}$ g
- ■ $m \geq 10^{-12}$ g
- ● $m \geq 10^{-10}$ g

Perihelion
Mercury Aphelion

Dust flux around Mercury's orbit from Mann et al. 2003

Flux (impact/m²s⁻¹)
Dust flux around Mercury's orbit

• Distribution of IDP
  – \( n(a) \sim a^{-1} \) from Poynting-Robertson drag
  – \( n(a) \sim a^{-1.3} \) from the zodiacal light model
    • Suggesting (collisional) production of dust in the inner region

• Dust flux at the detector \( \sim n\sigma v \sim a^{-s} \)
  – \( s = 1.5 \) at PR model, \( s = 1.8 \) at ZL model
    \( v \sim a^{-0.5} \)
  – Large \( s \) for beta meteoroids?

• Helios data
  – Measurement around perihelion \( \rightarrow \) total measurement time was limited
  – Interstellar dust (Altobelli et al. 2006)
Helios dust detectors

- Two types
  - IDP and beta meteoroids
  - Also ISD and meteoroid-related flux?
With a dust detector on board Mercury orbiter

• We can measure IDP / beta meteoroids / ISD between 0.31 – 0.47 AU.

• High relative v to IDP (6-14km/s)
  – Because of large e of Mercury

• Dust to/from Mercury from polar orbits.
  – Low v for dust from Mercury
BepiColombo Mercury Dust Monitor (MDM)

Relative v to ISD interstellar dust

Relative v to Keplerian IDP

Relative v to retrograde IDP

v [km/s]

v in km/s

t in days since 2020-155T00:00:00
Dust from Mercury

- Impact ejecta cloud
- Observed around satellites of Jupiter
**MMO polar orbits around Mercury**

*Perihelion 400km  Apohelem 12000km*

*Orbital period 9.2 hours*
MDM on board MMO BepiColombo

- **Solar cell**
- **High-gain antenna** (Conductive white paint)
- **SSM (mirror)**
- **Particle detector**
- **Wire antenna [15m x 4]**
- **Separation plane**
- **Middle-gain antenna**

180cm φ x 90cm, ~200kg
MDM-S 4 PZT sensors are in the frame
PZT (Pb-Zr-Ti): 4cm × 4cm × 2mm
Piezoelectric ceramics
Circuit board & sensor frame

Total mass
≈ 600 g

Power
≈ 3 W

Circuit BBM model

PZT Sensor
## Properties of the MDM instrument

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Material</td>
<td>Piezo-electric ceramics</td>
</tr>
<tr>
<td>Material</td>
<td>Lead zirconate titanate (PZT)</td>
</tr>
<tr>
<td>Dimension</td>
<td>4 cm x 4 cm x 2 mm, use 4 plates</td>
</tr>
<tr>
<td>Area</td>
<td>Total 64 cm²</td>
</tr>
<tr>
<td>Resonance frequency</td>
<td>~ 1 MHz</td>
</tr>
<tr>
<td>Operational temperature</td>
<td>−160 to 200 °C</td>
</tr>
<tr>
<td>Frame of the sensor</td>
<td>125 mm x 125 mm x 7 mm, CFRP</td>
</tr>
<tr>
<td>Field of view</td>
<td>Azimuth 360 deg</td>
</tr>
<tr>
<td></td>
<td>Elevation +/- 90 deg</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>&lt;180 deg</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>&gt;~ 1 pg km/s</td>
</tr>
<tr>
<td>Location</td>
<td>On the side panel of MMO</td>
</tr>
<tr>
<td>Mass</td>
<td>MDM-S (sensor) 220 g</td>
</tr>
<tr>
<td></td>
<td>MDM-E (electronics) 381 g</td>
</tr>
<tr>
<td>Power consumption</td>
<td>3.0 W at the maximum</td>
</tr>
</tbody>
</table>
PZT sensor calibration experiment

MDM calibration experiments have been performed at MPI-K (van de Graaff), HIT (van de Graaff) and ISAS(Light-gas gun).

Fe, Ag, C particles 0.5 - 1micron \(10^{-14}\) to \(10^{-11}\) g

We will use pyroxene (opx) particles in the experiment this month.

