Interaction of stellar flows with planets and moons: three dimensional hybrid simulations

June 4, 2008
1. Introduction

2. Hybrid Expanding Box (HEB) simulations

3. Global kinetic simulations of the Moon

4. Global kinetic simulations of Mercury
Humans try to explain events ongoing in the surrounding nature since early days. Over centuries: experiment and theory.

Technological advances: today we use spacecraft measurements to improve our knowledge about processes ongoing in space environment. On their basis we built up our theoretical models.

Advances in computer technology achieved in last decades allow us to use theoretical knowledge to formulate studied problems in the form of numerical models. Extension of our theoretical/experimental capabilities.
Introduction: Simulations vs. *in situ* experiments

**LEFT:** data acquired by the electron spectrometer PEACE and by a wave analyzer WHISPER onboard Cluster II spacecraft: waves generated in a space plasma at fundamental frequency and twice the plasma frequency.

**RIGHT:** analogical data from a numerical experiment. We use a model of electron VDF with an electron beam. We can observe corresponding wave emissions in a numerical model.

The spacecraft must be present at the place of the interesting event.

*In the case of the numerical simulation we can change different input parameters of our model and then observe, when the given phenomena reaches its maximum, or when the process is not ongoing at all.*

Stellar flows and moons and planets
Physics is essentially dimensionless (important are relative rather than absolute values), it scales with dimensions typical for the given problem. In a numerical we use:

- \( q = 1 \), \( m_p = 1 \).
- We use proton inertial length in the solar wind \( \Lambda_{psw} = c/\omega_{psw} \) and the inverse of the proton cyclotron frequency \( \Omega_{psw}^{-1} \) as spatial and temporal units respectively.
- i.e. \( n_{psw} = 1 \), \( B_{0sw} = 1 \), \( v_{Asw} = 1 \).
- Hermean radius (for example) in the units of the numerical model varies with the value of \( \Lambda_{psw} \) in SI units.
- **Consequently:** In generall - typical spatio temporal sizes of the studied interaction between a stellar flow and a moon or planet depend naturally on the physical properties of the flow (its density and magnetic field in it)
<table>
<thead>
<tr>
<th>Name</th>
<th>distance [AU]</th>
<th>(n_{PSW} \text{[cm}^{-3}])</th>
<th>(B_{SW} \text{[nT]})</th>
<th>(\Lambda_{SW} \text{[km]})</th>
<th>(v_{ASW} \text{[km s}^{-1}])</th>
<th>radius (R \text{[km]})</th>
<th>(v_{SW} = 300 \text{km/s})</th>
<th>(v_{A} \text{[km]})</th>
<th>(\Lambda_{I} \text{[\Lambda]})</th>
<th>(M_{\text{Earth}} \text{[M}^{-3} \text{B}<em>{SW}/\mu</em>{0}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.31</td>
<td>73</td>
<td>46</td>
<td>26.7</td>
<td>118</td>
<td>2439</td>
<td>2.5</td>
<td>4.7 \times 10^{-4}</td>
<td>5.4 \times 10^{7}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.47</td>
<td>32</td>
<td>21</td>
<td>40</td>
<td>82</td>
<td>2439</td>
<td>60</td>
<td>4.7 \times 10^{-4}</td>
<td>3.5 \times 10^{7}</td>
<td></td>
</tr>
<tr>
<td>Venus</td>
<td>0.72</td>
<td>14</td>
<td>10</td>
<td>61</td>
<td>59</td>
<td>6052</td>
<td>99</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Earth</td>
<td>1.0</td>
<td>7</td>
<td>6</td>
<td>86</td>
<td>50</td>
<td>6378</td>
<td>74</td>
<td>6</td>
<td>1.0</td>
<td>2.6 \times 10^{9}</td>
</tr>
<tr>
<td>Mars</td>
<td>1.5</td>
<td>3.1</td>
<td>3.4</td>
<td>129</td>
<td>42</td>
<td>3397</td>
<td>26</td>
<td>7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.2</td>
<td>0.26</td>
<td>0.83</td>
<td>447</td>
<td>36</td>
<td>71398</td>
<td>160</td>
<td>8</td>
<td>20.000</td>
<td>2.7 \times 10^{13}</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.6</td>
<td>0.076</td>
<td>0.44</td>
<td>827</td>
<td>35</td>
<td>60000</td>
<td>73</td>
<td>9</td>
<td>540</td>
<td>2.16 \times 10^{11}</td>
</tr>
<tr>
<td>Uranus</td>
<td>19.1</td>
<td>0.019</td>
<td>0.22</td>
<td>1654</td>
<td>35</td>
<td>25400</td>
<td>15</td>
<td>9</td>
<td>48</td>
<td>4.8 \times 10^{9}</td>
</tr>
<tr>
<td>Neptune</td>
<td>30.2</td>
<td>0.0077</td>
<td>0.14</td>
<td>2599</td>
<td>35</td>
<td>24300</td>
<td>9</td>
<td>9</td>
<td>26</td>
<td>1.0 \times 10^{9}</td>
</tr>
<tr>
<td>Pluto</td>
<td>39.4</td>
<td>35</td>
<td>0.14</td>
<td>2500</td>
<td>35</td>
<td>2500</td>
<td>9</td>
<td>unknown</td>
<td>unknown</td>
<td>-</td>
</tr>
</tbody>
</table>

