Effects of the Crustal Magnetic Fields and Changes in the IMF Orientation on the Magnetosphere of Mars: MAVEN Observations and LATHYS Results.

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Motivation

- Direct interaction between the SW and the atmosphere/ionosphere of Mars.
- Complex and **dynamic** plasma environment.
- Time-dependent physical processes play a significant role modifying the response of the obstacle, for ex: alter fluxes of planetary ions.

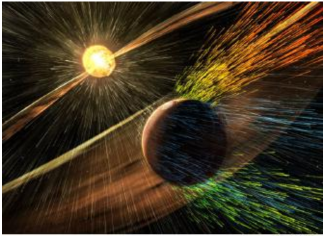

Image: Nasa/ GSFC

Some results from previous studies

- Heavy planetary ion escape increases by a factor of ~ 2.5 due to SW pressure pulses [Edberg et al. 2010]
- CME and CRI are capable of increasing the atmospheric escape by a factor of ~ 10 [Futaana et al. 2008; Dubinin et al. 2009]
- The location and shape of the BS and the MPB are strongly influenced by the SW dynamic pressure and electric field. Also important effects from the crustal magnetic fields and the solar EUV flux [Edberg et al. 2009]
- Enhancemets in the density and velocity of the SW, new quasi-equilibrium state of the Martian obstacle requires a few hours [Ma et al. 2014]

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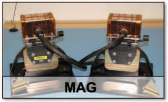
Introduction and adopted approach

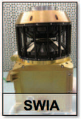
Objective: Study of the effects that a varying IMF and the crustal fields have on the Martian magnetosphere.

Time-dependent effects: main drivers

1) **Magnetized solar wind**
2) Solar photon EUV flux
3) Solar energetic particles
4) **Mars's orientation**
5) Shear related processes
6) Extreme events

- We analyze MAVEN MAG and SWIA measurements [Connerney et al 2015, Halekas et al 2015]





- We perform numerical hybrid simulations (LatHyS) [Modolo et al 2016, 2017]

Improve the understanding of the responses of the Martian IM to different structures in the incoming magnetized SW plasma flow.

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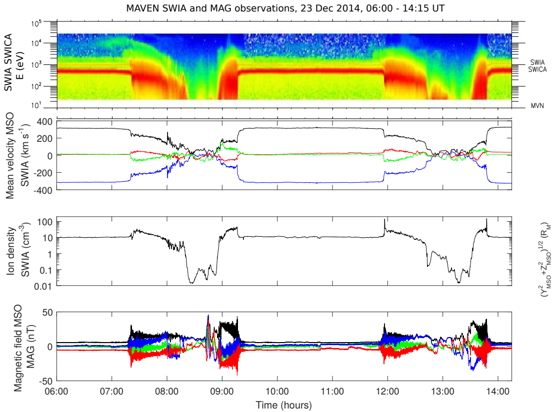
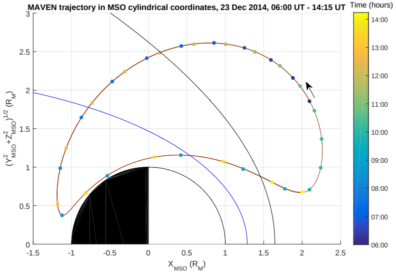
Presentation of the event on 23 Dec 2014





Key points

- First orbit: external conditions approximately constant.
- Closest approach in the Northern Hemisphere. Orbital period: 4.5 hours.
- Temporal variabilities in the IMF direction (Y-Z MSO plane) before the second inbound bow shock crossing.

