Hybrid plasma modelling of the planetary ionospheres and atmospheres

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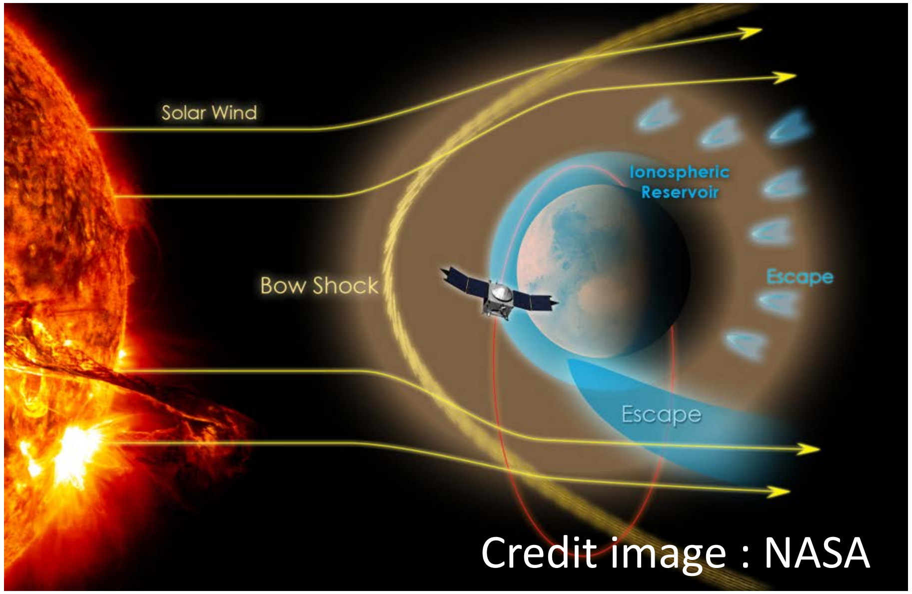
Introduction



It plays **a key role on volatile escape processes** and climate evolution

Closely couple to atmosphere of the planet

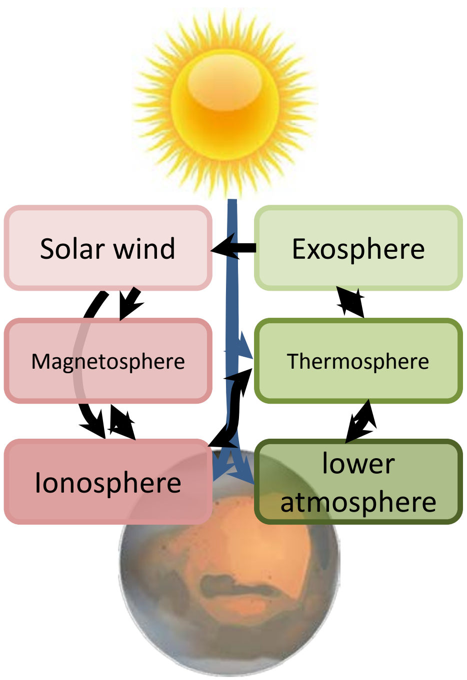
Convergence site of interaction mechanisms between the Sun and the planetary environment

- ✓ **Closure of currents**
- ✓ **Energy dissipation** (heating, precipitation)
- ✓ Large spatial and temporal variability

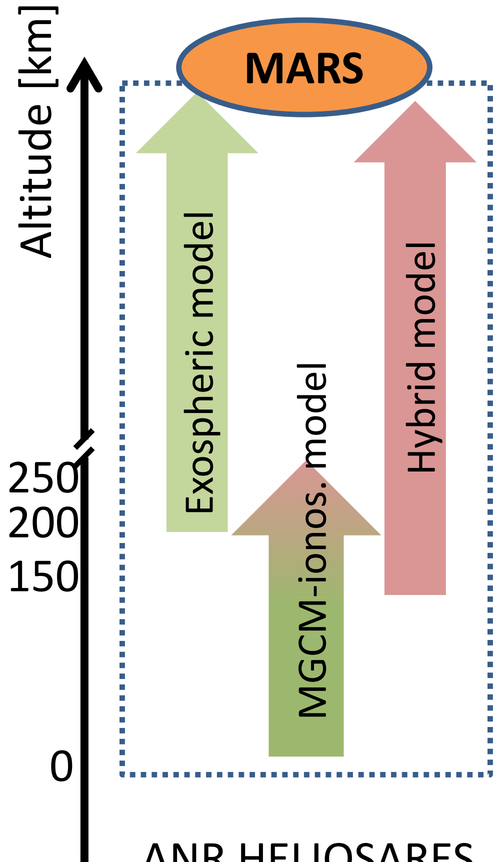
A careful modelling description is therefore required

