Heavy ion effects at the Hermean magnetopause: 2D full particle simulation

Takuma (T.K.M.) Nakamura
Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA)
takuma@stp.isas.jaxa.jp

Presented by:
M. Fujimoto
(ISAS/JAXA)
Hermean magnetosphere

- Small in size
- Rich in heavy ions

The two key factors that characterize the Hermean magnetosphere may join to show an curious effect at the magnetopause
Magnetopause:
Where a magnetosphere starts its interaction with the solar wind

Magnetopause separates

- Magnetic field of different origin origins (current sheet) → Can host magnetic reconnection

- Plasmas of different origin (velocity shear layer) → Can host Kelvin-Helmholtz instability

- Plasmas of different origin (density gradient layer) → Can host various plasma instabilities

Magnetopause processes are inevitably of multi-scale nature
Magnetopause: Where a magnetosphere starts its interaction with the solar wind

Magnetopause separates plasmas of different origin.

But

Heavy ions of exospheric origin can be present across the magnetopause, or, at the center of the velocity shear layer, in the context of the present talk.
When interplanetary magnetic field (IMF) is southward, the solar wind - magnetosphere interaction is dominated by magnetic reconnection.

[Dungey, 1961]
When IMF is northward, the solar wind - magnetosphere interaction is believed to involve the Kelvin-Helmholtz waves. [e.g., Sckopke et al., 1981; Fairfield et al., 2000]
Earth’s magnetopause under N-IMF

Under northward IMF, KH waves or vortices have been frequently observed around the Earth’s magnetopause [e.g., Hasegawa et al., 2004; 2010; Geotail, Cluster].

Observation
◆ The thickness of the magnetopause is always >> the ion gyro-radius.
   [Berchem & Russell, 1982]

◆ In Earth-like MHD-scale situations, the KHI seems described reasonably well by MHD.

# Not necessarily true in the non-linear regime.
Mercury’s magnetopause under N-IMF

Objective of this study.

Understand whether the generation process of the KHI is affected by ion kinetic effects in Mercury-like ion kinetic-scale situations.

Observation

◆ The thickness of the Mercury’s magnetopause may be comparable to ion gyro-radius.
[Boardsen et al., 2010]

No theory

◆ The generation process of the KHI in the ion-kinetic scale velocity shear layer has not yet been understood.

◆ Under northward IMF, KH vortex-like magnetic structures have recently been observed around the duskside magnetopause.
[e.g.; Slavin et al., 2008, Boardsen et al., 2010; MESSENGER]
Magnetopause as a velocity shear layer: Structure of convective electric field

Under northward IMF

⇒ In the dusk-side case, the convective $E$ points into the shear layer.
⇒ In the dawn-side case, the convective $E$ points out of the shear layer.

When ion kinetic effects are in, how is the shear layer affected?
Basic considerations
Simulation settings

Simulation method: **2-D full particle (EM-PIC) simulation**

- **Initial parameters**-

  - **Particles:** \( \text{H}^+ \) ions and electrons
  - \( N_{i0} = \text{uniform} \)
  - \( B_{x0} = B_{y0} = 0 \)
  - \( B_{z0} = B_0 = \text{uniform} \)
  - **Dusk-like shear:** \( V_{x0} = - V_0 \tanh(Y/D_0) \)
  - **Dawn-like shear:** \( V_{x0} = + V_0 \tanh(Y/D_0) \)
  - **Initial half thickness** \( D_0 \approx 1\pi \) (ion-kinetic scale)
  - \( V_0 = V_{Ai} \approx V_{thi} \)
  - \( \frac{T_i}{T_e} = 1, \frac{M_i}{M_e} = 25, \frac{\omega_{pe}}{\Omega_e} = 1.0 \)
  - 200 particles/cell

More or less a canonical setting except that the shear layer **thickness is very small** comparable to the ion Larmor radius.
Kinetic equilibrium

- The kinetic equilibrium is established for about an ion gyro-period.
- The shear layers are broadened only in the dawn-like case.
- The broadened thickness is about 1.5 times the initial thickness.
Why does the broadening occur?

- When $D_0 \sim \rho_i$
  - ions at the center of the shear layer feel the E-field gradient as they make Larmor motion.
  
  **(Dusk)**
  - The gyro-radius is made smaller.

  **(Dawn)**
  - The gyro-radius is expanded.

  
  - Shear layer broadening occurs only on dawnside

- When $D_0 > \rho_i'$
  - shear layer broadening does NOT occur.

- When $D_0 \gg \rho_i$
  - gyro-radius NOT extended
  - NO broadening
The modified Larmor radius

\[ \rho_i' = \rho_i \left(1 - \frac{E_y}{B_0} \cdot \frac{1}{V_{thi}}\right) = \rho_i \left(1 - \frac{V_0}{V_{thi}}\right) \]

\[ \sim 0.5 \rho_i < D_0 \]

No broadening (\(D' = D_0\))

\[ \rho_i' = \rho_i \left(1 + \frac{E_y}{B_0} \cdot \frac{1}{V_{thi}}\right) = \rho_i \left(1 + \frac{V_0}{V_{thi}}\right) \]

\[ \sim 1.5 \rho_i > D_0 \]

Broadening occurs!! (\(D' \sim \rho_i' \sim 1.5 \rho_i\))

\(\rho_0 \sim \rho_i\)
Growth of the Kelvin-Helmholtz instability

- Basically, the growth rate of the KHI $\gamma_{KH}$ is regulated by the thickness of the velocity shear layer.