- The Earth magnetic dipole moment is \(M_{\text{Earth}} = 8 \cdot 10^{22} \text{Am}^{2}\).
- Mercury is the most likely (magnetized) candidate to be studied by a global kinetic numerical model beside unmagnetized planets Venus and Mars.
- Effect of denser stellar flow at Mercury: from physical point of view the size of Mercury is comparable to Earth.
- Mercury also changes its diameter in the stellar flow of given desity thanks to its eccentric Solar orbit.
- Pluto almost can not be simulated by a hybrid code and its study requires a full particle in cell code.
Numerical codes

- Magnetohydrodynamic (MHD) codes: traditional codes used for global simulations of the interaction between stellar flows and moons and planets
  - Allow 3D modeling on global scales
  - Neglect kinetic effects and hence wave-particle interactions
- Particle in cell (PIC): use macro-particles to describe both electrons and ions
  - Include (all) kinetics for both electrons and ions
  - Require to use unrealistic parameters (for example, mass ratio)
- A compromise: Hybrid model [Alan Matthews, 1994]: treat electrons as fluid
  - Include ion kinetics
  - Allow ”realistic” parameters on a global scale
  - Do not include electron kinetics, some types of waves, if excited, can not interact with electrons and should be artificially dumped.
Properties of collisionless plasmas are largely determined by wave-particle interactions.

A homogeneous slowly expanding plasma (without any fluctuating wave energy) evolves adiabatically. The ion parallel and perpendicular temperatures $T_{\parallel}$ and $T_{\perp}$ satisfy the equations $T_{\parallel} \propto B$ and $T_{\perp} \propto n^2/B^2$, respectively.

In the case of a strictly radial expansion, $B(0) = (1, 0, 0)$, the temperature anisotropy evolves as $T_{\perp}/T_{\parallel} \propto (1 + t/t_e)^{-2}$, where $t_e = R_0/U$ is the characteristic time of the expansion ($R_0$ is initial distance from the Sun, $U$ is the (constant) solar wind speed).

In slowly expanding (or compressed) plasma temperature anisotropies naturally develop. Temperature anisotropy (i.e. departure from Maxwellian particle distribution function) represent a possible source of free energy for many different instabilities.

As a feedback, the instabilities constrain the shape of particle distribution functions.
Both panels show a color scale plot of the relative frequency of \( (\beta_p^||, T_p^\perp/T_p^||) \) in the WIND/SWE data (1995-2001) for the solar wind \( \nu_{SW} < 600 \text{ km/s} \).

The over plotted curves show the contours of the maximum growth rate (in units \( \omega_{cp} \)) in the corresponding bi-Maxwellian plasma:

- Proton cyclotron instability (solid curves)
- Parallel fire hose instability (dashed curves)
- Proton mirror instability (dotted curves)
- Oblique fire hose instability (dash-dotted curves)
Panel shows a gray shaded scale plot of the relative frequency of \((\beta_p^\parallel, T_p^\perp/T_p^\parallel)\) in the Helios data for the solar wind \(v_{SW} < 600\ \text{km/s}\). The over plotted curves show the contours of the maximum growth rate (in units \(\omega_{ce}\)) in the corresponding bi-Maxwellian plasma:

- whistler instability (dash-dotted curves)
- parallel electron fire hose instability (dashed curves)

[Stverak et al., 2008]
The stellar plasma flow is subject to the continuous radial expansion. It can be also subject of compression (in a planetary magnetosheath) and/or torsion caused by a velocity shear.