Plasma – neutral coupling in planetary environments

- Towards a realistic modelling description to characterize energy and momentum exchange : solar wind/magnetosphere/exosphere/atmosphere/ionosphere



Adapted from Bougher et al



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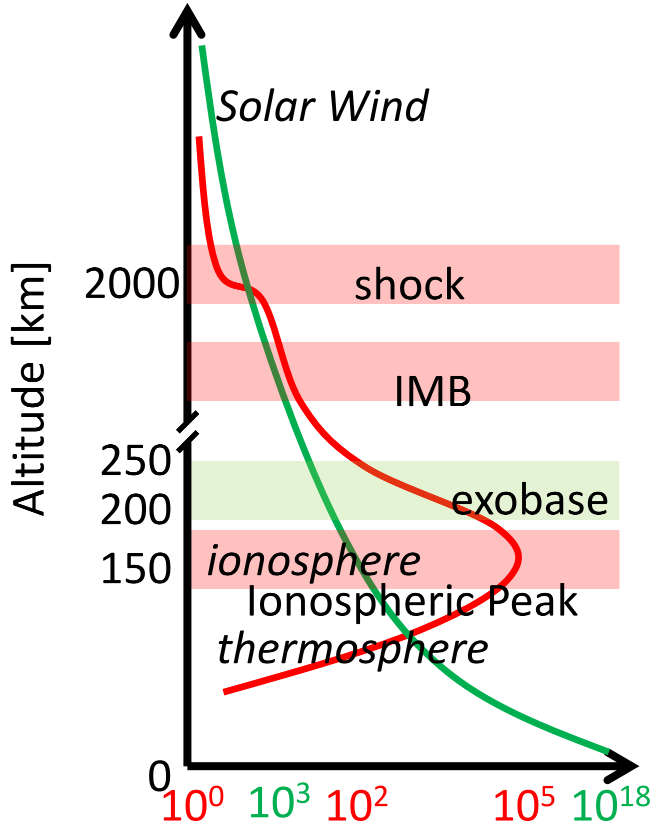


Density [cm-3]

Neutrals, ions-electrons

Lillis et al, SSR, 2015

Hybrid models

■ Larmor radii of planetary ions ≥ radius of the obstacle

⇒ Kinetic description of ions is more appropriate at higher altitude

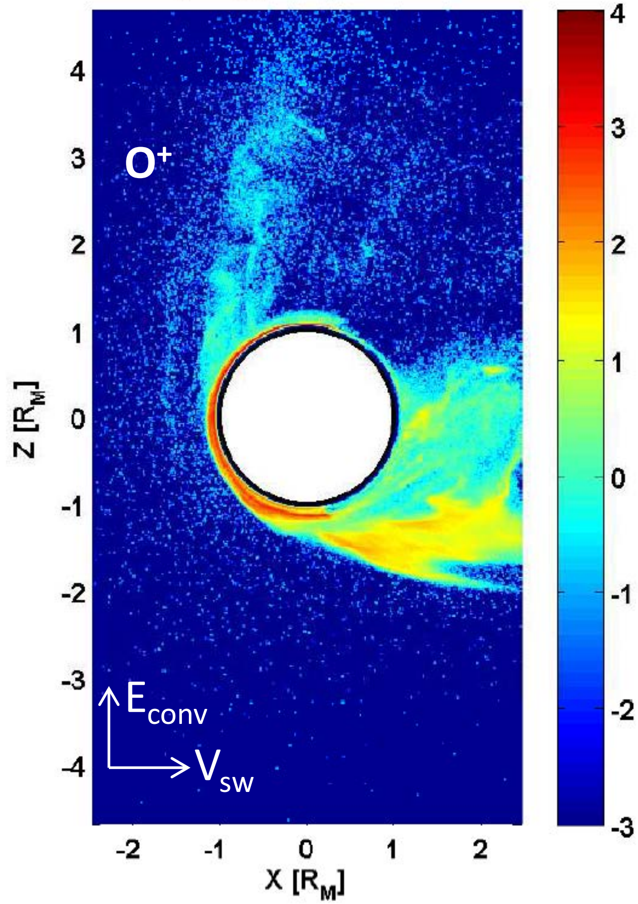
■ Hybrid formalism :

- 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

■ Ionospheric region is more fluid-like

⇒ **Main challenges** for hybrid modelling :

- **Optimization** of number of **macro-particles**
- **Grid resolution approaching neutral scale height** to have an accurate production rate and current system description



Modolo et al, JGR, 2016

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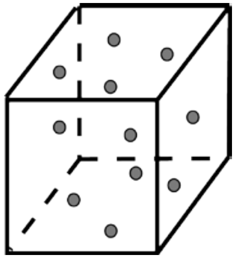
Kinetic approach

