Modeling the Solar Wind – Mars interaction under quasi-radial IMF configuration

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Abstract

In absence of a global intrinsic magnetosphere, the Solar Wind plasma interacts directly with the planet's conductive ionosphere and upper atmosphere, exchanging momentum and energy. The interplanetary magnetic field (IMF) plays a crucial role as it drapes around this nearly unmagnetized planet, it induces a magnetotail with a two-lobe structure of opposite polarity as well as a dayside magnetic pileup region upstream of the ionosphere. To investigate these different drivers, a series of hybrid simulations has been performed with the LatHyS model (Modolo et al, 2016) and we compare simulations results for cone angle of 57°, 20°, 5°, 2° and 0°, both with and without the presence of crustal magnetic fields. The results reveal a highly disturbed magnetic and plasma environment in the subsolar region, with a foreshock region that can extend to more than 10 Martian radii, a persistent bipolar tail structure, the disappearance of the plume region and increased precipitation of solar wind protons. Simulation results also emphasize the critical role of crustal fields in helping to stabilize this hybrid magnetosphere.

Introduction

This classical picture of the Mars-Solar wind interaction has been suggested to be largely modified when the IMF is quasi-radial leading to a so-called degenerated magnetosphere (Zhang et al, 2024). Among the main findings, MAVEN observations indicated

- a highly variable plasma environment near the subsolar region, which corresponds to the foreshock region associated to a quasi-parallel bow shock,
- a deeper penetration of solar wind ions down to MAVEN periapsis (about 230km),
- a magnetic barrier present at lower altitude and significant erosion of the upper ionosphere driving enhanced ion escape (Fowler et al, 2022).

More recently, Dubinin et al (2026) have analyzed MAVEN data for small cone angles (below 20° or larger than 160°) and found that the main patterns of the classical Martian induced magnetosphere under Parker spiral conditions generally persist.

Simulation model

- The LatHyS model is used to describe the solar wind plasma interaction with Mars (e.g. Modolo et al, 2016; 2018). ⇒ provides a 3D description of the moments (*n, u, T*) for each ion species of planetary and solar wind plasma as well as the electromagnetic field environment (Figure 1).

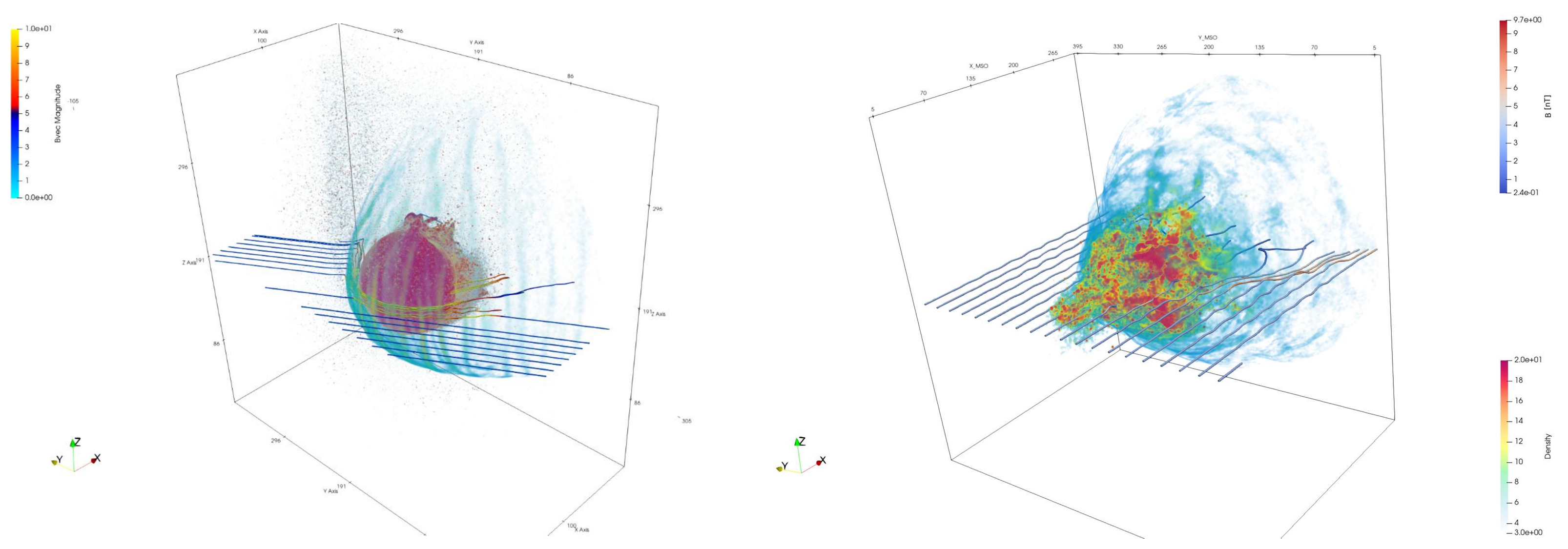
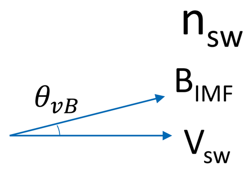


