MERCURY’S MAGNETOSPHERE IN RESPONSE TO ELEVATED, PROLONGED, SOLAR ACTIVITY IN DECEMBER, 2006: HYBRID MODELING RESULTS

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OUTLINE

- HYBRID MODEL
- MAGNETOSPHERE
  - NOMINAL V.S. HIGH SPEED SW
- HIGH ENERGY (~0.5 MeV) PROTONS
- Na+ IONS
- CONCLUSIONS
HYBRID MODEL

HYB- hybrid model: General features

• Quasineutral: \( \Sigma n_{\text{ion}} = n_{\text{electron}} \)
• Hybrid: \( H^+, O^+, \) and \( O_2^+ \) ions are particles, Electrons form a massless fluid
• Self-consistent model
• Dynamics:
  - Electrons "carry" the magnetic field \( (E = -U_e \times B) \)
  - Ions (\( H^+, Na^+, K^+ \) e.g.) are accelerated by the Lorentz force

• Hierarchically refined cubic grid
• Ion splitting and joining:
  - splitting: \( A \rightarrow A_1 + A_2 \)
  - joining: \( B_1 + B_2 + B_3 \rightarrow B_1 + B_2 \)
  (note: conserves \( E \) and \( p \))
MAGNETOSPHERE

FOUR RUNS

• Two ion species: H\(^+\) from the SW and planetary Na\(^+\)
• \(n_{sw}(H^+) = 72 \text{ cm}^{-3}\)  \(\text{Na}^+: 10^{23} \text{ s}^{-1}\) (exosphere) +\(10^{25} \text{ s}^{-1}\) (surface)

“NOMINAL RUN”

• \(U_{sw} = 430 \text{ km/s}\)
1. “Nominal north IMF run”: IMF = [0, 0, 10] nT
2. “Nominal Parker IMF run”: IMF = [32,10,0] nT

“HIGH SPEED RUN”

• \(U_{sw} = 1000 \text{ km/s}\)
3. “High speed north IMF run”: IMF = [0, 0, 10] nT
4. “High speed Parker IMF run”: IMF = [32,10,0] nT
Magnetosphere and the solar wind density

Nominal north IMF run (430 km/s)  
High speed Parker IMF run (1000 km/s)

Note: Increase of Usw results in a more “compressed” magnetosphere
HIGH ENERGY ($\sim$ 0.5 MEV) PROTONS

- $\sim$ 0.5MeV (6191 km/s) H$^+$ population was included in the solar wind in order to study how high energy solar wind H$^+$ ions are “shadowed” by Mercury’s magnetosphere. The population was assumed to move in the solar wind along $-\mathbf{B}_{\text{IMF}}$.

- Two upstream cases were studied:
  1. “Nominal Parker IMF run”:
     \[ \text{IMF} = [32,10,0] \text{ nT}, \ U_{\text{sw}} = 430 \text{ km/s} \]
  2. “High speed Parker IMF run”:
     \[ \text{IMF} = [32,10,0] \text{ nT}, \ U_{\text{sw}} = 1000 \text{ km/s} \]
High energy SW H$^+$ ions: Y = 0 plane

“Nominal Parker IMF run”: IMF = [32,10,0] nT, $U_{sw} = 430$ km/s

High energy SW H$^+$ population ($\sim 0.5$ MeV)  Main SW H$^+$ populations ($\sim 400$ km/s)

Normalized so that the undisturbed value is $\sim 1e-4$
High energy SW H$^+$ ions: $Z = 0$ plane

“Nominal Parker IMF run”: IMF = [32,10,0] nT, $U_{sw} = 430$ km/s

High energy SW H$^+$ population ($\sim 0.5$ MeV)  Main SW H$^+$ populations ($\sim 400$ km/s)

Normalized so that the undisturbed value is $\sim 1e-4$

Log$[n(H^+)]$  Log$[n(H^+)]$ [m$^{-3}$]
High energy SW H\(^+\) ions: X = 0 plane

“Nominal Parker IMF run”: IMF = [32,10,0] nT, U\(_{sw}\) = 430 km/s

- **High energy SW H\(^+\) population** (~ 0.5 MeV)
- **Main SW H\(^+\) populations** (~400 km/s)

Normalized so that the undisturbed value is ~1e-4
High energy SW H⁺ ions: Y = 0 plane

“High speed Parker IMF run”: IMF = [32,10,0] nT, $U_{sw} = 1000$ km/s

High energy SW H⁺ population (∼ 0.5 MeV)  Main SW H⁺ populations (∼400 km/s)

Normalized so that the undisturbed value is ∼ 1e-4

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High energy SW H⁺ ions: Z = 0 plane