- **Consists of computing the motion of a collection of charged particles**
- Introduction of concept of **numerical particles** (cloud of real charged particles)
- In the mathematical formulation of particle's approach we assume that the plasma distribution function is given by a superposition of several « elements » (num. particles)

$$f_s(\vec{x},\vec{v},t) = \sum_p f_p(\vec{x},\vec{v},t)$$

Each elements represent physical particles relatively close to each other in phase space

Common to describe the particles with 2 degrees of freedom



$$f_p(\vec{x},\vec{v},t) = N_p S_x(\vec{x}-\vec{x}_p(t)) S_v(\vec{v}-\vec{v}_p(t))$$

With Np : number of physical particle represented

xp,vp : position and velocity of the num. particle

x,v : position and velocity of physical particle inside the numerical particle

Sx,Sv : space and velocity shape factor for the num. particle

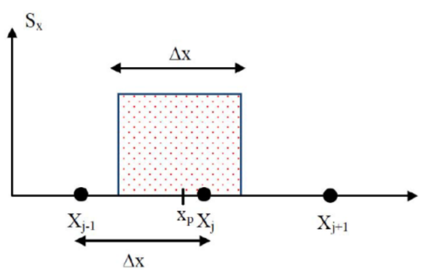
(Sx indicate the geometry of the particle, ex : if $S_x(\vec{x}-\vec{x}_p) = \delta(\vec{x}-\vec{x}_p)$ position of all physcial particles are identical to num. particle)

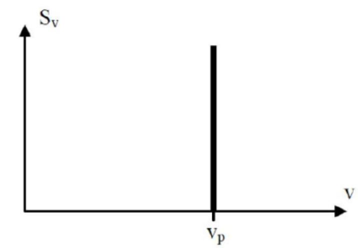
Kinetic approach

For simplification in 1D :

$$S_x(\vec{x}-\vec{x}_p(t)) = \begin{cases} 1/\Delta x & if\ \ x_p-\Delta x/2 \le x \le x_p+\Delta x/2 \\ 0 & elsewhere \end{cases}$$

$$S_v(\vec{v}-\vec{v}_p(t)) = \delta(\vec{v}-\vec{v}_p(t))$$





We can use more complicated shape factor but it should verify

$$\int_{-\infty}^{+\infty} S_x(\vec{x}-\vec{x}_p(t)) = 1$$

(same for Sv)

Equations governing the motion of the numerical particles are determined from the moments of Vlasov equation.

Since the plasma distribution function is a sum of several elements, the Vlasov equation can be solved for each element.

Obtaining the equations of motion

- Solving the Vlasov-Boltzmann set of equation for a collision free plasma

$$\frac{\partial f_p}{\partial t} + \vec{v} \cdot \frac{\partial f_p}{\partial \vec{x}} + \frac{q}{m}\left(\vec{E} + \vec{v} \times \vec{B}\right) \cdot \frac{\partial f_p}{\partial \vec{v}} = 0$$

- Moment calculation : averaging Vlasov equation over phase space

$$< \ldots > = \int\int \ldots \; dx^3 dv^3$$

- 0th order moment : $\Rightarrow \frac{dN_p}{dt} = 0$

Number of physical particles representing by one numerical particle does not evolve in time

- 1st order moment (in x) : $\Rightarrow \frac{d\vec{x}}{dt} = \vec{v}$
- 1st order moment (in v): $\Rightarrow \frac{d\vec{v}}{dt} = \frac{q\left(\vec{E} + \vec{v} \times \vec{B}\right)}{m}$

- Global models $\Rightarrow$ simulate different regions

  - large range of « physical » densities from 10^{-3} to 10^{5} cm^{-3} $\Rightarrow$ macro-particles are weighted $\Rightarrow$ good statistical representation of <u>minor and major species</u>

Electric field and electron temperature

- For massless electrons the momentum equation of the electron fluid takes the form of **a generalized Ohm's law** (*e.g. Braginskii, 1965*)

$$\vec{E} = -\frac{\overrightarrow{J_e} \times \vec{B}}{\rho} - \frac{\vec{\nabla} P_e}{\rho} - \frac{m_e}{e} \sum_s \nu_{e,s} \left(\left(\overrightarrow{U_i} - \overrightarrow{U_s} \right) - \frac{\vec{J}}{\rho} \right) - \frac{m_e \nu_{a,e0} \overrightarrow{U_e}}{e}$$

The **effective conductivity** which appears indirectly is

$\sigma_0 = \frac{n_e e^2}{m_e \nu_{e,s}}$ with $\nu_{e,s} = 5.4 \times 10^{-10} n_s \sqrt{T_e}$ the electron-neutral collision frequency (Kelley, 1985)

