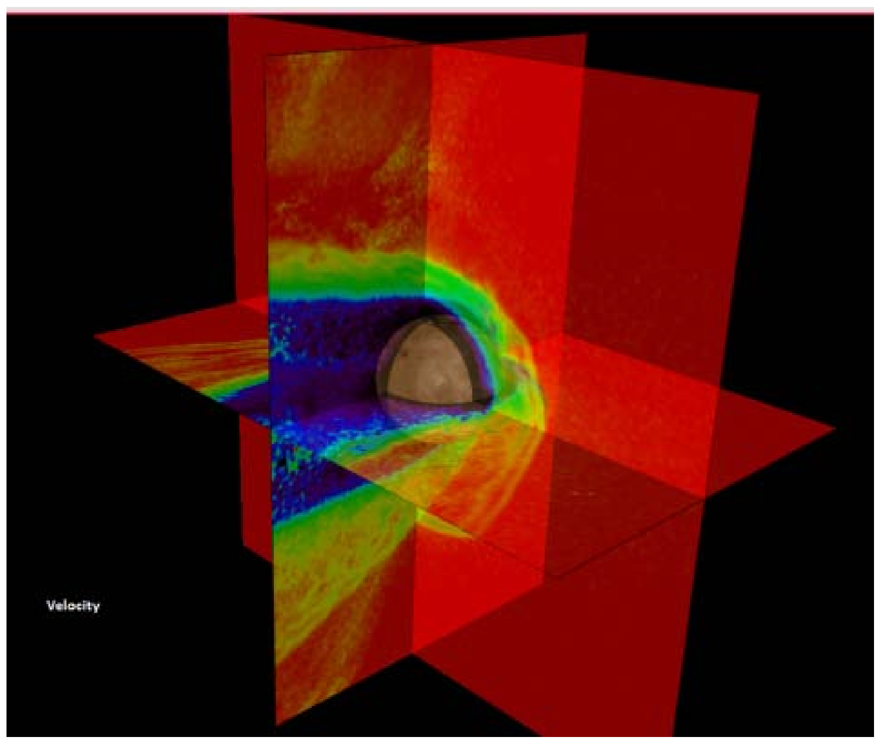
Modeling Mars-Solar wind interaction

R. Modolo, F. Leblanc, S. Hess, JY Chaufray, M. Yagi, G. Chanteur, F. Forget, F. Galindo-Gonzales, C. Mazelle, S. Grimald, L. Lorenzato et al

LATMOS, LMD, LPP, IRAP France

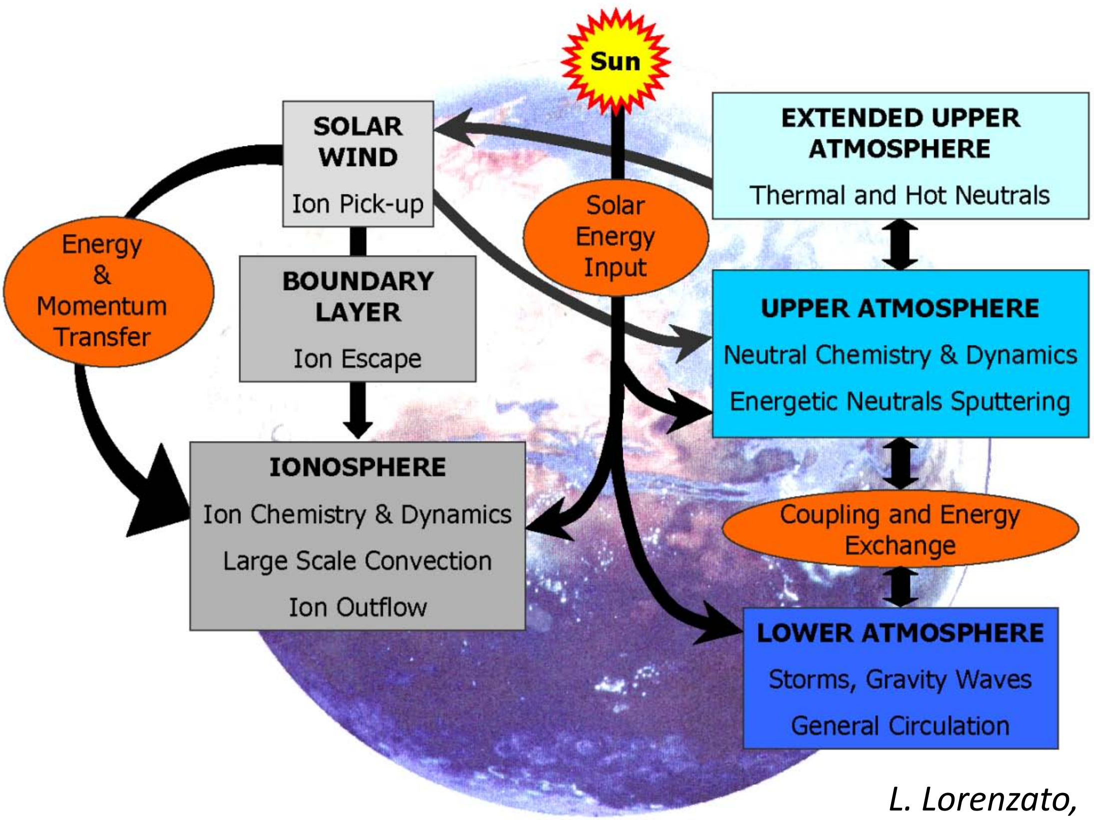


Outline

- Introduction
- Brief presentation of the hybrid model
- A 3D thermosphere-exosphere-(ionosphere)-magnetopshere coupling
- Effect of Crustal Fields on the Martian environment

HELIOSARES project (2009-2014)

HELIOSARES project : **PI F. Leblanc**, LATMOS
Co-Is : F. Forget (LMD), C. Mazelle (IRAP),
R. Modolo (LATMOS)