Figure 1 : LatHyS simulations for $\theta_{vB} = 57°$ (a) and $\theta_{vB} = 0°$ (b), illustrating the magnetic field draping (field lines) and density iso-volume emphasizing the location of the bow shock and ionospheric plasma population.

Solar wind and simulation parameters

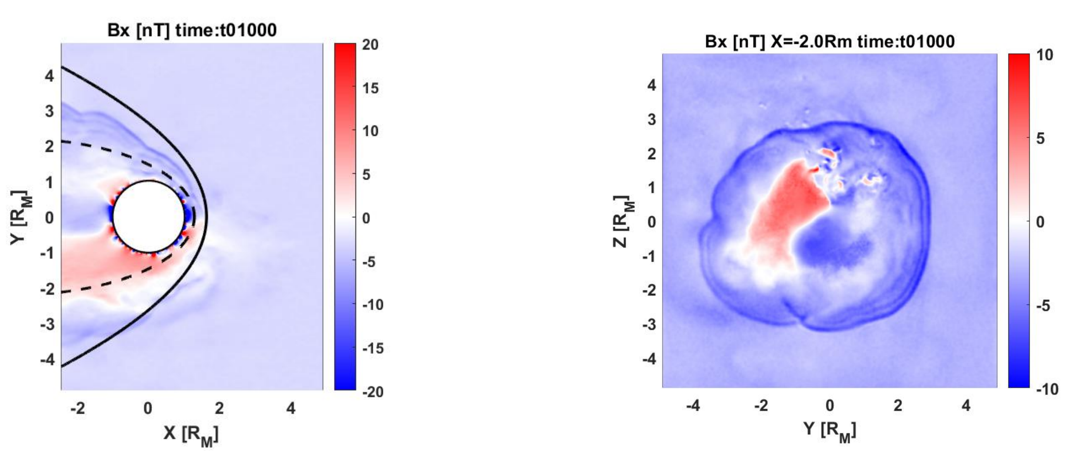
$|B_{IMF}|$ = 3 nT V_{sw} = [-400., 0., 0.] km/s (MSO) n_{sw} = 2,7 cm^{-3}
Bx <0 & By >0
T_{sw} = 12eV   5% He^{++}



Mars : Crustal Field (CF) 90 degrees internal potential (Cain et al, 2003)
Subsolar longitude = 180° (CF on dayside)
Simplified ionospheric chemistry, planetary ions H^+, O^+, O_2^+, CO_2^+
Δx = 80 km ~ 0,6 c/w_{pi} $\Delta t = 3\text{x}10^{-2}\ \Omega_{H+}^{-1}$ Nptot ~ 600 Millions
Δx = 100-130 km ~ 0,8-1 c/w_{pi} (for small cone angle)
Δx = 260 km ~ 2 c/w_{pi} (for extremely small cone angle)

Small IMF cone angle

θ_{VB}=5°, CF @SSL 180°, Δx = 80 km



- Bipolar magnetic tail signature is still present even at small cone angles (Figure 2)