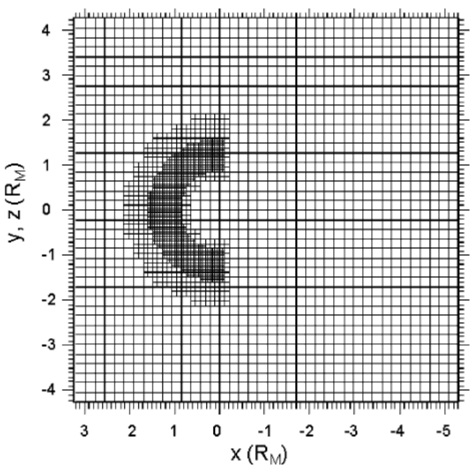
- **Electron temperature** in the ionospheric region is a key parameter

Some models solve an electron temperature equations (*eg Brecht et al, 2016; 2017*)

Other models **have two electron populations with different temperatures** (*eg Bosswetter et al, 2006; 2010; Modolo et al, 2008*)

Different techniques to model the ionospheric region

- Hierarchical grid with lower boundary conditions



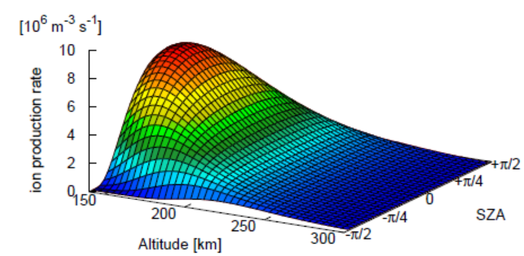
Ionospheric ions are produced by two sources : i- above the ionospheric peak the **production rate depends on neutral atmosphere and ionization frequencies** (q_{corona})

ii- **ionospheric ions are emitted from a spherical shell** (q_{iono})

Such approach has been used to model, for instance, Mars (*eg Kallio et al, 2006; 2010; Modolo et al, 2005*), Venus (*eg Jarvinen et al, 2008; 2013*)

- Photoproduction rates (including photoabsorption) or fixing iono profile

- **Computation of photoproduction rates** for the main ionospheric ions (approach used by eg *Bosswetter et al, 2010* – Mars; *Simon et al, 2010* – Titan)



- **Fixing ionospheric profile**s with immobile ions **+ ionospheric ion flux** of mobile ions (eg *Lipatov et al, 2011* – Io *; 2012* – Titan)

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Different techniques to model the ionospheric region (2)

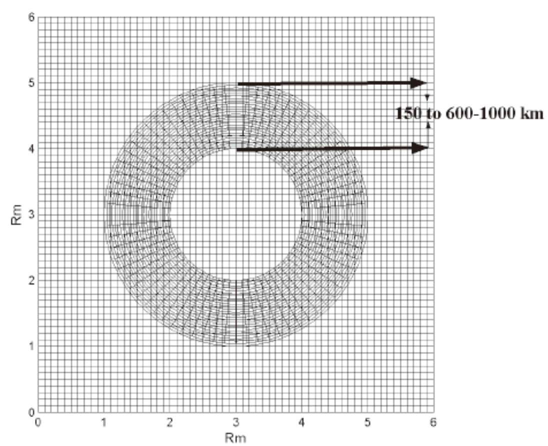
- ❑ Several global models are now incoroprating a ionospheric chemistry package
- ✓ Approach 1 :

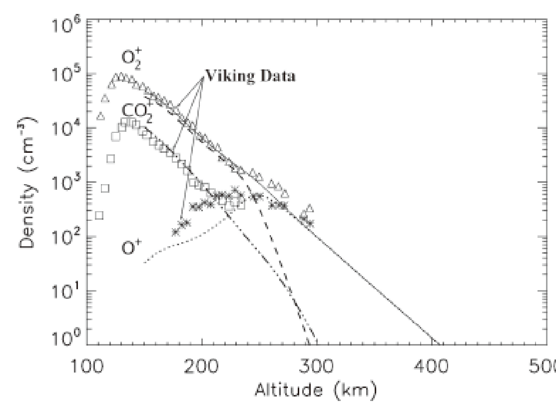
- introduction of a spherical grid where chemistry model is run until it achieves photochemical equilibrium

- Advection and electromagnetic field evolution is switch on + loading of new ionospheric particles if production is larger than loss

Approach used on Mars (*eg Brecht et al, 2010; 2011*) and Titan (*eg Ledvina et al, 2012*)

Reaction number	Reaction equation	Coefficient rates	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	$O_2^+ + e \longrightarrow O + O$	$1.95e^{-7}(300/T_e)^{0.7}$	$1.36e^{+10}$
9	$CO_2^+ + e \longrightarrow CO + O$	$3.5e^{-7}(300/T_e)^{0.5}$	$7.52e^{+9}$