“High speed Parker IMF run”: IMF = \([32,10,0]\) nT, \(U_{sw} = 1000\) km/s

High energy SW H⁺ population (~ 0.5 MeV)  Main SW H⁺ populations (~400 km/s)

Normalized so that the undisturbed value is \(\sim 1e-4\)
High energy SW H\(^+\) ions: X = 0 plane

“High speed Parker IMF run”: IMF = [32,10,0] nT, \(U_{sw} = 1000\) km/s

High energy SW H\(^+\) population (~0.5 MeV)  Main SW H\(^+\) populations (~400 km/s)

Normalized so that the undisturbed value is ~ 1e-4
Na\(^+\) IONS

The model contains two Na\(^+\) ion sources:

1. **Exosphere**: where \(10^{23}\) Na\(^+\) ions are formed per second by photoionization.

2. **Surface**: where \(10^{25}\) Na\(^+\) ions are emitted per second homogenously (in order to study asymmetries caused by the magnetosphere) from the surface both on the dayside and the nightside.
**Planetary ions: Na⁺ from the surface**

- **Na⁺ ionosphere**: Ions emitted from the surface (homogenous emission from the dayside and the nightside)
- Note how $U_{sw}$ affects the density of Na⁺ ions from the surface
- $3.674 \times 10^{-22} \text{ kg/m}^3$ corresponds to a Na⁺ ion density of $0.01 \text{ cm}^{-3}$

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\rho(\text{Na}^+)$ [kg/m$^3$]</th>
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<tbody>
<tr>
<td>Nominal north IMF run (430 km/s)</td>
<td><img src="image1.png" alt="Image of density distribution" /></td>
</tr>
<tr>
<td>High speed Parker IMF run (1000 km/s)</td>
<td><img src="image2.png" alt="Image of density distribution" /></td>
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</tbody>
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Planetary ions: Na$^+$ from the exosphere

- Na$^+$ exosphere: Photoions
- Note how Usw affects the density of Na$^+$ ions from the surface
- $1 \times 10^{-22}$ kg/m$^3$ corresponds to a Na$^+$ ion density of $0.0027$ cm$^{-3}$
Planetary ions: Na$^+$ from the exosphere

Nominal north IMF run (430 km/s)  High speed Parker IMF run (1000 km/s)

Approximate orbit of MESSENGER during the 3$^{rd}$ flyby

http://messenger.jhuapl.edu/the_mission/MESSENGERTimeline/MercuryFlyby3Files/Mercury3AboveNorthPoleFull.jpg
Planetary ions: Na$^+$ from the surface

Nominal north IMF run (430 km/s)  High speed Parker IMF run (1000 km/s)

Approximate orbit of MESSENGER during the 3$^{rd}$ flyby
Similar HYB modelling for Mars (which features a draped induced magnetic field) was carried out earlier and revealed under extreme solar wind conditions similar to those that pertained in March, 1989, a different pattern of magnetic shadowing to that displayed (above) at Mercury.
The model results at Mars shows an encouraging similarity to in situ measurements made by the SLED instrument aboard Phobos-2 during the prolonged SEP of March 1989 (study ongoing).
CONCLUSIONS

- The Hermean intrinsic magnetic field is strong enough to form a bow shock, a magnetosphere, a magnetotail and a plasma sheet.

- A fast solar wind (1000 km/s) results in compression of Mercury’s magnetosphere.

- Mercury’s intrinsic magnetic field is strong enough to prevent high energy (~ 0.5 MeV) H+ ions from impacting freely on its surface, even under nominal solar wind plasma conditions.

- The modelled spatial distribution of Na+ ions show a clear dawn-dusk asymmetry at Mercury, even though these test particles were launched upstream axi-symmetrically.
The model showed that the magnitude of the upstream solar wind velocity affects:

- size of the magnetosphere
- shielding of high energy H+ ions
- the spatial distribution of incoming Na+ ions

Overall it is important to have information on upstream solar wind conditions in order to interpret in situ particle observations at Mercury.
Four major solar flares took place between 5-14 December, 2006 at the start of the minimum phase of Solar Cycle 23.

NOAA Active Region 0930, transited the solar east limb on December 5, 2006 at S06º and produced over the following 9 days four X-class flares each accompanied by a metric Type II burst.

This activity occurred at the start of the minimum phase of Solar Cycle 23.

- X9.0 (December 5, 10:34UT)
- X6.5 (December 6, 18:42 UT)
- X3.4 (December 13, 02:24 UT)
- X1.5 (December 14, 22:10 UT)

It is planned in future to use the solar wind parameters that pertained during the SEP events of December, 2006 to model/study differences between the magnetic shielding offered by the inner planets Mars and Mercury under extreme interplanetary circumstances.