HEB code uses Vlasov equations in such a way that we can study a given volume of continuously expanding plasma in a simulation box (1D or 2D) with periodic boundary conditions.
LEFT: Evolution during the numerical simulation of plasma stretching in the space \((\beta_{\parallel}, T_{p\perp}/T_{p\parallel})\). The evolution (solid line) follows initially the adiabatic prediction. The over plotted curves show the contours of the maximum growth rate (in units of \(\omega_{cp}\)) (left) for the proton cyclotron instability and (right) the mirror proton instability.

RIGHT: In situ observations made by HIA experiment

[Travnicek et al., 2007]
LEFT: The panel shows the total fluctuating magnetic energy $\delta B^2 / B_0^2$ (solid curve) as a function of $\beta_{p\parallel}$. The dotted curve corresponds to the mirror fluctuating magnetic energy $\delta B_{\text{mir}}^2 / B_0^2$ whereas the dashed curve corresponds to the proton cyclotron fluctuating magnetic energy $\delta B_{\text{PC}}^2 / B_0^2$. RIGHT: The panel shows a coloured plot of the fluctuating magnetic energy $\delta B^2 / B_0^2$ as a function of $\beta_{p\parallel}$ and $\Theta_{kB}$. The gray dashed vertical line denotes $\beta_{p\parallel}$ for which the simulation reaches the linear mirror threshold.
When the solar wind interacts with the Moon, plasma is absorbed at the lunar surface leaving a void on the nightside referred to as the wake-tail.

- No atmosphere and minimal exosphere eliminates the Moon as a source of plasma.
- The wake-tail is one of the best natural vacuums in the solar system.

The solar wind IMF passes through the unmagnetized, non-conducting Moon.

- Crustal magnetic fields on the lunar surface may form localized mini-magnetospheres, causing ”limb compressions” in the vicinity of the wake-tail.

The lunar wake-tail is actively being studied to understand the solar wind refilling processes and its overall three-dimensional structure.

Today computers can accommodate 2D/3D global hybrid (kinetic) simulations of the solar wind interaction with the Moon.
Wind data showed:

- density depletion region
- $e$- temperature increase
- beams flowing into the depletion region from either side of cavity
- enhanced magnetic field in depletion region
- Plasma waves excited in and around the density depletion region observed at $\sim 7 \, R_L$ by WIND [Farrell et al., 1996]
- Ion gyrofrequency waves observed further downstream in the wake-tail $\sim 25 \, R_L$ by WIND [Travnicek et al., 2005]
Observations of streaming and anisotropic plasma distributions, as well as plasma waves of various types indicate that kinetic processes are important in the refilling and formation of the wake-tail.

We use 2D and 3D global hybrid (kinetic) simulations to model the solar wind interaction with the Moon.
Moon: Simulations - setup

- 2D: \( L_x \times L_y = 3200 \Delta x \times 1280 \Delta y = 53 \, R_L \times 26 \, R_L \)
- 3D: \( L_x \times L_y \times L_z = 300 \Delta x \times 160 \Delta y \times 160 \Delta z = 10R_L \times 5R_L \times 5R_L \)
- Solar wind speed: \( v_{sw} = 5v_A \); electron beta: \( \beta_e = 1.0 \)
- IMF direction (wrt to solar wind flow): \( \Theta = -45^\circ \)
- Cavity in near-moon wake; downstream a density enhancement occurs at center of the depletion region
- Counter-streaming ion distributions in depletion region center; large temperature anisotropies at edges
- Left-hand polarized ion gyrofrequency wave fluctuations in wake-tail
Moon: Simulation results: 3D [Travnicek et al., 2008]

Stellar flows and moons and planets
Wake refilling is described by a magnetized plasma to vacuum expansion with plasma flow primarily in the magnetic field aligned direction.

The density gradient at the cavity’s edge provides an electric field accelerating protons towards the center of the cavity.

The current associated with the plasma to vacuum expansion leads to an enhancement of the magnetic field inside the plasma depletion region.

The rate of the plasma refilling process depends on the solar wind speed, plasma temperature and IMF orientation.

The density cavity is filled with counterstreaming ion beams; at the cavity’s edge the plasma is anisotropic in temperature ($T_\perp > T_\parallel$).

Density enhancement bump forms in center of far downstream wake due to a counterstreaming beams.

Asymmetries form in the density depletion region because of the skewed IMF orientation with respect to solar wind flow direction.