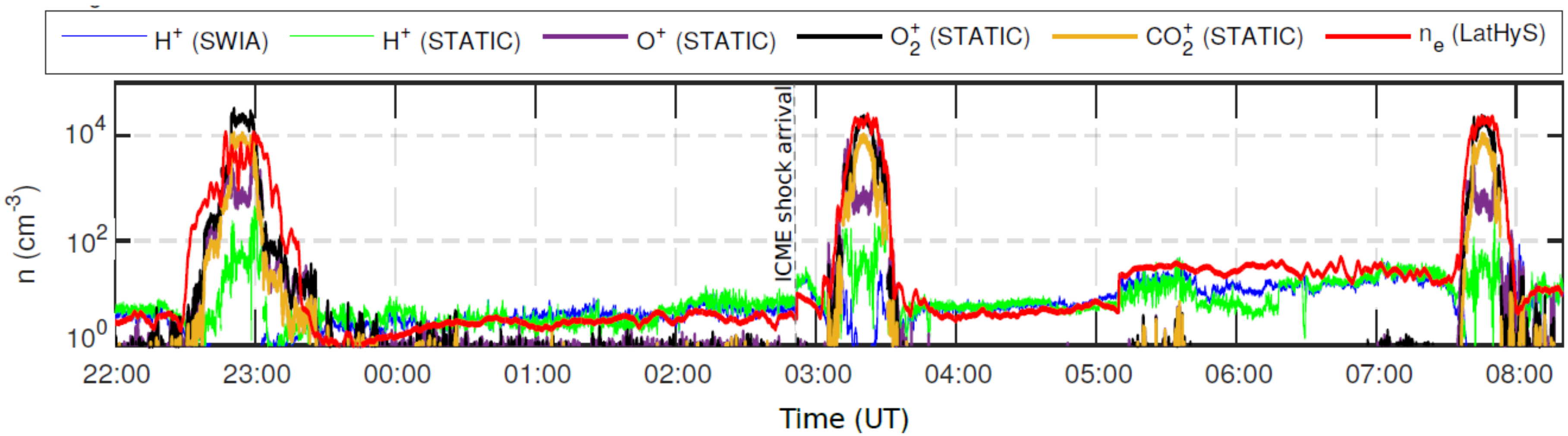




Different techniques to model the ionospheric region (3)

✓ Approach 2 :

- Assuming a photochemical equilibrium and computation of ionospheric density profiles. Loading ionospheric particle at initialisation
- Advection and electromagnetic field evolution is switch on + loading of new ionospheric particles if production is larger than loss (*Modolo et al, 2016; 2018*)