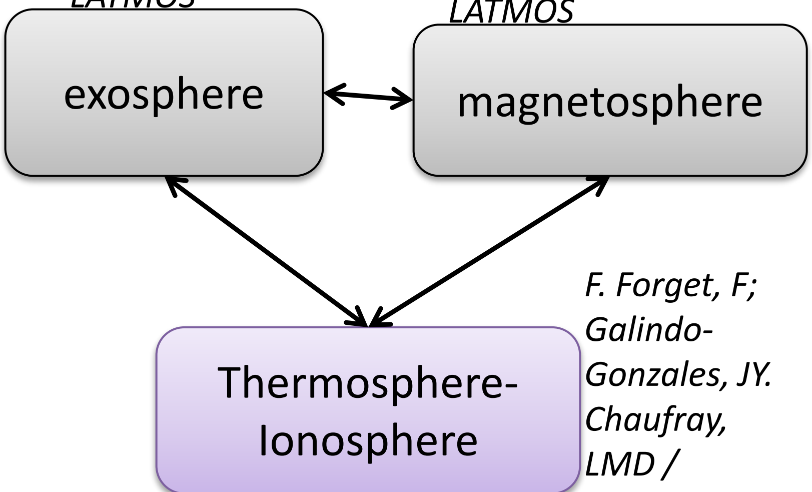
Adatped from S. Bougher

L. Lorenzato, C. Mazelle, A. Fedorov IRAP

Technical developpments ended in 2012

F. Leblanc, M. Yagi, JY Chaufray LATMOS

R. Modolo, M. Mancini, S. Hess LATMOS



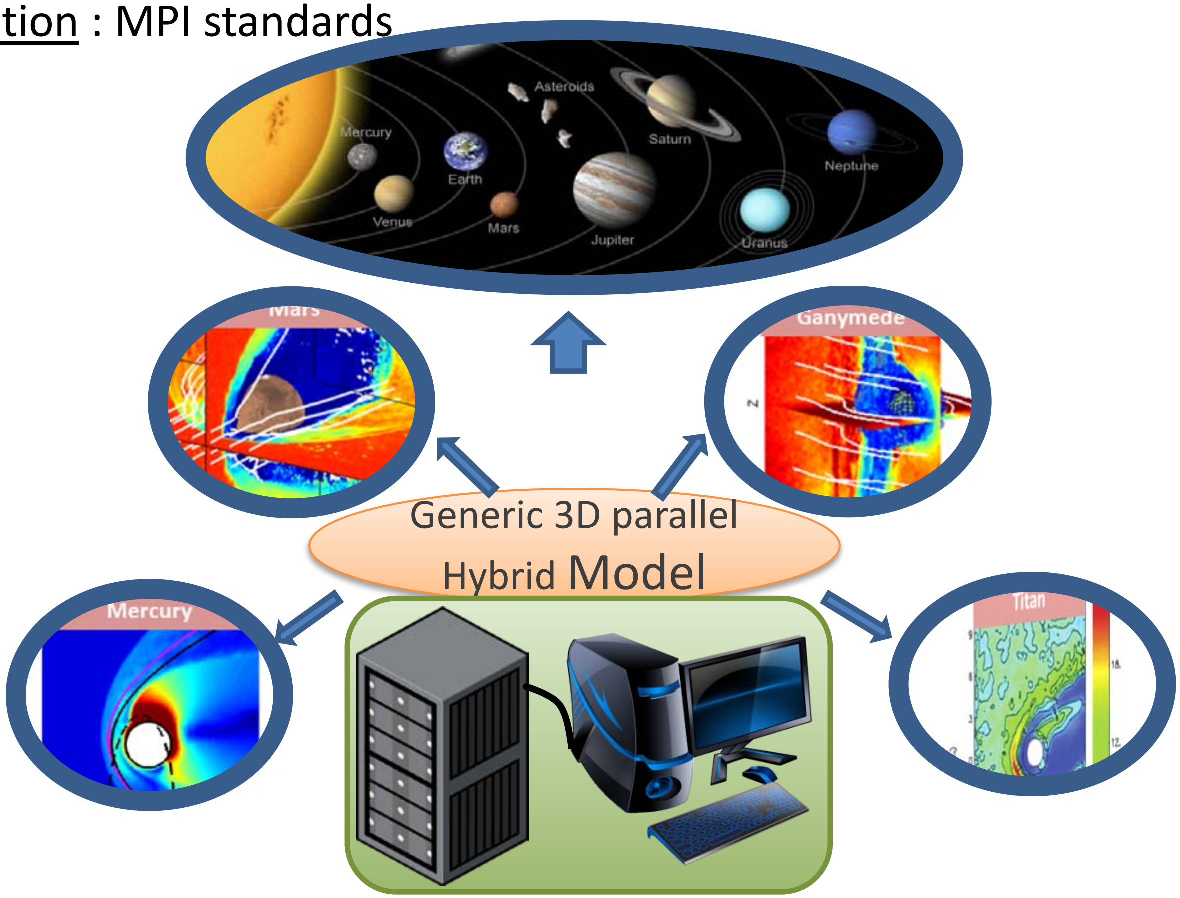
F. Forget, F; Galindo-Gonzales, JY. Chaufray, LMD / LATMOS

Validation / Comparison to observations (Phobos-2, MGS, MeX, *MAVEN*)

A generic 3D multi-species parallel hybrid model dedicated to plasma interaction with solar system objects

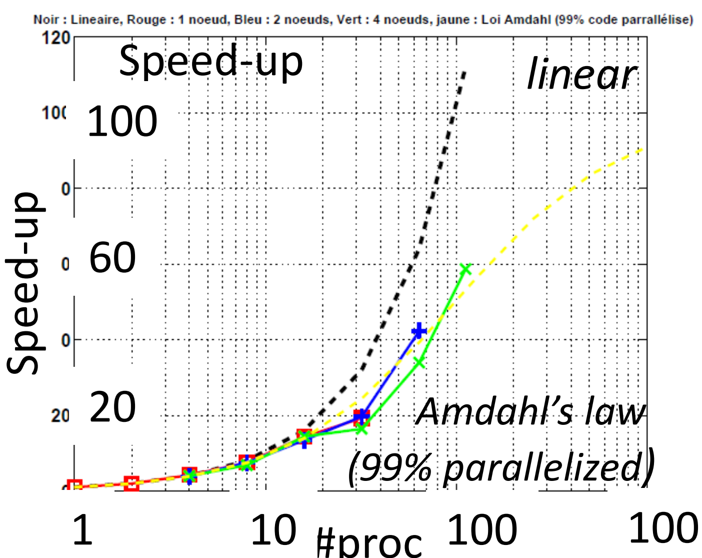
Simulation model : Hybrid formalism – kinetic description for ions and fluid description for electrons

Parallel computation : MPI standards



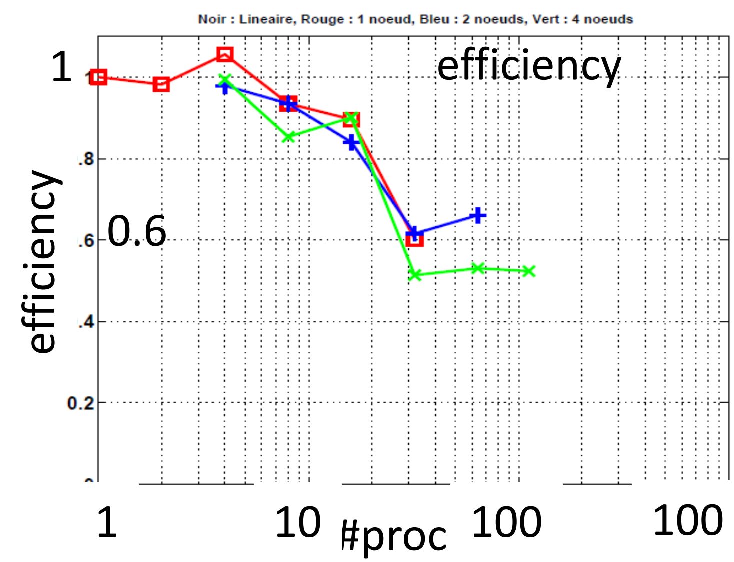
General information and model performances