Left-hand polarized VLF waves near ion cyclotron frequency are generated at $28 \, R_L < X < 40 \, R_L$, due to an anisotropy or heat flux instability.
Mercury: Observations

- Mercury is smaller than Earth, however is embedded into a denser plasma.
- Till January 14, 2008 Mercury has been observed by single spacecraft (Mariner 10) in 70th (two encounters).
- Both encounters have shown that Mercury has its own (weak) magnetosphere.
- Mercury orbits Earth on an excentric orbit = significant changes in its magnetosphere.
- New probes: MESSENGER (NASA), BepiColombo (ESA).
Mercury: Observations

- Magnetometer data from two flybys by the Mariner 10 established that Mercury has an intrinsic magnetic field \([Ness et al., 1974]\).
- Magnetic dipole moment has been estimated to be between 170 nT \(R_M^3\) \((\approx 2.5 \cdot 10^{19} \text{ Am}^2\) \([Jackson and Beard, 1977]\) and 349 nT \(R_M^3\) \((\approx 5 \cdot 10^{19} \text{ Am}^2\) \([Ness et al., 1975]\).
- MESSENGER: 250 nT \(R_M^3\).
- The standoff distance was estimated to be between 1.3 and 2.1 \(R_M\).
- Mariner 10 electron data indicated that a substorm-like event may have occurred, suggesting magnetic reconnection in magnetotail \([Siscoe et al., 1975; Eraker and Simpson, 1986]\).
- Small Hermean magnetosphere can be exposed to solar wind with speeds ranging from 200 km/s up to 600 km/s \([Russell et al., 1988]\).
- MESSENGER 1st flyby: \(v_{sw} = 400 \text{ km/s}\).
Numerical model: Global Simulations to date

All (global) numerical models employ some compromises:

- MHD 3D simulations [Kabin et al., 2001].
- Hybrid models with spatial resolution of several $c/\omega_{pi}$ [Kalio and Janhunen, 2003] (typical Larmor radius at Mercury is 2-3 $c/\omega_{pi}$).
- Global 2D hybrid models of solar wind interacting with magnetized obstacles have been also considered [Omidi et al., 2002].
- **Scaled down model with spatial resolution of the order $c/\omega_{pi}$ and reasonable ratio between Larmor radius and the scaled down size of the planet** [Travnicek et al., 2007a].
We used a scaled down model of Mercury with a magnetic moment \( M = 25,000 B_{sw} \Lambda_{p_{sw}}^3 4\pi/\mu_0 = 3.76 \cdot 10^{19}/\varepsilon \) Am\(^2\) for both studies, where the scaling factor \( \varepsilon \) equals to \( \approx 166 \) and \( \approx 111 \) for the high and low solar wind pressure cases respectively.

Consequently we use \( R_M = 16.36 \Lambda_{p_{sw}} \) and \( R_M = 12.48 \Lambda_{p_{sw}} \) for the two studied cases.

The downscaling preserves the stand-off distance of the magnetopause predicted by \( R_{mp} = (2B_{eq}^2/(\mu_0 P_{ram,sw}))^{1/6} R_M \), where \( B_{eq} \) is the magnetic field at the equator of the planet with radius \( R_M \) and \( P_{ram,sw} \) is solar wind ram pressure \( n_{sw} m_p v_{sw}^2 \), where \( m_p \) is the proton mass (\( m_p = 1 \) in simulation units).

Although scaled down, the radius \( R_M \) is always sufficiently larger than the local Larmor radius \( r_L \).
Numerical model: Initial and boundary conditions

- IMF $B_{0sw} = (B_x, B_y, 0)$, $B_{0sw} = 1$ makes an angle of $\varphi = -30^\circ$ with respect to the $-X$ axis (i.e., with respect to the solar wind flow direction). The dipolar field is defined by

$$B_M = \left( M/r^3 \right) B_{sw} \left[ -2 \sin \lambda e_r + \cos \lambda e_\lambda \right].$$

No dipole tilt is applied.

- We keep $\partial B/\partial t = 0$ and $E = 0$ in the interior of the planet.

- A resistivity layer $\eta \approx 0.8 \exp(-h^2/h_0^2)$ (where $h$ is radial distance from the surface, $h_0 = 3 \Lambda p_{sw}$), is applied near the planet’s surface.

- We have also injected $H^+$ ions with density of the order $n_p \sim 10^{-4} n_{sw}$ isotropically from Mercury’s surface in both cases with velocity $v_p \sim 0.05 v_A$ perpendicular to the surface.

