Particle and chemical sputtering as a source for the exosphere of Mercury: modeling and data comparison

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1 Model description

2 Mercury tail and radiation pressure

3 Transit observation and modeling: chemical sputtering

4 A Monte-Carlo model with planetary rotation

5 MESSENGER observations and modeling: neutral and ion tails

6 Themis observations and modeling: Sodium migration timescales
Exosphere-magnetosphere model
Magnetic and electric field

Adapted Luhmann and Friesen, 1979 model (as in Delcourt et al., 2003)
Proton precipitation
Mercury surface processes
\[ T(\alpha) = T_n + (T_d - T_n)[\cos(\alpha)]^{1/4}, \]

\[ \Phi_{TD}(t) = \nu N C(t) e^{-U_{TD}/k_B T} \]
Johnson et al., 2002

\[ f(E) = \frac{E}{(k_B T)^2} e^{-E/k_B T}, \quad \text{Gaussian} \]

\[ f(E) = \beta (1 + \beta) \frac{EU^\beta}{(E + U)^{2+\beta}}, \quad \text{Non-Gaussian} \]
• H+ can’t give all its energy to a single heavy target atom
• The sputtering energy spectrum falls at 50-100 eV
Doppler shifted
\[ p_1 + p_2 \cdot \cos(2\alpha) + p_3 \cdot \cos(\alpha) + p_4 \cdot \cos(\alpha/2) \]

\[
\begin{align*}
p_1 &= 10.21 + 0.017U \\
p_2 &= -2.89 - 0.0015U \\
p_3 &= 1.352 + 0.00026U \\
p_4 &= 1.0759 + 0.001073U
\end{align*}
\]
\[ p_1 + p_2 \cdot \cos(2 \alpha) + p_3 \cdot \cos(\alpha) + p_4 \cdot \cos(\alpha/2) \]

\[
p_1 = -1.514 + 0.0024 \cdot T
\]
\[
p_2 = 2.091 - 0.0029 \cdot T
\]
\[
p_3 = -0.3567 + 0.00079 \cdot T
\]
\[
p_4 = -0.1799 + 0.0009 \cdot T
\]
Fraction (%) of ionized particles

\[
\frac{(0.779 + 0.000313 \cdot T)}{R^2}
\]

(R in AU)
Fraction (%) of ionized particles

\[
\frac{(0.23374 + 0.000468 \cdot T)}{R^2}
\]

(R in AU)
Sodium tail from simulation (Mura et al., 2005). Sources: PSD, TD, Sputtering @ \( R_{SM} = 0.38 \) AU.

Solar flux@1 AU = 3.3 \( \times 10^{19} \) \( m^2 \cdot s^{-1} \). Solar wind flux = 60 \( \text{cm}^3 \cdot \text{s}^{-1} \) \( \times 400 \text{ km/s}^{-1} \),

\( T_{day} = 650 \text{K, } f_{Na} = 5\% \), unconstrained flux.

From Potter et al., (2002)
• North-south asymmetry: north column density is higher
• Dawn-dusk asymmetry: dawn column density is higher
Negative Bx component of IMF causes reconnection in the North Emisphere

Reconnection in the North Emisphere causes higher S/W proton precipitation fluxes

Sarantos et al., 2003, Kallio et al, 2003)
Anomaly: 150°
Distance: 0.45 AU
S/W velocity: 700 km/s
IMF: -20, 10, -10 nT
Radiation pressure: -60 cm/s²

Measured by ACE, during May 7-9, 2003, distance from spacecraft to Earth, components of magnetic field, solar wind proton speed and density (http://www.srl.caltech.edu/ACE/ASC/level2/index.html).
• We assumed that IMF-x condition could explain the N/S asymmetry
• We modeled the H+ flux onto the surface with a numerical model
The N/S asymmetry is explained but...
Scale high is too large
Column densities are lower by a factor 100
Dawn/dusk asymmetry is not explained
Morgan et al. (1988) reported an average value of $2 \times 10^5$ (cm$^{-2}$ s$^{-1}$) released Na at aphelion, a factor 2 higher than the value reported by Cintala (1992). The first value is a factor 100 lower than our averaged PSD flux.

We assume that the ejecta have a thermal velocity distribution at about 2500 K (Killen et al., 2007).