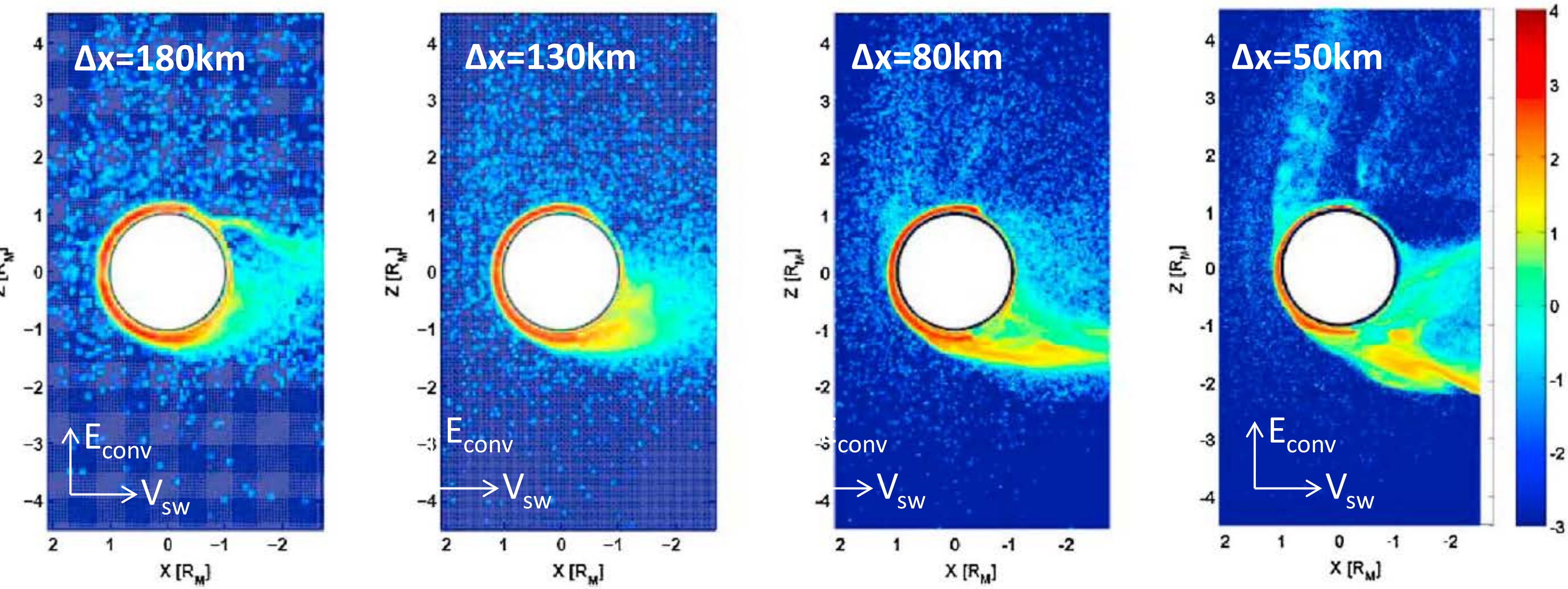


Sept 12, 2017

Romanelli et al, GRL, 2018

Spatial resolution influence on ionosphere and outflow

4 identical simulations performed at different spatial resolution



Modolo et al, JGR, 2016

Better representation of the plume dynamics and small scale structure of ion outflow for lower grid resolution

Ionosphere is more ‘extended’ for coarse grid => larger effective obstacle

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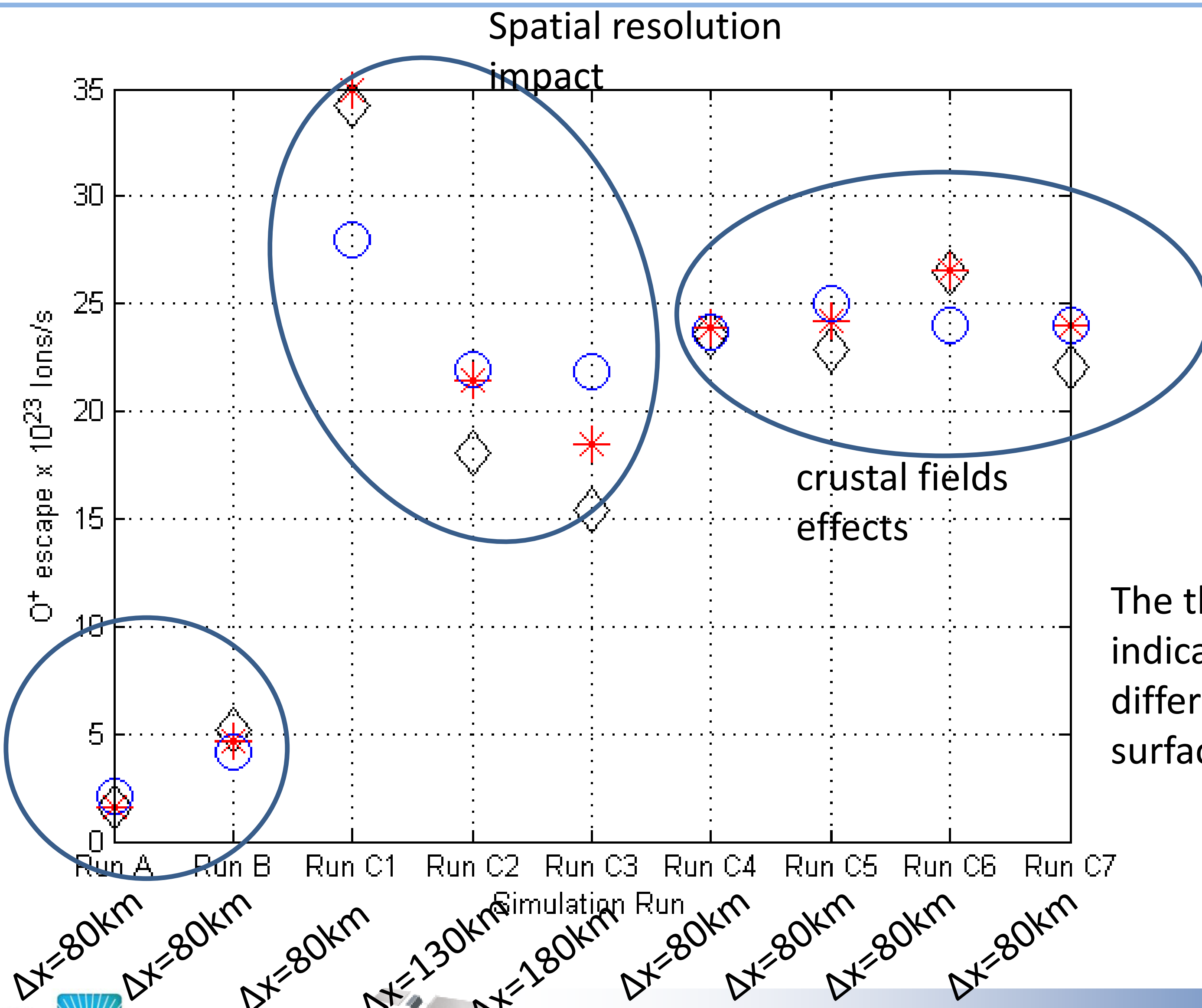
Influence of grid resolution on total O+ escape