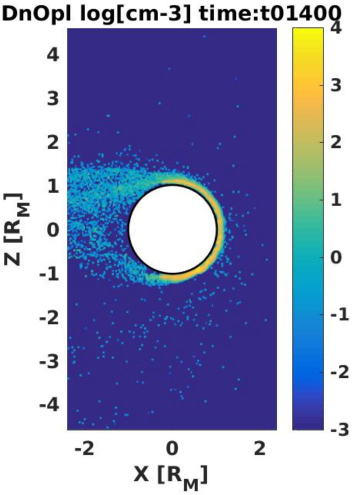
Latmos Hybrid Simulation (LatHyS) code

- Larmor radii of planetary ions ≥ radius of the obstacle: Kinetic description of ions is more appropriate at higher altitudes

Hybrid formalism:

- Ions are described by macroparticles
- Electrons are treated as a neutralizing inertialess fluid

- LatHyS is described in detail in Modolo et al [2016, 2017] and references therein.

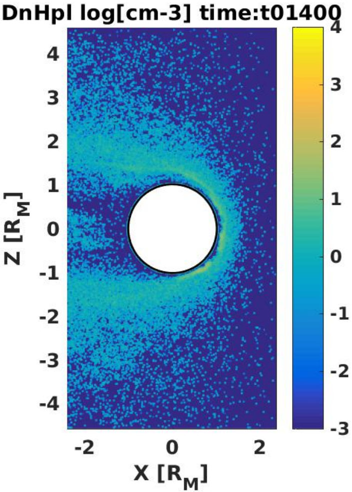


Latmos Hybrid Simulation (LatHyS) code

- Ionic species taken into account: H^+_{SW}, He^{++}, H^+_{PL}, O^+, O_2^+, CO_2^+

- Plasma/neutral coupling taken into account self-consistently, distinction between the ionization processes:

  - Photoionization
  - Electronic impacts
  - Charge exchange reactions



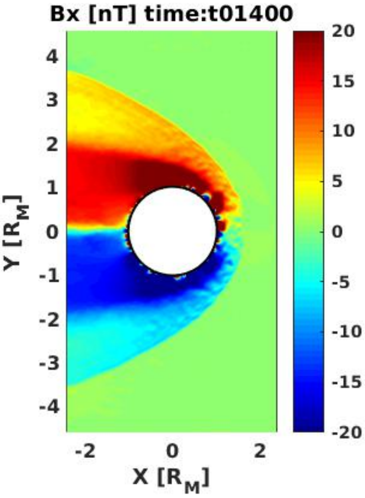
Latmos Hybrid Simulation (LatHyS) code

- We set up several external conditions based on MAVEN MAG and SWIA observations:

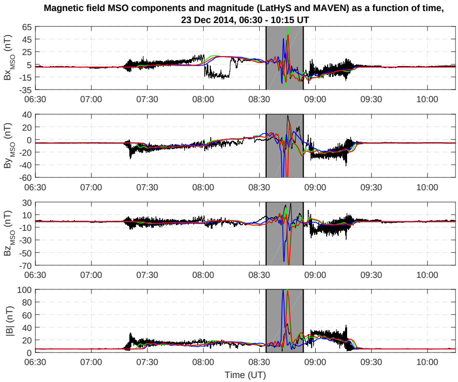
- $|B| = 5.6$ nT
- $V_{SW} = 313$ km/s
- $n_{SW} = 11$ cm^{-3}
- Solar wind composition: H^{+}_{SW} and He^{++} (5%)

- Profiles assumed for the Exosphere / Atmosphere : O, H and CO_2
- Crustal fields based on Cain et al [2003]
- Several chemical reactions in the ionosphere taken into account.

Required CPU time: $\sim$ 2000h on 256 CPUs (0.5 millions of CPU hours)



MAVEN MAG - LATHYS comparison for 23 Dec 2014, 06:00 - 10:15 UT

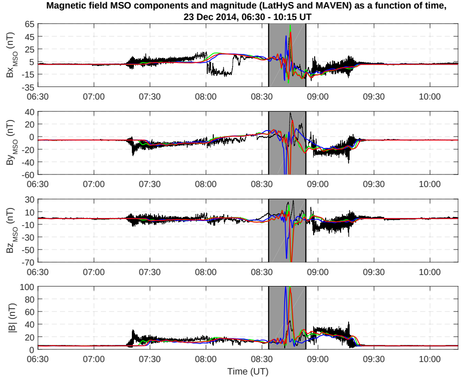


Fixed external conditions
Rotation of the crustal fields

Blue curve: Stationary state with ssl=157° (07:00 UT)
Green curve: Stationary state with ssl=132° (08:43 UT)
Red curve: Dynamical simulation
Grey box: Altitudes < 400 km