	Low Resolution	Medium Resolution	High Resolution
Spatial step	160 km	80 km	50 km
Grid	127x202x202	187x354x356	450x730x730
# of particles	$40x10^6$	$260x10^6$	$9x10^9$
# time steps	12000	12000	20000
CPU time	509h	4600h	43000h (~5 years)
Memory	11.3Gb	52Gb	420Gb
#CPU, #nodes	32 / 1	48 / 2	128 / 2
Restitution time	16h	96h	336h (2weeks)



Excellent platform (CICLAD), comm. Internodes efficient

-good behaviour of the code



LATMOS
UNIVERSITÉ DE VERSAILLES SAINT-QUENTIN-EN-YVELINES

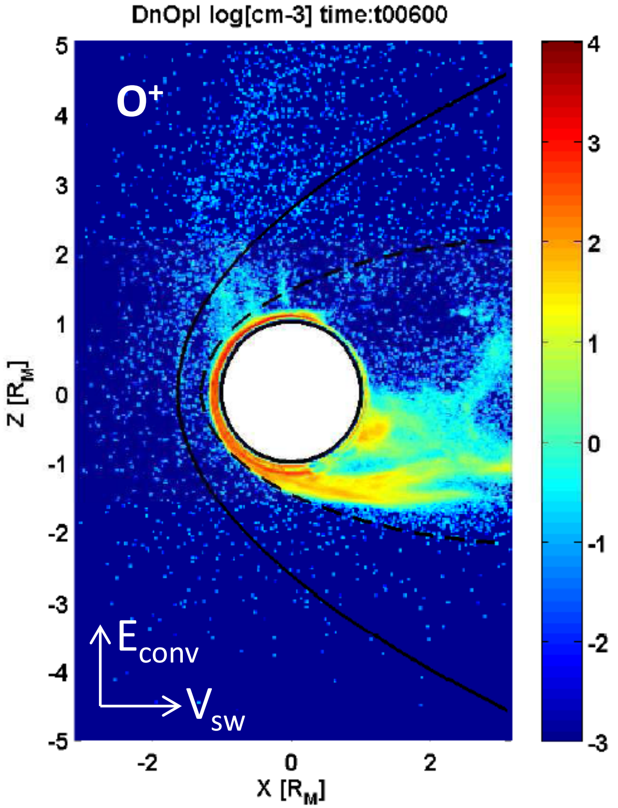
Description of the model

- Larmor radii of planetary ions ≥ radius of the obstacle

⇒ Kinetic description of ions is more appropriate at higher altitude

- Hybrid formalism :
  - Ions are described by macro-particles
  - Electrons are treated as a neutralizing inertialess fluid
  - Maxwell's equations reduce to divB=0, Ampere's and Faraday's equations

- Specific features for planetary environments
  - Weigthed macro-particles ⇨ description of a large range of density ($10^{-3} \rightarrow 10^{4}$ cm^{-3})



- Diversity of neutral environment description :
  - •Analytical density profiles
  - •Load 3D from thermosphere GCM model :
    LMD, Paris, F. Forget, JY. Chaufray
    Univ. Michigan, S. Bougher
  - •Load 3D exosphere: *LATMOS Monte Carlo model, F. Leblanc, JY Chaufray*
- Many charged species are represented :

  Mars : H^+_{sw}, He^{++}, H^+_{pl}, O^+, O_2^+,CO_2^+

  2 electronic fluids (solar wind / ionospheric)
- Plasma/neutral coupling taken into account self-consistently, distinction between ionisation processes
  - *Photoionisation* $\Rightarrow$ $h\nu + X \rightarrow X^+ + e^-$
  - *Electronic impacts* $\Rightarrow$ $X + e^- \rightarrow X^+ + 2e^-$
  - *Charge exchange reactions* $\Rightarrow$ $M^+ + X \rightarrow M + X^+$

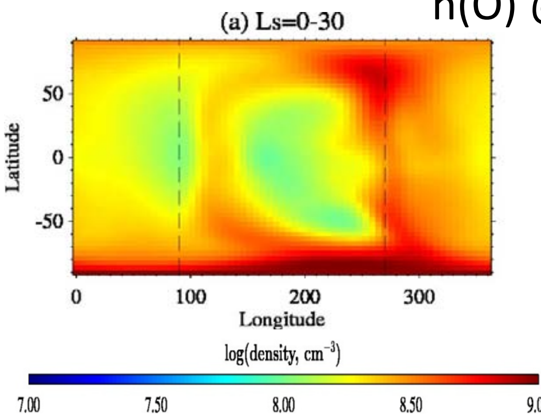
Ionization rates are computed locally from neutral densities and ionisation frequencies or cross sections

- Simplified ionospheric chemistry
- Crustal fields

1- Coupling magnetospheric + exospheric + GCM models : 1st attempt

- 3D thermosphere + exosphere (Yagi et al, 2012)
  - -Thermal CO2
  - -Thermal + Non-thermal O
  - -Ls 0°-30° (Spring)
  - -Solar mean