Solar min
No vs hot
corona

The three symbols indicate the different collecting surface

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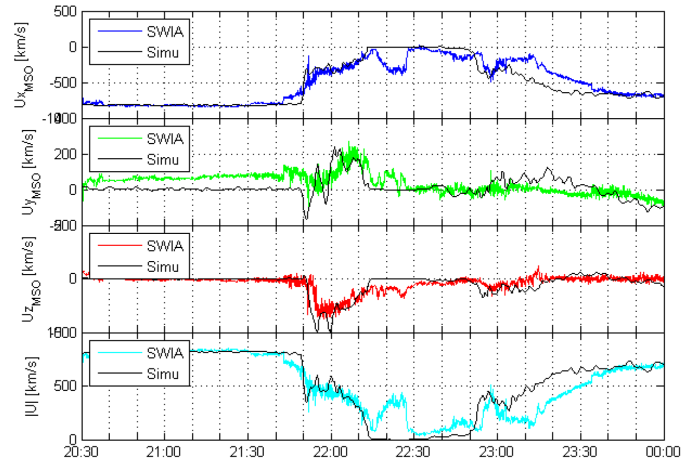
From the ionosphere to the solar wind

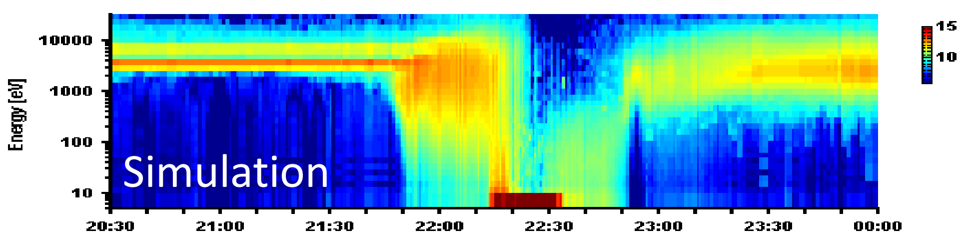
Modeling the ICME **shock phase** [Curry et al, 2015; Jakosky et al, 2015, Ma et al, 2016]

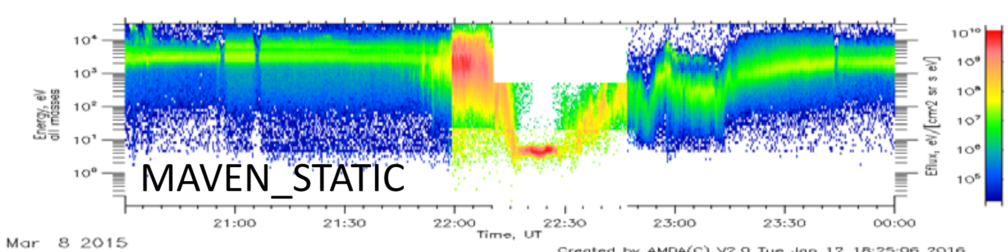
Thermosphere LMD-MGCM model @LS 300

Exosphere : EGM

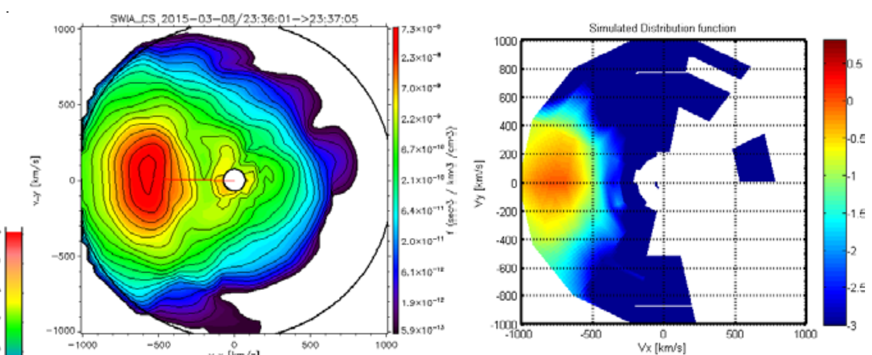
Hybrid Model
(+input SW parameters)