- **Draping of the IMF well reproduced** (except between 08:00 - 08:14 UT)
- **No significant differences between the three curves** (b,r,g) except around CA (08:43 UT) and the BS crossings.
- Differences between MAVEN and LATHYS around CA are due to the Cain model and its interpolation into a cartesian grid.
- Differences (MAVEN vs LATHYS) in the bow shock location: stronger in the inbound BS crossing (assumption of the atmospheric/exospheric profiles)
- Consistently, this difference is reduced in the OB BS crossing (nose vs flank)

MAVEN MAG - LATHYS comparison for 23 Dec 2014, 06:00 - 10:15 UT



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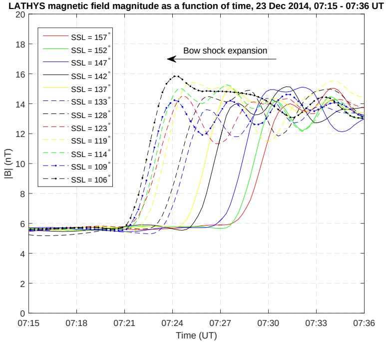
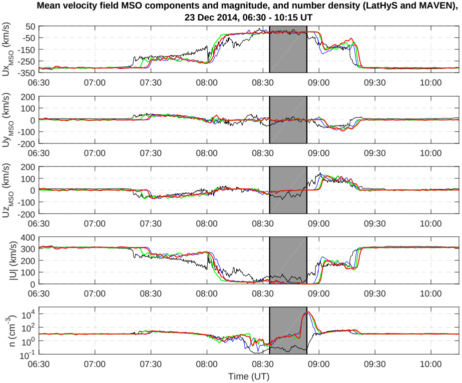


Fixed external conditions
Rotation of the crustal fields

MAVEN SWIA - LATHYS comparison for 23 Dec 2014, 06:00 - 10:15 UT



- Simulation in good agreement with observations, exceptions: predicted bow shock location and mass loading effect.

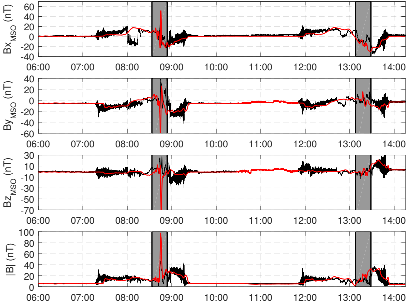
- Both discrepancies likely due to the assumed atmospheric/exospheric profile.

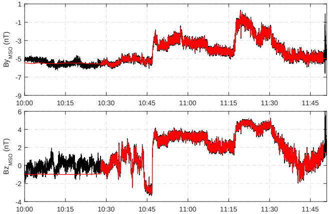
- Differences between the blue, green and red curves mainly in the predicted bow shock location (CF effects).

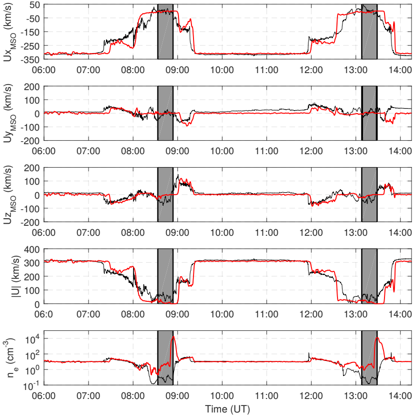
Fixed external conditions
Rotation of the crustal fields

MAVEN - LATHYS dynamical simulations, 23 Dec 2014, 06:00 - 14:15 UT

- Fixed external conditions during the first orbit
- Changing IMF before and during the second orbit
- Rotation of the crustal fields