n(O) @200km

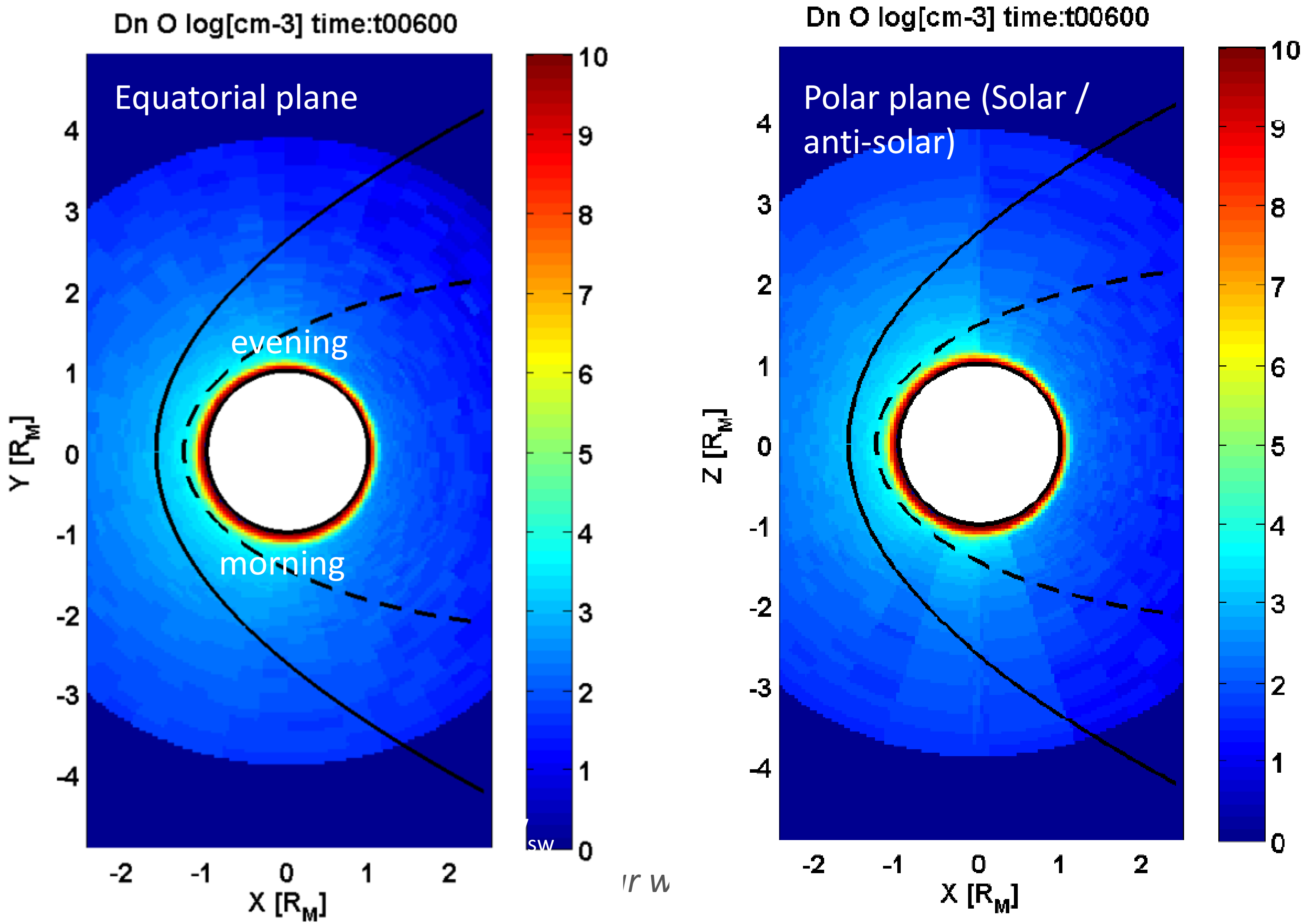


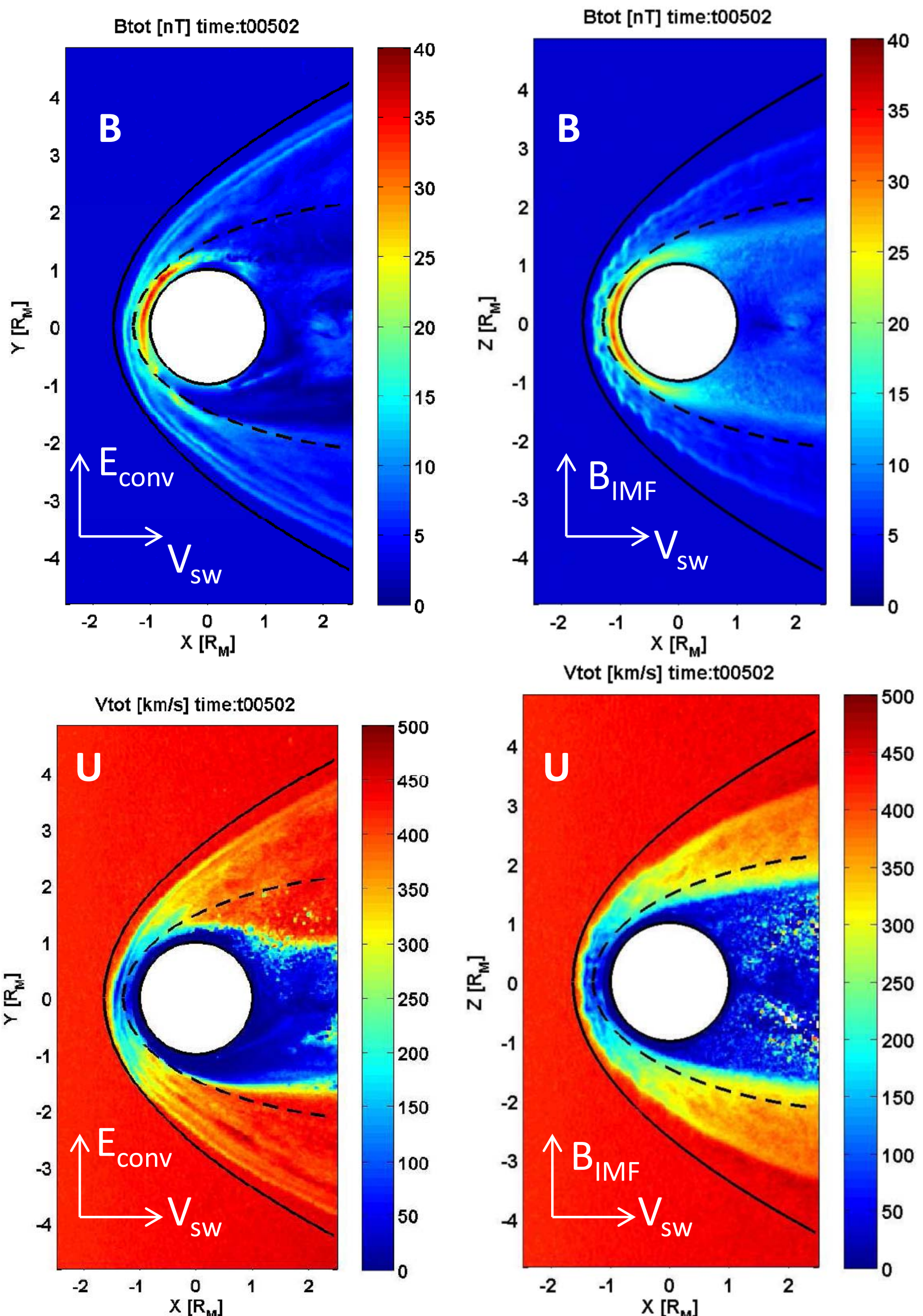
- 3D Hybrid with ionospheric description
  - n_{sw}=2.7 cm-3
  - B_{IMF}=(0,0,3)nT
  - Δx=60 km (0.45 c/w_{pi})
  - V_{sw} = 450 km/s (11 V_A)
  - F10.7cm = 120
  - no Crustal fields