The simulated tangential column densities are lower than the observed ones by a factor 100.
Production of sodium and water by proton sputtering of sodium-bearing silicates was considered by the chemical sputtering mechanism.

Potter, 1995

\[
2H + Na_2SiO_3 \rightarrow 2Na + SiO_2 + H_2O
\]
Enhanced diffusion due to proton precipitation

- Proton precipitation can also enhance the diffusion of Na atoms inside surface grains.
- The effect due to precipitation is able to enhance the diffusion-limited PSD by a factor 2.

\[ \Phi_{Na} = \varepsilon \ \Phi_+ + \Phi_{\text{diff}} \]
Sodium variability

Dawn

Dusk

Rotation

Ions

PSD

TD

Ions

PSD

TD

Ions

PSD

TD
Magnetic field
H+ precipitate in the open field-line regions (cusps) and in the nightside
Starting from a Na-poor surface, H+ flux enriches the Na surf. abundance
PSD and TD release Na particles that migrate (ballistic traj.) to a larger area
Na migration

• Na abundance is lower where PSD anb TD processes are more effective
• The Na abundance in the night side is enhanced
As soon as the rotation brings a surface element to the dayside, PSD and TD deplete the Na abundance again.
At the equilibrium, the Na flux from the surface is similar to the H+ one, but broadened and with a “dawn” feature.
Time=Day 000, 06:00, Average C = 0.09%
Comparison between data and simulation

- The model reproduces well all asymmetry features
- The model reproduces well column density (within a 50% error)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (max)</td>
<td>2500 cm⁻³</td>
<td>1000 cm⁻³</td>
</tr>
<tr>
<td>Column dens. (max)</td>
<td>7⋅10¹⁰ cm⁻²</td>
<td>5⋅10¹⁰ cm⁻²</td>
</tr>
<tr>
<td>Total amount</td>
<td>4⋅10²⁷</td>
<td>5⋅10²⁷ (*)</td>
</tr>
<tr>
<td>Scale height</td>
<td>200÷500 km</td>
<td>~1000 km</td>
</tr>
<tr>
<td>parallel doppler width</td>
<td>1.6 km/s</td>
<td>1.4 km/s</td>
</tr>
</tbody>
</table>

OBSERVATIONS

SIMULATION

Schleicher et al., 2004
Mura et al., 2008
The wavelength dependence of the excess absorption (see Fig. 3) can be approximated by a Gaussian profile \( \sim \exp\left(-\frac{(\Delta \lambda/\Delta \lambda_D)^2}{2}\right) \) with \( \Delta \lambda_D = 3.3 \) pm. Taking into account the spectral resolution of the spectrograph, the intrinsic Doppler width is \( 3.1 \pm 0.1 \) pm, corresponding to a velocity distribution along the line-of-sight of \( 1.6 \pm 0.1 \) km s\(^{-1}\). No significant spatial variation of the line widths is found.

From Schleicher et al., 2004

Parallel (\( x \)) velocity distribution of the simulated particles (blue line). The simulated data can be fitted by using a gaussian function: \( \sim \exp\left(-v^2/v_{th}^2\right) \), with \( v_{th} = 1.4 \) km/s. The observed velocity distribution can be reproduced by a gaussian function with \( v_{th} = 1.4 \) km/s (in red).
$L_{out} \Phi_{out} = L_{in} \Phi_{in}$

$n = \frac{\Phi_{out}}{\nu}$

$N = n L_{out}$

$N = \frac{\Phi_{in} L_{in}}{\nu}$

$\Phi_{in} = 10^6 \sim 10^7 \text{ cm}^{-2} \text{ s}^{-1}$
JEANS ESCAPE, TAIL

SURFACE ELEMENT \( C(\lambda, \phi, t) \)

DIFFUSION

PLANET ROTATION

ION FLUX

CHEM. SPUT.