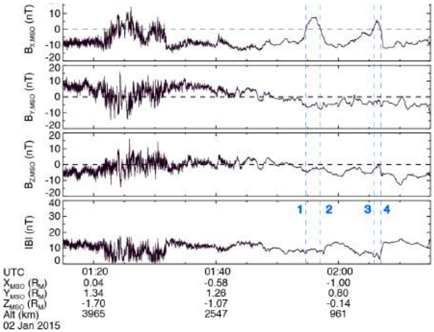






Deviation from nominal draping without signatures of IMF variations

MAVEN MAG observations of the Martian magnetotail [DiBraccio et al., 2015 2017]



Technique for diagnosing the flapping motion of magnetotail current sheets [Rong et al., 2015a]

- Based on single-point magnetic field anal- ysis (MVA)

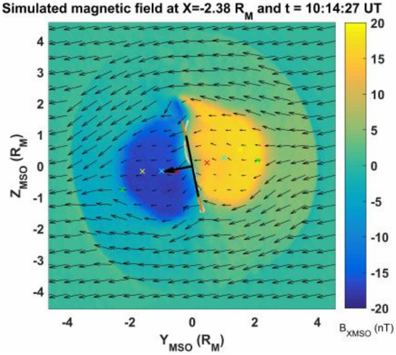
-Relies on the observation of a sequence of multiple CS crossings.

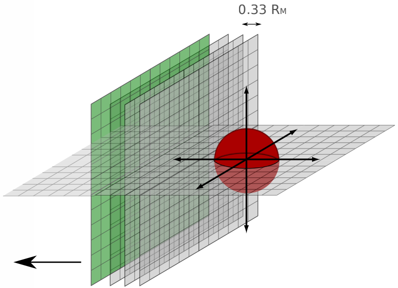
- This technique has been applied to study the flapping motion of the Venusian mag- netotail (VEX observations) [Rong et al., 2015b].

Several mechanisms proposed: Magnetic reconnection, Kelvin-Helmholtz instabilities, and Alfvenic wave effects

Flapping (statistically) observed up to distances of 1 R_M in the B_{IMF}^{Y-ZMSO} direction (limit of nominal wake) [DiBraccio et al 2017]

Recovery timescales of the magnetotail and magnetosheath



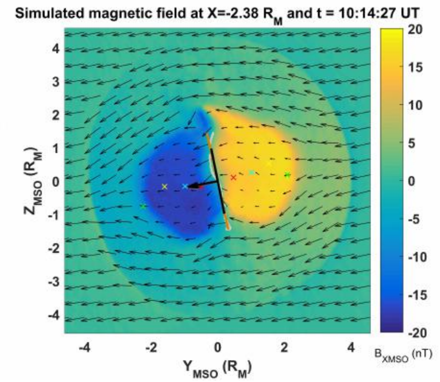


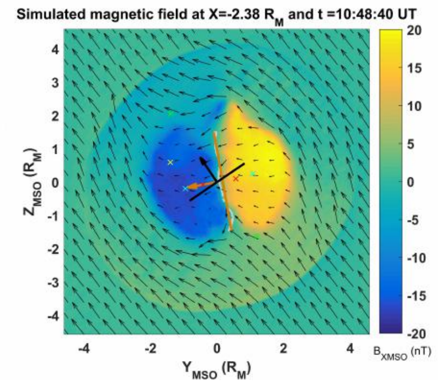
Characterization of the tail

- Determination of the center of mass of the $Bx_{MSO} > 0$ and $Bx_{MSO} < 0$ regions inside several rings centered on $YMSO = 0$ and $ZMSO = 0$.
- Definition of vectors based on them provides an estimation of the orientation of the tail structure.
- Additional estimate of the normal to the current sheet: linear fitting of points where $|Bx| < 0.5nT$, inside a radius of 1 R_M.