Figure 2 : Bx component of magnetic field in XY and YZ MSO plane

Extended ionosphere

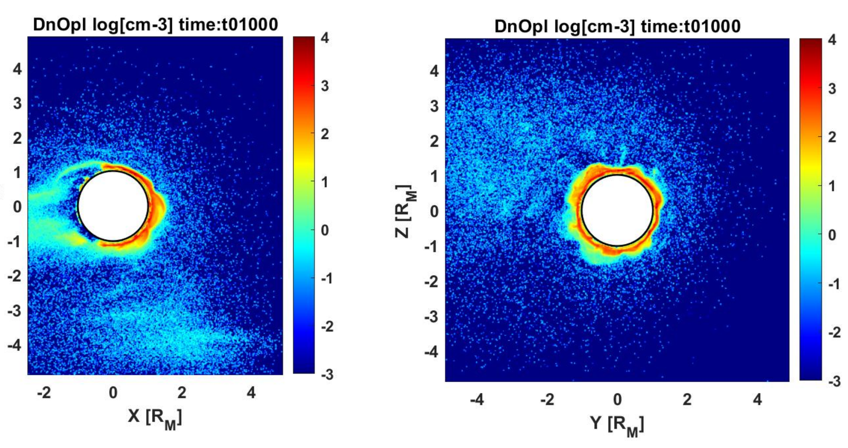


Figure 3 : O+ density maps in XY and YZ terminator plane

For $\theta_{VB} = 5°$, $\boldsymbol{E} = -\boldsymbol{U} \times \boldsymbol{B}$ almost vanishes

- No clear planetary ion plume signatures (should be along +Z) more homogenous distribution of planetary ions (Figure 3)
  - $\boldsymbol{E} \times \boldsymbol{B}$ (small) drift along –Y axis
- The ionosphere extends to higher altitude
  - Pthermal balances Pmag at higher altitude (weak pileup)

- A cavity void of SW ions is still present in the Martian wake
- Larger precipitating flux at 340 km altitude (Figure 4)

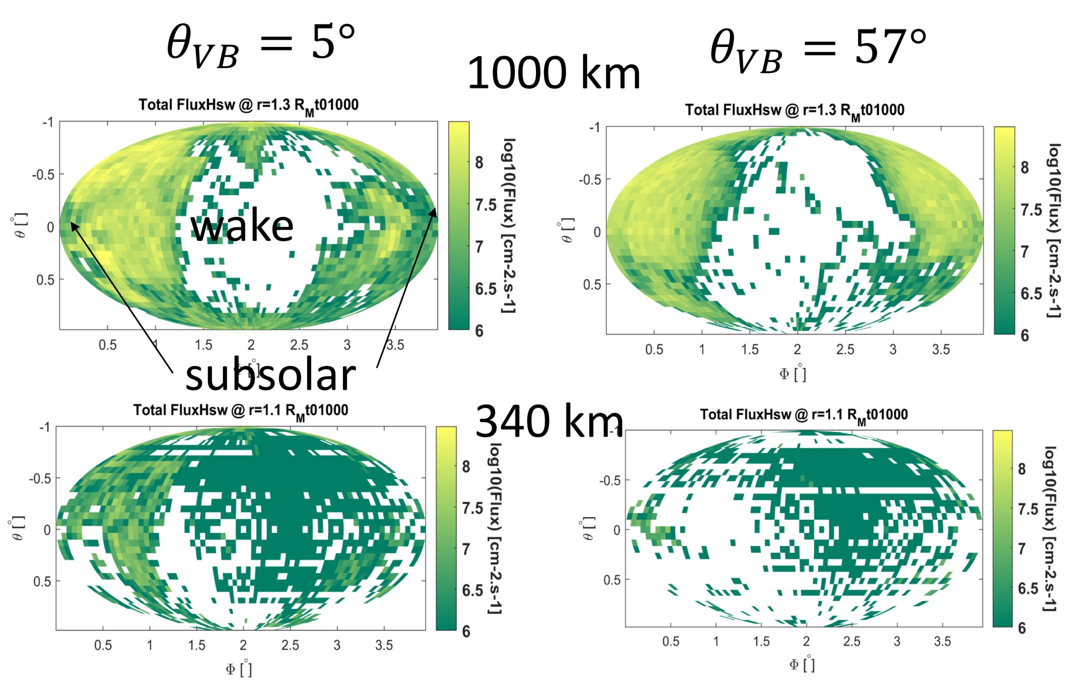


Figure 4 : H+ precipitation maps at 1000 km and 340 km for θ_{vB}=5° and θ_{vB}=57°

Impact of absence of crustal fields

- Clear absence of Magnetic Pileup Boundary
- Ion foreshock structure present at 8 R upstream
- Dayside BS highly disturbed (almost disappeared)
- Flank BS location further away from the planet
- Bipolar tail structure still persists (although less extended)