- Both numerical experiments reached times $\sim 40 \Omega_{psw}^{-1}$ which is sufficiently higher than the system transit time.
### Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High $P_{\text{ram,sw}}$</th>
<th>Low $P_{\text{ram,sw}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution $\Delta x/\Delta y = \Delta z$</td>
<td>0.4/1.0 $\Lambda_{psw}$</td>
<td></td>
</tr>
<tr>
<td>Time step $\Delta t$</td>
<td>0.02 $\Omega^{-1}_{psw}$</td>
<td></td>
</tr>
<tr>
<td>$\beta_e$</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Number of pcles / cell</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>$\beta_p$</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Solar wind velocity ($M_A$)</td>
<td>5.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Orientation of IMF $\Theta$</td>
<td>30°</td>
<td></td>
</tr>
<tr>
<td>Radius of the planet ($90/60 \Lambda_{psw}$)</td>
<td>16.4 $\Lambda_{psw}$</td>
<td>12.5 $\Lambda_{psw}$</td>
</tr>
<tr>
<td>Total duration</td>
<td>40.0-80.0 $\Omega^{-1}_p$</td>
<td></td>
</tr>
</tbody>
</table>

- $n_p = 73 \, \text{cm}^{-3}$, $B_{sw} = 46 \, \text{nT}$, i.e. $R_M = 91c/\omega_{pi}$, $v_{Asw} = 118 \, \text{km/s}$ in relatively fast solar wind (i.e. $v_{sw} = 600 \, \text{km/s} \approx 5 \, v_{Asw}$).
- $n_p = 32 \, \text{cm}^{-3}$, $B_{sw} = 21 \, \text{nT}$, i.e. $R_M = 60c/\omega_{pi}$, $v_{Asw} = 82 \, \text{km/s}$ in relatively slow solar wind (namely $v_{sw} = 250 \, \text{km/s} \approx 3 \, v_{Asw}$).
Results: Virtual measurements

- We can perform 3D measurements of any basic plasma entity: $B$, $n_i$, $E$, $j$, $T_\parallel$, $T_\perp$, $v_{th}$, $r_L$, ...
- Derived entities: curvature of magnetic field, electric and magnetic drifts (to understand particle motion).
- Full 3D picture of the overall structure of the magnetosphere: from foreshock to magneto-tail (to understand energy distribution).
- Energetic budget on boundaries.
- (multispacecraft) flybys on non-gravitationally driven trajectories: plasma flow lines (cf. HEB).
- Role of initial conditions: parameters in of the solar wind and/or the obstacle itself
- Fourier analysis (waves modes) and their origin, propagation, dumping.
Mercury: Density $\text{H}^+$

Stellar flows and moons and planets
Mercury: Temperature

Stellar flows and moons and planets
We injected $H^+$ ions into the system from the planetary surface to include a zero-order model of ions sputtered of the surface. These ions were injected with density of the order $n_p \sim 10^{-4} n_{sw}$ isotropically from Mercury’s surface in both cases with velocity $v_p \sim 0.05 v_A$ perpendicular to the surface.
Protons ejected from Hermean surface:

\[ v_{psw} = 5v_{Asw} \text{ vs. } v_{psw} = 3v_{Asw} \]
Aim of the scaled down model: preserve wave-particle interactions. Temperature anisotropy $A_p = T_\perp / T_\parallel = A_p(\beta_\parallel)$ shall be bounded by regions unstable with respect to the anisotropy driven instabilities.

Examining temperature anisotropy in our model:
- Can provide useful indication whether in our simulations wave-particle interactions are resolved properly
- Provides predictions about the compression/expansion of the Hermean magnetospheric plasma at different locations and possibly excited anisotropy driven instabilities: enhancement of HEB observations
Temperature anisotropy profile $A_p = T_\perp / T_\parallel$
HEB simulation and Cluster II observations

LEFT: Magnetosheath plasma in a HEB simulation
RIGHT: Magnetosheath plasma observed by Cluster II (from [Travnicek et al., 2007b])
Small planet: Solar wind plasma

We use for the solar wind $\beta_p = 0.5$ in both simulations.
Small planet: Subsolar magnetosheath plasma

Stellar flows and moons and planets
Small planet: Quasi-parallel magnetosheath plasma

Stellar flows and moons and planets
Small planet: Quasi-perpendicular magnetosheath plasma

Stellar flows and moons and planets
Small planet: Radiation belt plasma

Stellar flows and moons and planets
Two-fluid MHD predicts $T_\perp \propto B$, $T_\parallel \propto n^2/B^2$. Temperature anisotropies emerge naturally when plasma is compressed, stretched, expanding.