$\Rightarrow \gamma_{KH}$ in the dawnside case tend to be smaller, since the dawnside shear layer tends to be thicker.

The dawn-dusk asymmetry cannot be there in MHD.

![Graph showing the comparison between dawn and dusk cases]
Summary:
If MP-thickness is comparable to ion Larmor radius
The Hermean magnetopause may be thin by itself but it may be even more so in the presence of heavy ions.
Simulation settings

Initial parameters are same in Case-1 except that heavy ions are included.

<table>
<thead>
<tr>
<th>Mass</th>
<th>$M_h : M_i : M_e$</th>
<th>$400 : 25 : 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>$T_h : T_i : T_e$</td>
<td>$1 : 1 : 1$</td>
</tr>
<tr>
<td>Gyro-radius</td>
<td>$\rho_h : \rho_i : \rho_e$</td>
<td>$20 : 5 : 1$</td>
</tr>
<tr>
<td>Number density</td>
<td>$N_h : N_i : N_e$</td>
<td>$0.1 : 0.9 : 1.0$</td>
</tr>
</tbody>
</table>

Heavy ions are expected to broaden the shear layer more severely in the dawn case.

\[
\rho_i' = \frac{\rho_i(1+V_0/V_{th_i})}{\rho_i} \sim 1.5 \rho_i \sim 1.5D_0 \\
\rho_h' = \frac{\rho_h(1+V_0/V_{th_h})}{\rho_h} \sim 3.2 \rho_h \sim 12D_0 \gg D_0
\]
**Kinetic equilibrium**

Profiles of convective bulk flow $V_{ix}$ and $V_{hx}$

- **Dusk**
- **Dawn**

- **Dawn** The shear layer broadens more in the presence of heavy ions, since $\rho_h' > \rho_i' > D_0$.  
  
  **A double shear layer structure**

$\rho_i' \sim 1.5 \rho_i \sim 1.5 D_0$

$\rho_h' \sim 3.2 \rho_h \sim 12 D_0$
The double shear layer

The heavy ions inside the shear layer broadens.

Heavy ion density at $|Y|<\rho_h'$ decreases.

Additional electric field $E_{\text{add}}$ is produces to satisfy Gauss's low.

$$\nabla \cdot E = 4\pi e(N_i + N_h - N_e)$$

$$E_{\text{add}} \sim 4\pi eN_{h0}\rho_h = \frac{4\pi \cdot M_h N_{h0} V_{th-h}}{B}$$

$\propto \sqrt{M_h, N_h, \sqrt{T_h}}$
The growth rate of the KHI $\gamma_{KH}$ is also regulated by the velocity jump across the shear layer.

$E_{\text{add}}$ makes the shear layer to be thicker and the velocity jump is decreased by $E_{\text{add}}$.

$\Rightarrow \gamma_{KH}$ in the dawnside case becomes smaller.
In the non-linear stage

Density contours for ions initially at lower regions (Y<0)

◆ The growth of KH vortices (non-linear growth of the KHI) in the dawn case is also weaker than that in the dusk case.
Effects of Na\(^+\) at the Mercury’s magnetopause

Estimated values in Mercury-like situations

\[
\rho_{Na^+} \sim 500\text{km} \cdot \left(\frac{10nT}{B_0}\right) \cdot \left(\frac{T_{Na^+}}{100\text{eV}}\right)^{1/2}
\]

\[
\rho_{Na^+}' \sim \rho_{Na^+} \left[1 + 2.4 \cdot \left(\frac{V_0}{100\text{km/s}}\right) \left(\frac{100\text{eV}}{T_{Na^+}}\right)^{1/2}\right]
\]

\[
\frac{E_{\text{add}}}{E_0} \sim \gamma_{\text{decrease}}/\gamma_{KH} \sim 0.3 \cdot \left(\frac{10nT}{B_0}\right)^2 \cdot \left(\frac{N_{Na^+}}{0.01/\text{cc}}\right) \cdot \left(\frac{100\text{km/s}}{V_0}\right) \cdot \left(\frac{T_{Na^+}}{100\text{eV}}\right)^{1/2}
\]

After re-scaling, we may well expect to see the heavy ion effects seen in the simulation at Mercury.

T\sim 1\text{ gyro-period for heavy ions}

\[
\rho_{h}' \sim 3.2\rho_{h}
\]

\[
\frac{E_{\text{add}}}{E_0} \sim 0.35
\]
At the Mercury’s magnetopause, large dawn-dusk asymmetries are expected to appear.

⇒ The double shear layer structure on dawnside.
⇒ Vigorous KH waves only on duskside.
Indeed, the double magnetopause signature has been observed by MESSENGER (M1) at the dawnside magnetopause [Slavin et al., 2008].

Furthermore, clear KH wave-like magnetic fluctuations have been observed by MESSENGER (M1 & 3) at the duskside magnetopause [Slavin et al., 2009; Boardsen et al., 2010].
Summary/Prediction

Northward IMF

Double shear layer

Magnetopause

Single shear layer

Mercury

Weak KH waves

Strong KH waves

dawnward

duskward

T=000

000=1