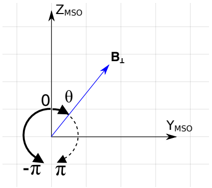
Recovery timescales of the magnetotail and magnetosheath

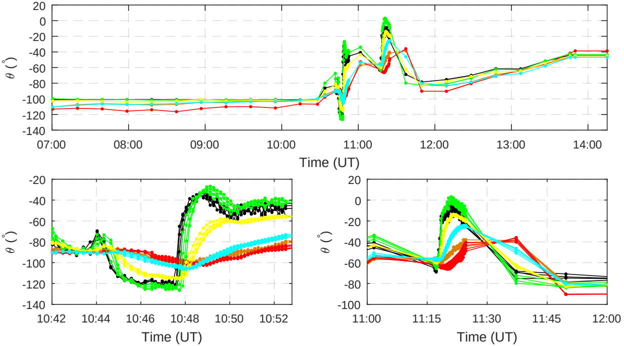
A magnetotail cross section at a quasi-stationary state (Left) and at a non-equilibrium state (Right)





Recovery timescales of the magnetotail and magnetosheath

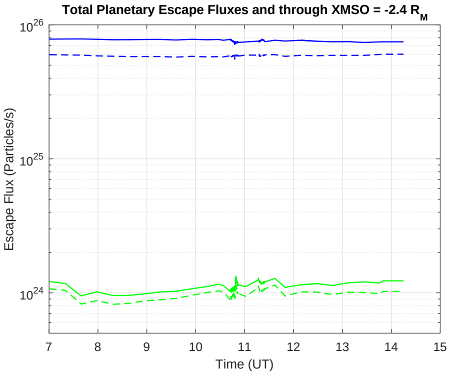




Preliminary results

- Highly similar reaction of each magnetotail region for Y-Z MSO planes between 1.38 R_M and 2.38 R_M.
- Assuming angular velocity of $\sim 7^{\circ}/min$, Recovery time of the magnetotail lobes: $\Delta t_{LOBE} \sim 6 - 7$ min.
- Recovery time of the magnetosheath $\sim 10 - 15$ sec.

Escaping H^+_{PL} and O^+ fluxes



Solid line: Total H^+_{PL} flux escape

Dash line: H^+_{PL} flux escape through $X = -2.4$ R_M

Solid line: Total O^+ flux escape

Dash line: O^+ flux escape through $X = -2.4$ R_M

Mean values for total planetary escape fluxes

- H^+ escape: $[7.56 \pm 0.16] \times 10^{25}$ ions/s (2%)
- O^+ escape: $[1.14 \pm 0.08] \times 10^{24}$ ions/s (7%)

Conclusions (1/2)

- Time-dependent physical processes play significant roles modifying the response of the Martian magnetosphere to the incoming SW [e.g., Edberg et al 2010, Futaana et al 2008, Dubinin 2009, Jakosky 2015].
- However, very often there is lack of coordinated observations of the upstream SW conditions and the plasma properties in the magnetosphere.
- We analyze magnetic field and plasma measurements provided by MAVEN on 23 December 2014, 06:00 - 14:20 UT. External conditions remained approximately constant during the first orbit. MAVEN observed changes in the IMF orientation before visiting the magnetosphere for the second time.
- We investigate the response of the Martian plasma environment to the rotation of the CF and the change of the background magnetic field orientation, performing LatHyS runs.

Conclusions (2/2)

- General good agreement between the simulations results and MAVEN MAG and SWIA observations during these two orbits.
- Differences found in the predicted bow shock location are likely due to the atmospheric profiles assumed during this time interval.
- An expected correlation between the predicted bow shock location at the flank and the ssl is observed.
- Differences between MAVEN MAG observations and LATHYS simulations at altitudes < 400 km are associated with the interpolation of the Cain model into a cartesian grid.
- Event between 08:00 and 08:14 UT can not be explained in terms of nominal draping. Not the first time that this is observed [DiBraccio et al 2015, 2017].
- Recovery time scales of the magnetotail lobes $\sim 6-7$ min, and the magnetosheath $\sim 10-15$ s.
- Escaping total fluxes of H and O planetary ions are estimated: $[7.56 \pm 0.16] \times 10^{25}$ ions/s, $[1.14 \pm 0.08] \times 10^{24}$ ions/s.