Convention: $a > 0$: expansion, $a < 0$: compression (special case: $a_\parallel$ - stretching)

Calculate symmetric tensor field $T_{ij} = 1/2(\partial u_i/\partial x_j + \partial u_j/\partial x_i)$ (i.e. evaluate $T_{ij}$ in each point of the simulation domain).

Diagonalize $T_{ij}$ and find eigenvectors $v_1, v_2, v_3$ and eigenvalues $a_1, a_2, a_3$.

Calculate the stretching rate $a_\parallel \sim \partial u_\parallel/\partial x_\parallel$, and two expansion rates $a_c, a_\parallel \times c$. The direction $c$ is given by the vector of magnetic fieldline curvature.

Similarly, calculate the antisymmetric tensor field $T^*_{ij} = 1/2(\partial u_i/\partial x_j - \partial u_j/\partial x_i)$ and obtain a measure of the velocity shear: $1/3\sqrt{a^2 + b^2 + c^2}$, where $a, b, c$ are non-diagonal elements of the antisymmetric tensor $T^*_{ij}$. 
Small planet: Stretching/Expansion of the plasma for $\beta = 1$

Stellar flows and moons and planets
Small planet: Stretching/Expansion of the plasma for $\beta = 4$

Stellar flows and moons and planets
Small planet: Torsion of the plasma for $\beta = 1$ and $\beta = 4$
Setup of another numerical experiment

\[ n_{sw} = B_{sw} = v_{A,sw} = c / \omega_{pi,sw} = 1 \text{ (unit)} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution ( \Delta x / \Delta y = \Delta z )</td>
<td>0.4/1.0 ( c / \omega_{pi,sw} )</td>
</tr>
<tr>
<td>Time step ( \Delta t )</td>
<td>0.02 ( \Omega_{p,sw}^{-1} )</td>
</tr>
<tr>
<td>Spatial size of the system ( L_x / L_y = L_z )</td>
<td>260 / 265 ( c / \omega_{pi,sw} )</td>
</tr>
<tr>
<td>Total duration</td>
<td>64.0 ( \Omega_{p,sw}^{-1} )</td>
</tr>
<tr>
<td>( \beta_p / \beta_e )</td>
<td>1.0 / 1.0</td>
</tr>
<tr>
<td>Number of macro-particles per cell</td>
<td>70 (total ( \sim 3.2 \cdot 10^9 ))</td>
</tr>
<tr>
<td>Solar wind velocity ( (M_A) v_{sw} )</td>
<td>4.0 ( v_{A,sw} )</td>
</tr>
<tr>
<td>Orientation of IMF</td>
<td>-16° ( (B_z = 0) )</td>
</tr>
<tr>
<td>Mercury’s magnetic moment ( M_M )</td>
<td>= 250 nT (( = B_{eq} )) (no tilt)</td>
</tr>
</tbody>
</table>

Radius of Mercury \( R_M \)
\[
\left[ 25000 \frac{B_{sw}}{B_{eq}} \right]^{1/3} \frac{c}{\omega_{pi,sw}}
\]

Simulation coordinate system: \( X^+ \parallel \) to the solar wind flow,
\( Y^+ \parallel \) to Mercury’s orbital speed, \( Z^+ \parallel \) towards north pole
(antiparallel with respect to \( M_M \))
$H^+$ density with overplotted (virtual) MESSENGER trajectory (equatorial plane):
MESSENGER in situ observations

[Slavin et al., 2008]
Simulation results: density and magnetic field

Stellar flows and moons and planets
Simulation results: S/C trajectory in the $(\beta_{||}, T_{\perp}/T_{||})$ space
Mercury: Conclusions

- We have carried out a case study which confirms several phenomena observed by the MESSENGER spacecraft observed in situ and helps to interpret the nature of the wave-particle effects.
- Inbound flyby: whistler waves in the foot of the nearly strictly perpendicular shock, mirror waves downstream the quasi-perpendicular bow shock, sheath turbulence, signatures of the presence of Mercury’s belt in magnetic field measurements.
- The numerical results support presence of Kelvin-Helmholtz vortices formed near the inbound magnetopause.
- Quasi-parallel magnetosheath is filled with a cascade of large amplitude mirror-like structures formed in a cascade of magnetic field line stretching and compression.
- Outbound magnetosheath suggests presence of two transition layers one possibly in the form of a slow mode or intermediate shock.