	Reactions	Rate coefficients	Column rate
1	$CO_2 + h\nu \longrightarrow CO_2^+ + e$	$\lambda < 902$ Å	$1.24e^{+10}$
2	$CO_2 + h\nu \longrightarrow O^+ + CO + e$	$\lambda < 650$ Å	$1.09e^{+9}$
3	$O + h\nu \longrightarrow O^+ + e$	$\lambda < 911$ Å	$1.20e^{+8}$
4	$H + h\nu \longrightarrow H^+ + e$	$\lambda < 911$ Å	$1.00e^{+5}$
5	$CO_2^+ + O \longrightarrow O_2^+ + CO$	$1.64e^{-10}$	$8.07e^{+9}$
6	$CO_2^+ + O \longrightarrow O^+ + CO_2$	$9.6e^{-11}$	$4.72e^{+9}$
7	$O^+ + CO_2 \longrightarrow O_2^+ + CO$	$1.1e^{-9}$	$6.28e^{+9}$
8	$O_2^+ + e \longrightarrow O + O$	$7.38e^{-8}$	$1.36e^{+10}$
9	$CO_2^+ + e \longrightarrow CO + O$	$3.88e^{-7}(300/T_e)^{0.5}$	$7.52e^{+9}$

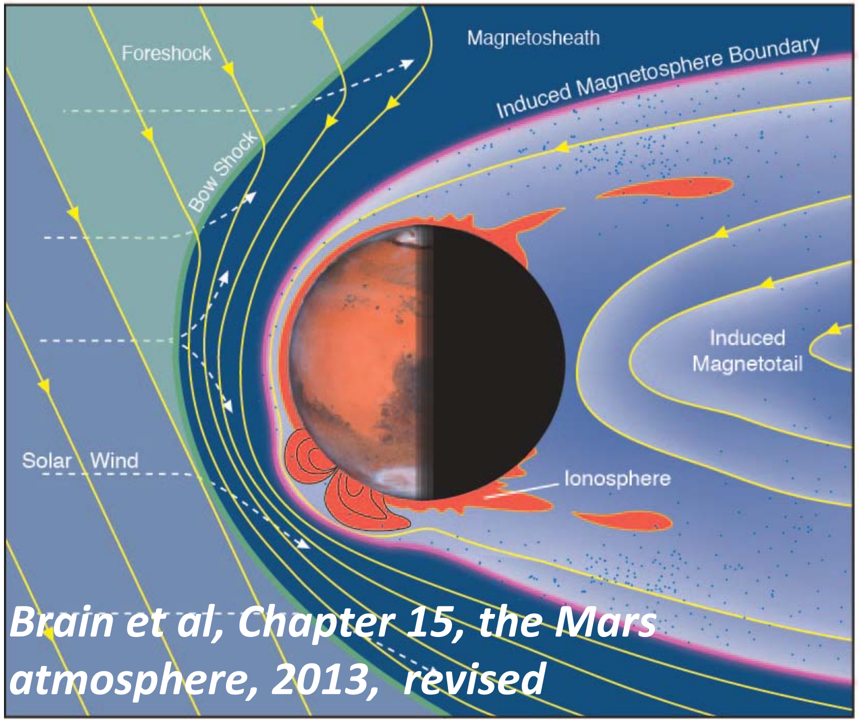
Numerical solution presented after 500 sw proton gyroperiods (corresponds to about 40 transit time of SW ions in the box)

Thermal+Non-thermal O (Input)

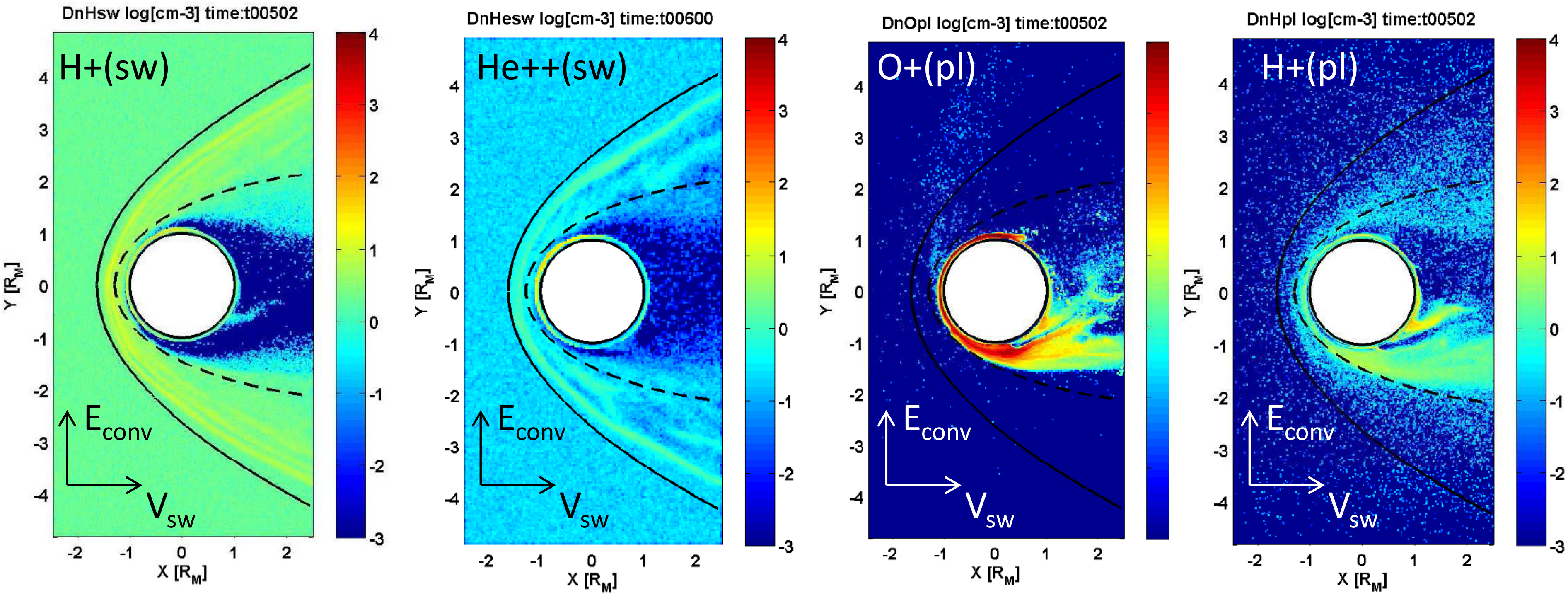




- Bow shock and Induced Magnetospheric Boundary position in good agreement with Phobos-2, MGS and MeX oservations
- Global structures well reproduced



Brain et al, Chapter 15, the Mars atmosphere, 2013, revised

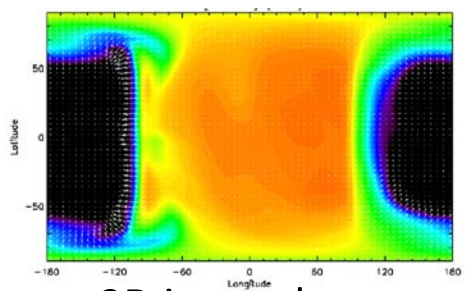


- A cavity void of SW ions is clearly seen and in agreement with MeX observations.
- This region is populated by heavy planetary ions which does not mix with the SW plasma.
- Strong asymetry of the planetary plasma maps (opposite to Econv direction)

Toward a thermospheric-exospheric-ionospheric-magnetospheric coupling

Goal: to get accurate ion escaping flux and investigate seasonal effect on planetary plasma we need an accurate ionospheric description

