Magnetospheric Charged Particle Observations and Modeling at Mercury

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"As the Universe consists almost entirely of plasma (the plasma universe, Alfven, 1986), the understanding of astrophysical phenomena must depend critically on our understanding of how matter behaves in the plasma state.

In situ observations in the near-Earth cosmical plasma or that of other accessible celestial bodies such as Mercury offer an excellent opportunity of gaining such an understanding."

C.G. Fälthammar, 1988
That the terrestrial magnetosphere had such a rich and complex structure was all but trivial!
That the hermean magnetosphere has such a rich and complex structure will be all but trivial!
"Around 19:00, the spacecraft altitude fell below ~800 km, and the magnetic field intensity began to increase quickly as MESSENGER moved into the region dominated by Mercury’s dipolar planetary magnetic field."

Slavin et al., 2008
"Centered dipole solutions yield a **southward planetary moment of 230 to 290 nT R}_M^3..."

Anderson et al., 2008
Transposition from Earth to Mercury

Slavin et al. [2009]
"The extraordinary length of the sodium tail of Mercury portrays Na source conditions versus time. All the sodium seen in the extended tail was on the surface of Mercury less than a day earlier."

Baumgardner et al., 2008
Neutral tail and ionized tail (2/2)

different timeline for charged particles as compared to neutrals
⇒ "source conditions versus time" ?
Mercury vs. Earth (1/3)

⇒ how similar is "similar"?

Slavin [2004]
$\Rightarrow$ just the "same thing" but on smaller scales?
Not quite the "same":
⇒ different boundary conditions
(inner boundary conductivity,
tenuous atmosphere,
solar wind parameters...)

⇒ just the "same thing"
but on smaller scales?
Not quite the "same":
⇒ some quantities are not rescaled (solar wind speed, particle mass...)

⇒ just the "same thing" but on smaller scales?
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⇒ interaction of the solar wind with a weakly magnetized body in the innermost heliosphere?
⇒ role of (possibly abundant) material of planetary origin in structure and dynamics of a magnetosphere?
Circulation of planetary material at Earth

Daglis [2001]

Chappell et al. [1987]

Seki et al. [1996]
Circulation of planetary material at Mercury (1/7)

Leblanc et al. [2008]

Zurbuchen et al. [2008]

Vervack et al. [2010]
Circulation of planetary material at Mercury (2/7)

⇒ tenuous atmosphere but extended source with respect to magnetospheric scales

Leblanc and Johnson [2003]

Horwitz [1984]
Circulation of planetary material at Mercury (3/7)

⇒ season (TAA) dependent loading of the magnetosphere due to exosphere variability (close connection) ?
⇒ season (TAA) dependent dynamics ?

Leblanc and Johnson [2003]

Delcourt et al. [2003]
Circulation of planetary material at Mercury (4/7)

⇒ lobe characteristic energy?
(enriched "bead-on-rotating-rod" like centrifugal acceleration due to $E \times B$)

Leblanc and Johnson [2003]

Delcourt et al. [2003]
Circulation of heavy material at Mercury (5/7)

⇒ lobe characteristic energy?
⇒ non-gyrotropic kinetics?
(nonadiabatic transport throughout equatorial magnetosphere)

\[ \kappa = \sqrt{\frac{RC}{\rho}} \]

Delcourt et al. [2003]
Circulation of heavy material at Mercury (5/7)

⇒ lobe characteristic energy ?  
⇒ non-gyrotropic kinetics ?  
⇒ IMF control of planetary material recycling in innermost region ?
Circulation of planetary material at Mercury (7/7)

A. Ion sputtering

B. PSD with high-speed tail

C. Maxwellian PSD, T=1500 K

Sarantos et al. [2009]
Impulsive transport at Mercury (1/9)

nominal Parker spiral

Kabin et al. [2000]

Newell et al. [1991]

cusp-mantle like solar wind precipitation?
Impulsive transport at Mercury (2/9)

nominal Parker spiral

"... Its size should make Mercury’s magnetosphere especially prone to disturbances that are driven by the changing external boundary conditions..."

Luhmann et al., 1998
Saito et al. [2008]

Mercury

Moon

"bald spot"

⇒ downstream entry path of scattered material into compressed magnetosphere?
**Impulsive transport at Mercury (3/9)**

solar wind ram pressure increase from \(\sim 2 \text{ nPa} \) to \(\sim 15 \text{ nPa} \)
\[ \Rightarrow \text{inward short-lived transport of } \sim 2 \text{ \(R_E\) in 2 min} \]

\[ \Rightarrow \text{at Earth: adiabatic response during compression in the high-altitude lobe} \]

Cladis et al. [2000]
short-lived inward transport of $\sim 0.5 \, R_M$ in 20 s

Delcourt et al. [2010]
Impulsive transport at Mercury (5/9)

- Na$^+$: Increase in mobility
- Ca$^+$: Increase in mobility
- H$^+$: No increase in mobility
Impulsive transport at Mercury (6/9)

⇒ at Earth: mass selective energization during dipolarization in the equatorial magnetosphere

Mitchell et al. [2003]
Impulsive transport at Mercury (7/9)

Na$^+$ 20 s

Na$^+$ 10 s

$\tau_C/\tau_B = 1$
Impulsive transport at Mercury (8/9)

⇒ during compression, prominent nonadiabatic heating off-equator? (large ion gyroperiods - small intrinsic B - in addition to small temporal scales)
⇒ abrupt production of energetic planetary material in the lobes?
Impulsive transport at Mercury (9/9)

resonant nonadiabatic heating of $H^+$ in the "dipolarizing" region

⇒ at Earth: mass selective energization during dipolarization in the equatorial magnetosphere

⇒ at Mercury: preferential energization of light ions in the equatorial magnetosphere?
Some more open questions (1/2) ⇒ energetic particle injections?
Some more open questions (1/2) \[\Rightarrow\text{energetic particle injections?}\]
Some more open questions (1/2)  ⇒ energetic particle injections?

cuspward mirror force
Some more open questions (2/2) ⇒ electron dynamics?

Kabin et al. [2000]

Kallio and Janhunen [2003]
Some more open questions (2/2)  ⇒ electron dynamics?

Sergeev et al. [1993]
Not quite the "same":
⇒ some quantities are not rescaled (solar wind speed, particle mass...)
⇒ just the "same thing" but on smaller scales?
⇒ reduced scales together with (possibly abundant) material of planetary origin
⇒ environment of its own at the small-scale end of the magnetosphere spectrum
Thanks to his binoculars, Galileo Galilei noticed that the separator between dark side and bright side of the Moon is not rectilinear but indented. Based on this observation, he drew an analogy with what can be observed on Earth, that is: valleys are in the dark while mountains already are or still are sunlit. From his detailed and skillful account (Sidereus Nuncius), it was impossible not to be convinced that the surface of the Moon is covered with mountains, very much like Earth. And this is precisely what Galileo Galilei aimed at demonstrating: Moon is like Earth, Earth is like Moon.

F. Balibar, 2003
The NASA MESSENGER mission

5 months to go with "classical" view of Mercury's ionized environment...
The ESA-JAXA Bepi Colombo mission

... and a bit more before full-scale investigation