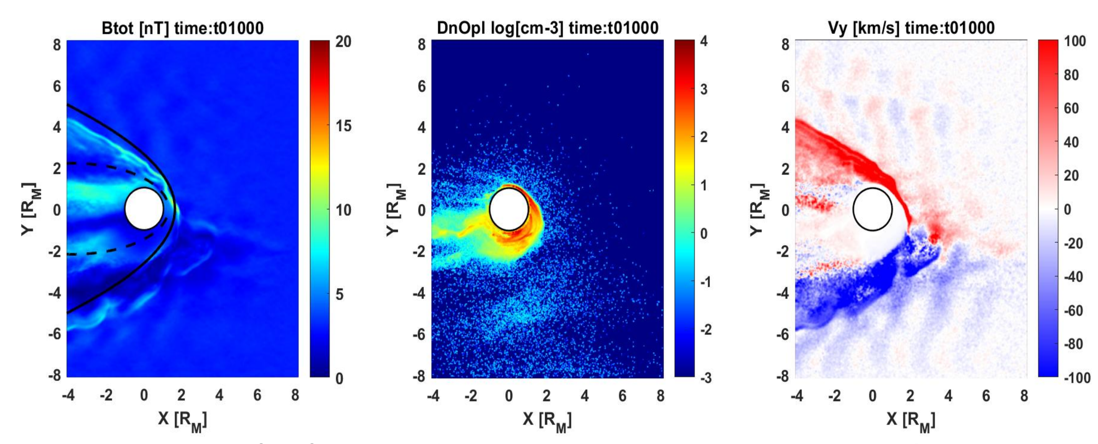


Figure 4 : |B|, O+ density, Vy maps in XY planes for θ_{vB}=5° , without Crustal Fields

- Large asymetry of planetary plasma flow in $E \times B$ direction (along –Y axis)
- Larger flux of precipitating SW protons
- Presence of CF seems to prevent precipitating fluxes

Plasma escape

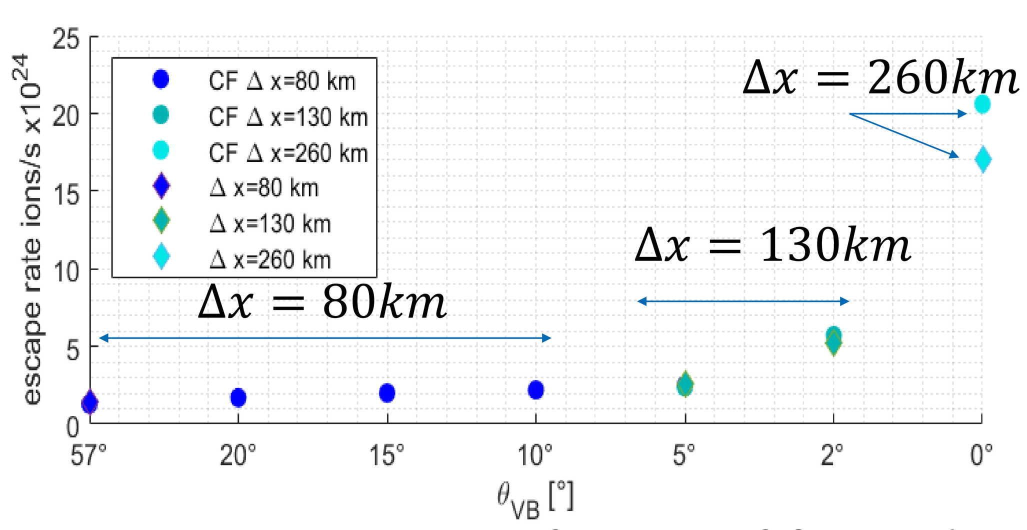


Figure 5 : O+ escape in function of θ_{vB} angles, with and without CF

- O^+ ion escape rate increase while θ_{VB} decreases
- Caveat 1 : escape rates have been calculated on the edge of the simulation box, need to be consolidated with other surface escape calculation
- Caveat 2 : for $\Delta x = 260km$ simulations, ionosphere is coarsely described

Preliminary conclusions

- Dayside bow shock highly disturbed, disappearing near subsolar region
- Absence of Magnetic pile up
- Increase of the precipitating solar wind protons while θ_VB decreases (to be better characterized, Global flux calculation, Energy distribution,…)
- Extended ionosphere
- Ion foreshock seems to expands up to 15 Rm