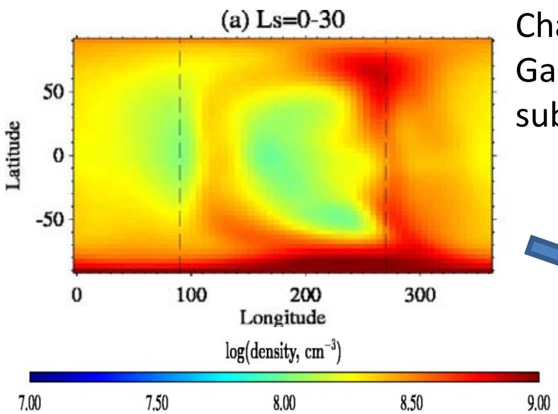
Procedure : coupling with ionospheric and thermospheric model to get a a 3D ionosphere + exospheric model (3D exosphere)



3D thermosphere

Forget et al, 1999

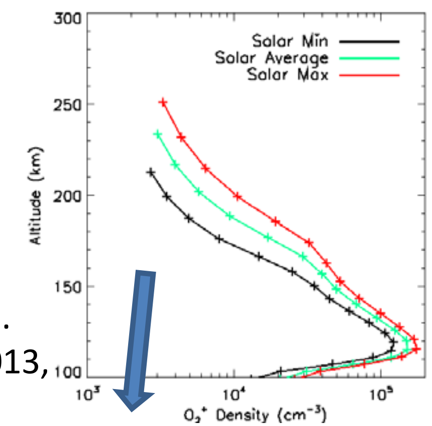
Galindo-Gonzales et al, 2009



3D ionosphere

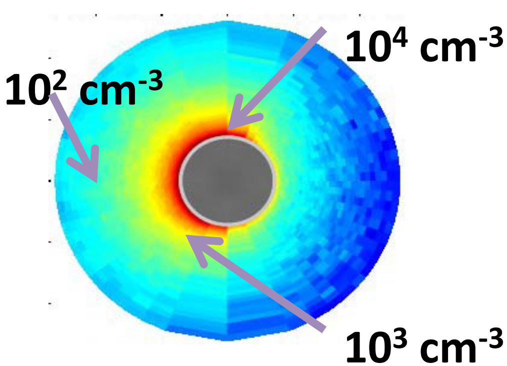
Chaufray et al, 2013 subm.

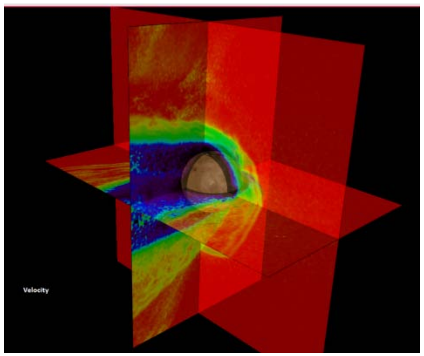
Galindo-Gonzales et al, 2013, subm.



3D exosphere

Yagi et al, 2012





3D hybrid

Modolo et al, 2013, in prep

Hess et al, 2013, in prep

2-CF effects on the Martian environment

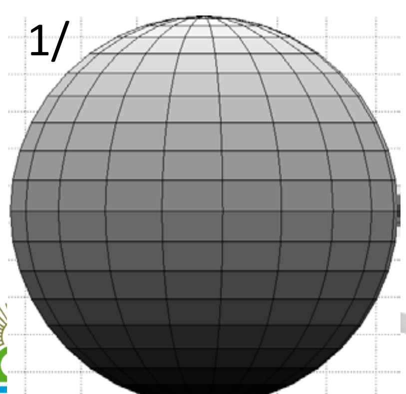
- Ma et al, 2002 (MHD)
  - CF did not cause major distorsion on the BS.
  - affect locally the altitude of the ionopause and magnetosheath
  - presence of CF slightly decreases escape rates

- Brecht and Ledvina, 2012 (hybrid)
  - presence of CF changes global BS shape and location
  - decreases by 20 the O+ escape rate and by 30 the O2+

- Comparison of 3 simulations (same inputs, Δx=80 km) :

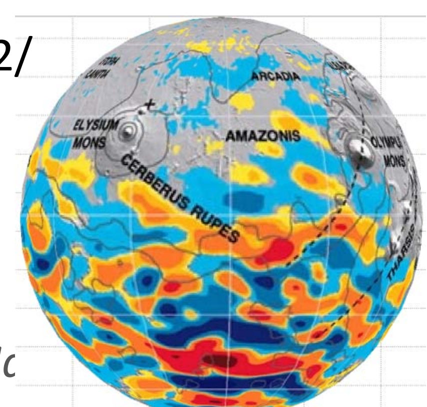
1/ without CF, 2/ position of main CF 0°, 3/ position of main CF 90°