MPI-K concept

HIT concept
Chamber of the dust accelerator at MPI
PZT sensor in the dust accelerator chamber
Typical waveform (MPI-K)

Velocity dependence (Iron particles)

- **5.5 km/s**: 28 pg (Slow)
- **7.2 km/s**: 5.5 pg (Medium)
- **25 km/s**: 29 fg (High speed)
- **9.7 km/s**: 1.2 pg
Momentum vs signal amplitude
$v < 6\text{km/s}$
Output charge vs particle momentum capability of PZT sensor

Steel ball  
Large m, low v

Accelerator  
Small m, high v

Light gas gun  
Moderate m, high v
Little dependence on incident angle

Nogami et al. (2010)

Fe particles 1-30pg 3-5 km.s
Typical waveform (MPI-K)

Velocity dependence (Iron particles)

5.5 km/s
28 pg

Slow

7.2 km/s
5.5 pg

Medium

25 km/s
29 fg

High speed

9.7 km/s
1.2 pg
Rise time vs. velocity of single peaked pulse

High speed impact (> 8 km/s)
Expected data rate

$10^{-3} \text{ m}^{-2} \text{ s}^{-1}$ corresponding to 0.5 / day by 64 cm$^2$ sensor

100 μs length data are recorded after impact by (10 ~ 40 MHz) 16bit ADC.
1 impact event = 8 kbyte

However, there will be much more noise events. For safety = 100 event / day
8 kbyte x 100 = 0.8 Mbyte / day
Statas bit + temperature data = 3 kbyte / day
Conclusion – dust around Mercury

- Dust flux measurements around Mercury region is important for characterizing IDP, beta meteoroids, ISD in the inner solar system.
- Dust particles to (and from) Mercury are also important for the source of the atmosphere and for the cause of space weathering.
- MDM-Bepi Colombo is the first direct dust measurement after Helios.
Conclusion – MDM

• MDM (Mercury dust monitor) is PZT sensor with the total aperture 64 cm$^2$.
• At lower $v$ range ($< 6\text{km/s}$), momentum ($mv$) can be derived from amplitude of the output voltage oscillation.
• For high $v$ particles ($> 8\text{km/s}$), $v$ can be directly estimated from signal risetime.
• Little dependence on the incident angle.
• Measure dust environment around Mercury from 2020 (for 2 years and more).
Levitation dust

- MDM cannot measure (electrostatically) levitated dust from Mercury's surface.
- Presence of levitated dust in debate for the Moon. Measurement by LADEE.
- MMO periapsis

- Dust related ionosphere around Mercury could be detected by radio occultation.
- Experiments using subsatellite of KAGUYA.
Radio occultation

**Electron density integrated along the ray path was derived**

**Earth’s ionosphere: the major error source**

**Vstar: sub-satellite**

*KAGUYA radio occultation experiment: PI T. Imamura (JAXA)*
Profiles for SZA < 60 degrees

Column density \( \text{(TECU, } 10^{16} \text{ m}^{-2}) \)

- Typical value of \(~0.03\) TECU is similar to those of Soviet Luna results.
KAGUYA radio occultation summary

- In contrast to the Soviet Luna mission results, which reported high electron densities all over the sunlit side including the terminator, our results do not indicate such an ubiquitous ionized layer on the sunlit side.

- There is a tendency that electron density is enhanced near the sub-solar region (SZA < 60 degrees). The vertical extent and the peak density are similar to those in the Luna mission results. Since the measurement uncertainty due to the contamination of the terrestrial ionosphere component is quite large, analyses to confirm the conclusions are continuing.

- The much depleted electron layer might be due to the extremely low solar activity during the KAGUYA mission.
PZT output signal at HIT (low v)
momentum vs. P-P amplitude

Momentum vs. P-P amplitude (HIT)

Coefficient values ± one standard deviation

\[ a = 0.018628 \pm 0.0125 \]
\[ b = 1.3257 \times 10^9 \pm 1.1 \times 10^8 \]
Dependence of the incident angle to the output voltage of the PZT

![Graph showing the dependence of the output voltage on momentum for different incident angles (0°, 15°, 30°, 45°, 60°).]