SPUTTERING

chem. sput. eff. = 5%

sticking = 50% \( \sim \) 100%

diffusion lim. = \( 10^7 \) cm\(^{-2} \) s\(^{-1} \)

Killen et al., 2004

chem. sput. eff. = 5%
Sodium observations (MESSENGER)

McClintock et al., 2009

McClintock et al., 2008
First observations of emission from ionized calcium in Mercury's tail region compared with simultaneous observations of neutral calcium. Neutral calcium is rapidly converted to ionized calcium by sunlight, explaining the generally rapid decrease of neutral calcium away from the planet. The high degree of correlation between the two observed distributions reflects the rapid conversion of neutrals to ions and demonstrates that ionized calcium represents a significant fraction of the overall calcium abundance. Simultaneous measurement of the abundances of calcium neutrals and ions is therefore necessary to determine accurately the total calcium abundance in Mercury's exosphere. This situation is in contrast to that for sodium and magnesium, which are ionized much more slowly. The significantly longer lifetime for neutral magnesium may explain why its abundance is more widely distributed in the tail region than calcium (Image 2.4).
Sputtered Ca, Ca+: MESSENGER and model
- The Na lifetime is approximately independent on the H+ flux.
- For a (example) 1-hour precipitation, the lifetime after the H+ precipitation ceases is several hours.
OBSERVATIONS

MODEL, C.S.+DIFF seeing=1 Rm

MODEL, ONLY C.S. seeing=1 Rm
OBSERVATIONS

MODEL
CONCLUSION

- Chemical sputtering and/or proton-enhanced diffusion can explain most of the ground-based or MESSENGER (1st FB) observation of the Na exosphere of Mercury.

- To find general good agreement between data and simulation, \( U = 0.086 \) eV (resulting in \( T = 2000 \) or more), \( \varepsilon = 5\% \) can be taken.

- A diffusion-limited flux of about \( 10^7 \) cm\(^{-2}\) s\(^{-1}\) is compatible with the observation during the transit, and necessary to explain the observations of Na at the dayside.

- A time-evolving MonteCarlo model with planet rotation is able to explain the dawn-dusk asymmetry as seen during transit.

- Thermal desorption and Photon-stimulated desorption move the Na in areas far from the H\(^+\) precipitation: no need of complex, accurate H\(^+\) flux model for this simulations.

- The timescale for proton precipitation-induced enrichment and depletion of Na is about 10 hours.

- Proton-enhanced diffusion can also explain the relation between proton precipitation and enhanced Na release.
Web interface

This page hosts the client/server version of the magnetospheric/planetary model (CPSM-NASA). It is able to simulate ion and neutral transport at various energies, from different sources. It is unique in its ability to run simulations using virtual neutrons and ions of various species. Please select the simulation language below. You will receive an email with the simulation results. The simulation can be run from minutes (especially if you simulate just neutrals) up to several hours (especially if you simulate a large number of ions). You can find an example of a typical data set, and some useful tools for handling data, in the Reference section.

1: Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_max (km)</td>
<td>1000</td>
</tr>
<tr>
<td>Simulates ions?</td>
<td>Yes</td>
</tr>
<tr>
<td>Simulates neutrals?</td>
<td>Yes</td>
</tr>
<tr>
<td>Desired accuracy</td>
<td>1%</td>
</tr>
<tr>
<td>Particles to simulate</td>
<td>1000</td>
</tr>
<tr>
<td>Minimum integration time-step</td>
<td>0.1 s</td>
</tr>
</tbody>
</table>

2: Physical parameters

**Magnetic field parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bx, By, Bz (nT)</td>
<td></td>
</tr>
<tr>
<td>Corrective parameter</td>
<td></td>
</tr>
<tr>
<td>Model name</td>
<td></td>
</tr>
</tbody>
</table>

**Electric field parameters**

The electric field is calculated by assuming that the surface of Mercury has an electric potential similar to that of Jupiter (1.87). The electric potential in any other point of the space is calculated by assuming that any magnetic field line is equipotential. However, since this evaluation could be very slow, the calculated electric potential is stored in a grid of 100 x 100 x 100 grid points. The potential at any point of the space is then calculated by linear interpolation between nearest grid vertices. It is possible to choose the strength of the electric field by changing the cross-field potential drop (in Vols).

**Independent sources**

This model needs to specify which physical processes are included in the model. Six different sources are available:

- Solar wind (SW, 1)
- Protons (proton injection from the solar wind, 2)
- Thermal excitation (3)
- Hydrogen spitting on the surface (4)
- Magnetic field (5)
- Neutral injection (6)

It is possible to include an unlimited number of sources for an unlimited number of species at the same time. Just add a line in the following form using these codes:

```
1 (SW, 1) 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
```

Some templates have been included. In this example, Sodium PSC is enabled, all other processes are disabled. Just remove the minus sign to uncomment a line.

Go to: http://elena.ifsi-roma.inaf.it