1/

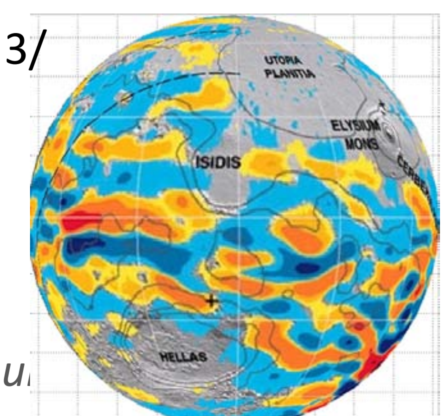


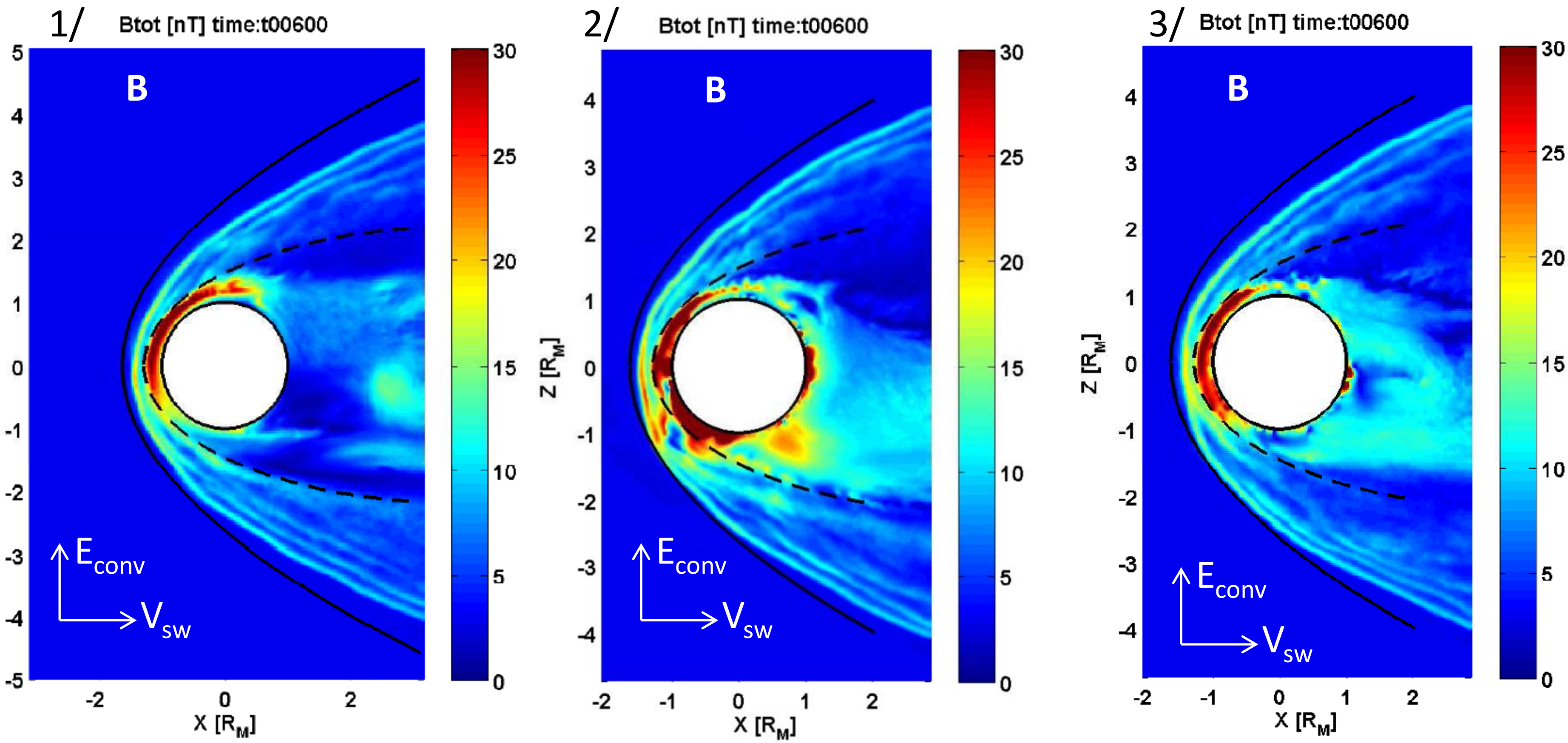
Sun direct. ⊙

2/

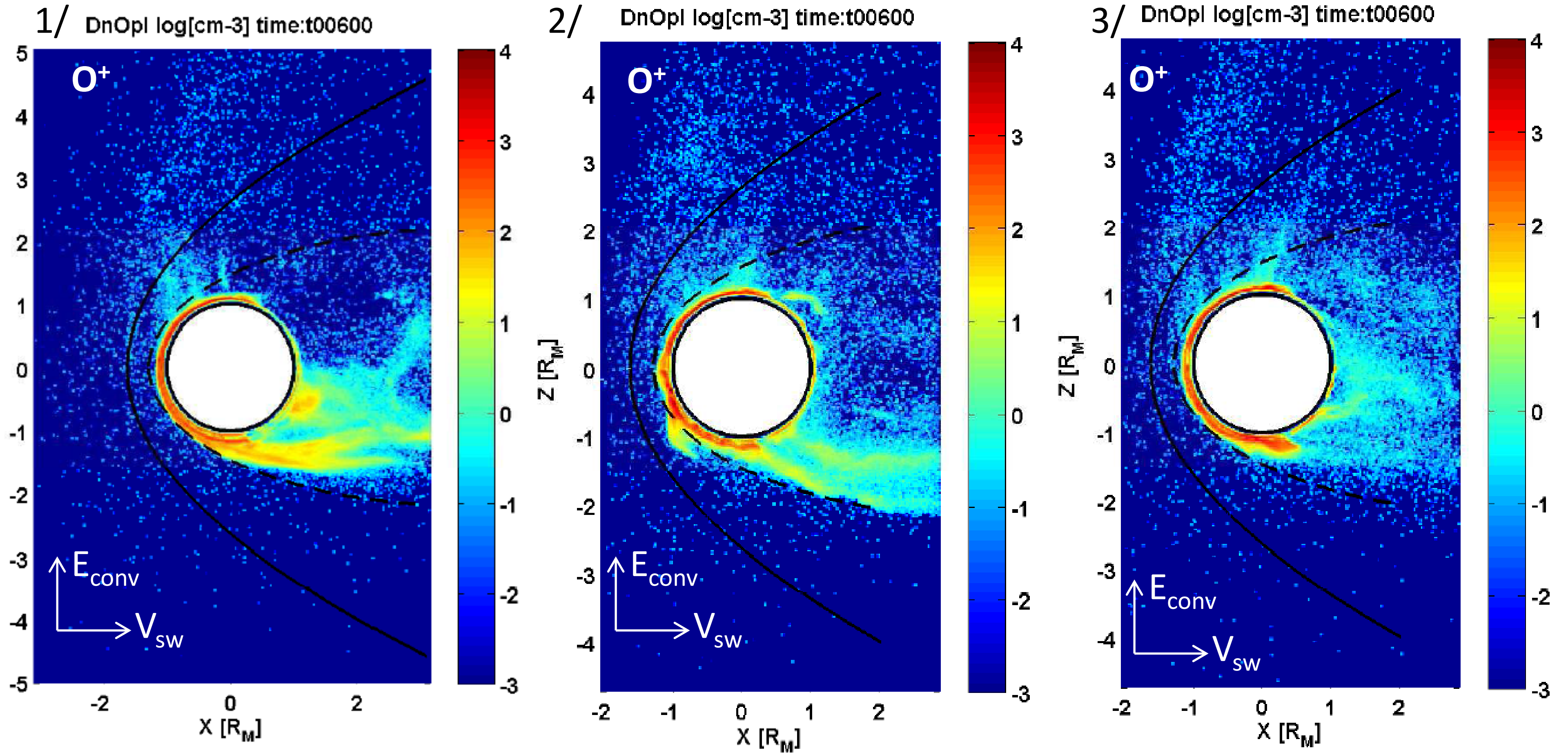


3/





- BS position seems not affected by crustal fields presence and orientation
- MPB is locally affected
- Crustal fields change the magnetic topology of the induced magnetosphere



- Planetary plasma dynamic sensitive to the presence of curstal fields and their locations
- plasma sheet density and structure modified by CF.
- « ionopause » higher in dayside close field lines region

Escape rates

- Ma et al (2007) results

Table 1. Input Parameters Used for the Different Calculations

	Solar Wind Density, cm^{-3}	Solar Wind Velocity, km/sec	Solar Condition	"Position" of Crustal Field
Case 1	2	300	solar minimum	0°
Case 2	2	300	solar minimum	90°
Case 3	2	300	solar minimum	180°
Case 4	4	400	solar minimum	0°
Case 5[a]	2	300	solar minimum	0°
Case 6	4	400	solar maximum	0°
Case 7[b]	20	1000	solar maximum	0°

[a]Case 5 is the same as case 1 except that charge exchange and impact ionization of the corona were not included.
[b]The magnetic field was set to $B_y = 20$ nT for case 7.