F(vx,vy) observed and simulated at 23:37



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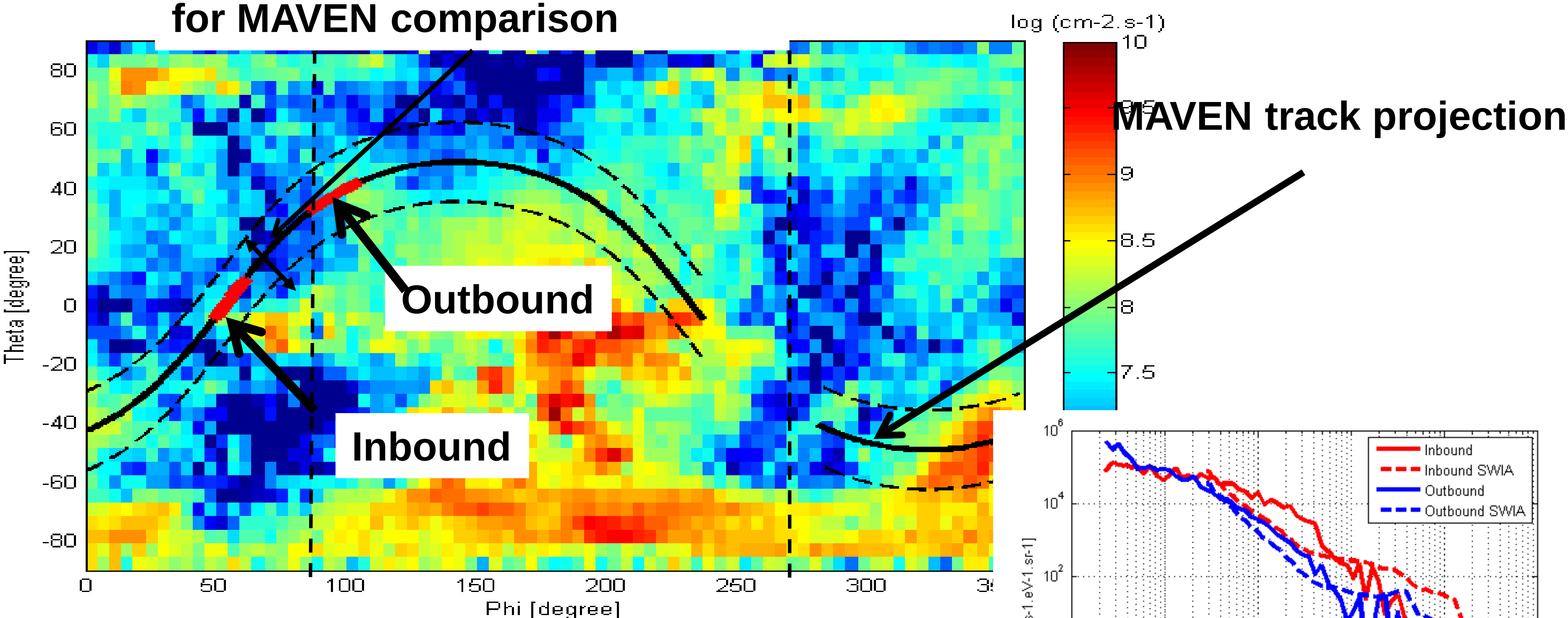
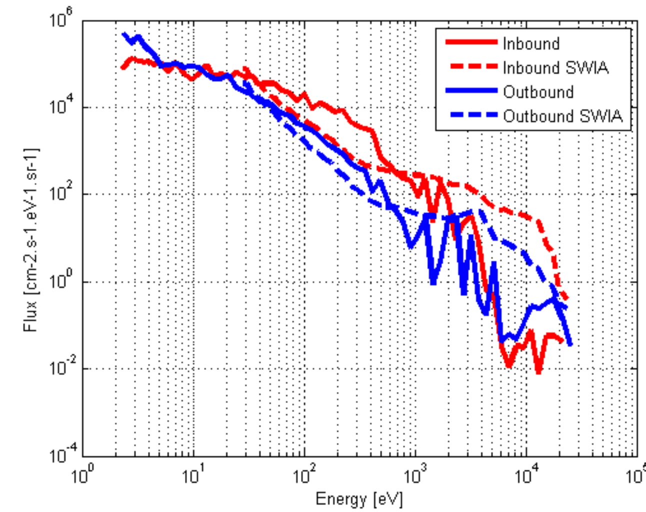
Precipitation of O^+ ions in Mars' atmosphere

Lat-lon averaging simu spectra for MAVEN comparison





Computation of precipitation fluxes during ICME event (ex : March 8th, 2015 20:30-00:00)

$\Rightarrow$ Precipitation information are used to determine the sputtering contribution of the O corona (cf *Leblanc et al, 2017*)

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Summary

- Describing the ionosphere in global kinetic models is a challenging task
- Several efforts have been carried out to properly describe the ionospheric region with hybrid models
- **Best spatial resolution** achieved with the LatHyS code (uniform cartesian grid)

- Mars : 50 km (0.4 c/wpi) - Ganymede: 110 km (0.25 c/wpi)
- Mercury: 40 km (1 c/wpi)

- **Hierarchical grid** is one way to both approach the production scale height and describe accurately the current system, however it requires splitting and merging of numerical particles
  – Adaptation of the multi-grid hybrid model (Ganymede, Leclercq et al, JCP, 2016) to other planetary objects in progress