Table 2. Calculated Escape Rate[a]

	O^+	O_2^+	CO_2^+	Total
Case 1	3.3×10^{23}	1.00×10^{23}	5.7×10^{22}	4.9×10^{23}
Case 2	4.7×10^{23}	2.8×10^{23}	1.1×10^{23}	8.6×10^{23}
Case 3	4.4×10^{23}	2.5×10^{23}	1.2×10^{23}	8.1×10^{23}
Case 4	7.2×10^{23}	1.9×10^{23}	1.3×10^{23}	1.0×10^{24}
Case 5	1.3×10^{23}	9.3×10^{22}	4.9×10^{22}	2.7×10^{23}
Case 6	1.8×10^{24}	4.1×10^{23}	1.8×10^{23}	2.4×10^{24}
Case 7	2.3×10^{25}	3.3×10^{24}	4.1×10^{24}	3.0×10^{25}

[a]Escape rates in sec^{-1}.

- Estimate for this study (escape rate in s-1)

CF location	O+	O2+	CO2+	Total
N/A	1.0×10^{25}	6.4×10^{23}	1.8×10^{23}	1.0×10^{25}
0° Lon	7.2×10^{24}	1.9×10^{24}	3.8×10^{23}	9.4×10^{24}
90° Lon	6.9×10^{24}	1.2×10^{24}	1.0×10^{23}	8.1×10^{24}

- Up to 30% decrease in escape rates due to CF presence
- Globally in agreement with Ma et al (2007), disagreement with Brecht and Ledvina (2012)

Summary

- **3D parallel multi-species hybrid model developped for planetary environments :**

  -Mars -Ganymede

  -Mercury -Titan

- **Best spatial resolution achieved for kinetic models (Mars : 50-60 km uniform grid)**
- **Coupling with GCM (LMD GCM or MTGCM, Bougher's model) and exospheric models** => consistent and realistic description of neutral coronae
- 'Full' **coupling thermosphere-exosphere-ionosphere-magnetosphere** in progress
- Presence of **crustal fields** :

  - CF **did not cause major distorsion on the BS**.

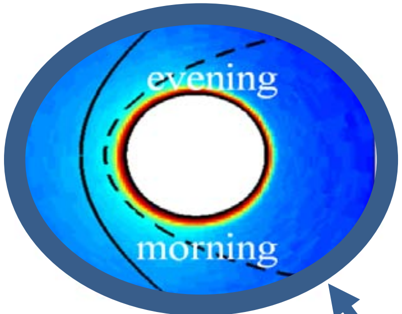
  - affect locally the altitude of the ionopause and magnetosheath

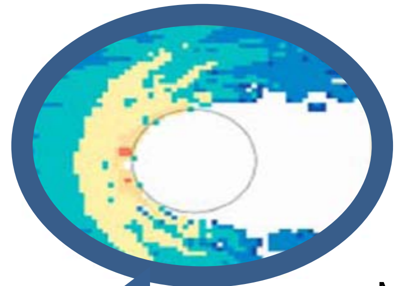
  - **presence of CF slightly affect escape rates**

  - in agreement with Ma et al (2007) MHD model and Nadjib et al (2011) multi-fluid MHD

Many applications

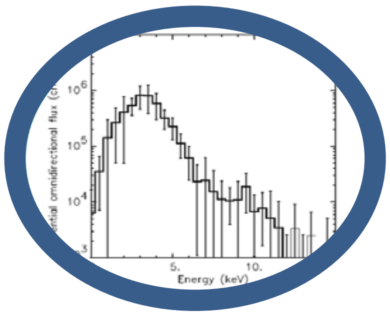
3D exosphere / magnetosphere coupling
Chaufray et al, 2007

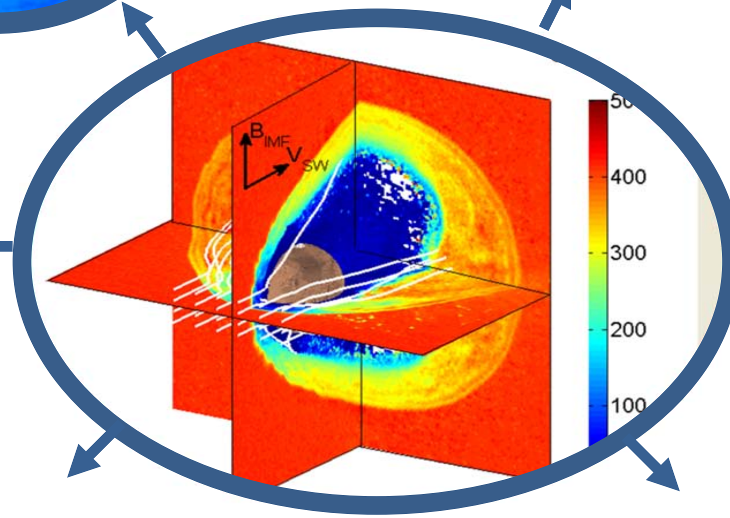


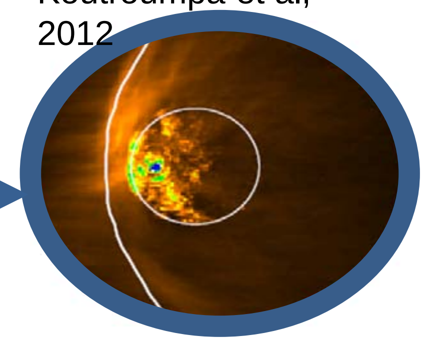


He++ atmospheric capture
Chanteur et al, 2009

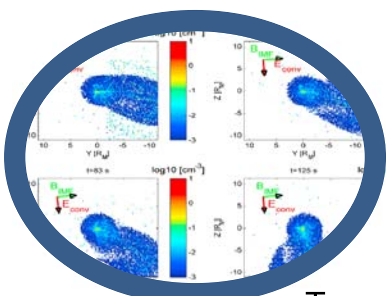
Martian X-ray
Koutroumpa et al, 2012



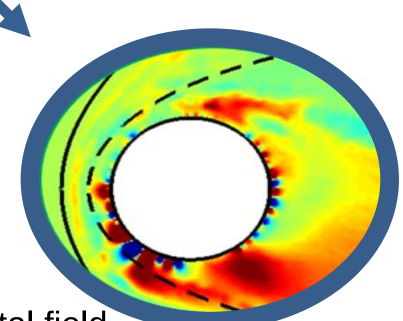




Ion foreshock
Richer et al, 2012



Global description
Modolo et al, 2005; 2006; 2013



Transient phenomena
Modolo et al, 2012

Crustal field influence
Hess et al, 2013

LATMOS
UNIVERSITÉ DE VERSAILLES SAINT-QUENTIN-EN-YVELINES