Magnetospheric modelling

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HELIOSARES meeting

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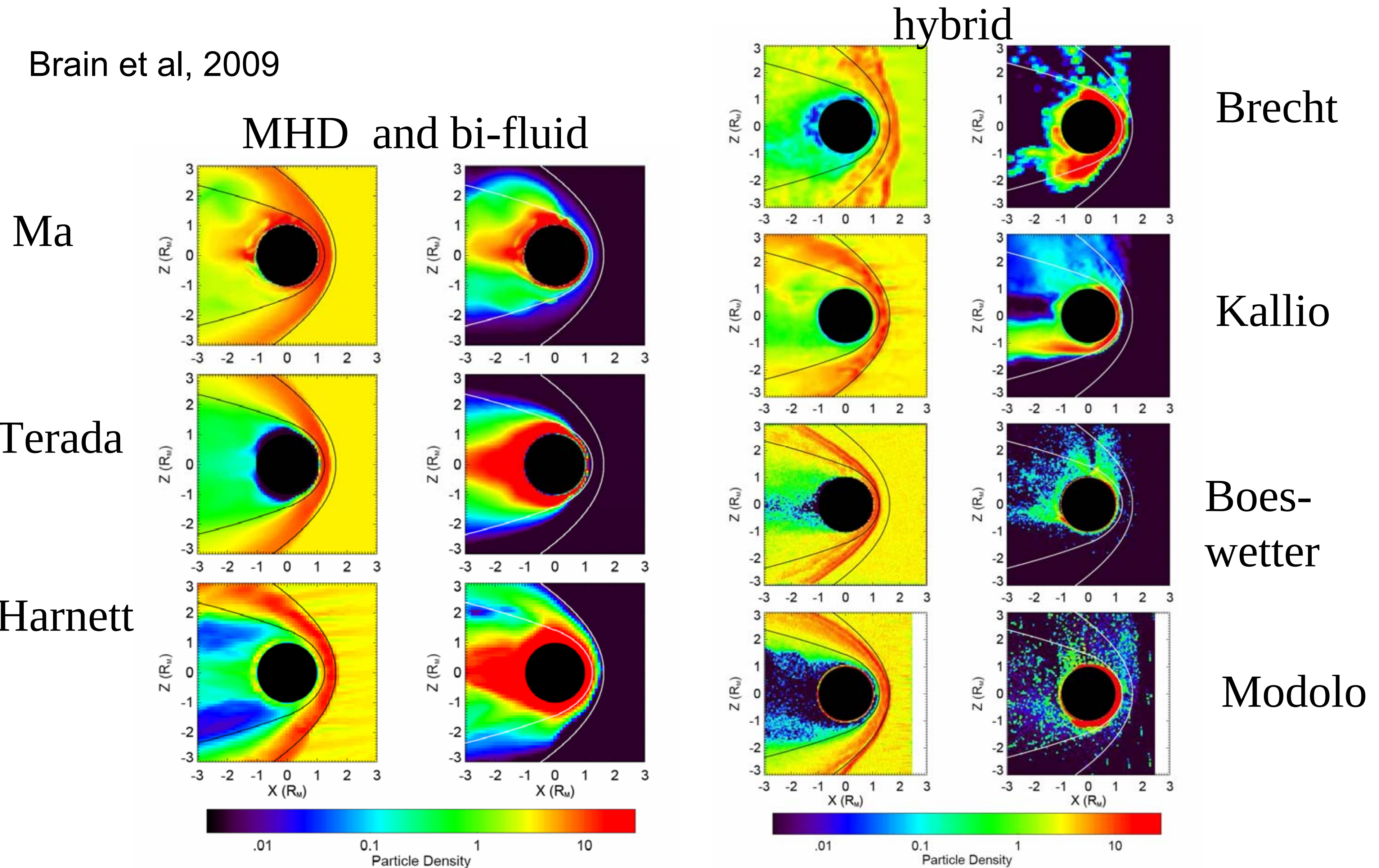
Global Models for the Solar Wind Interaction with Mars – ISSI group

Brain et al, 2009

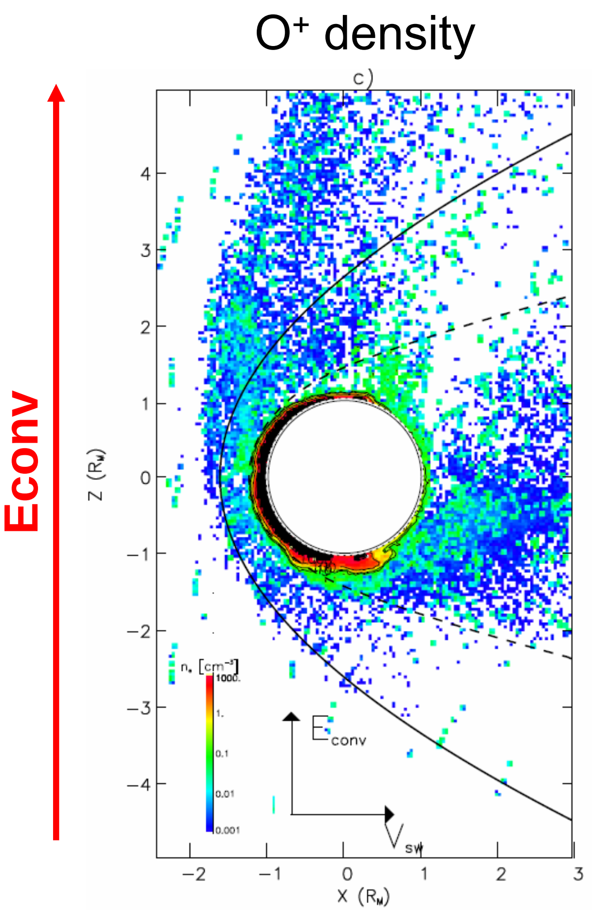


Description of the model

- 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



Description of the model (2)

■ Specific features for planetary environments

➢ Weigthed macro-particles ⇨ description of a large range of density ($10^{-3} \rightarrow 10^{4}$ cm^{-3})

➢ Many ionic species are represented :

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

➢ Plasma/neutral coupling taken into account self-consistently, distinction between the ionisation processes

- *Photoionisation* ⇒ $h\nu + X \rightarrow X^+ + e^-$
- *Electronic impacts* ⇒ $X + e^- \rightarrow X^+ + 2e^-$
- *Charge exchange reactions* ⇒ $M^+ + X \rightarrow M + X^+$

Ionisation rates are not imposed but are computed locally from neutral densities and ionisation frequencies or cross sections

Mars / Solar Wind Interaction - Ingredients

- ☐ Solar Wind: H^+ et He^{++} (5%), $n_{sw} \approx 1\text{-}3\ cm^{-3}$, $V_{sw} \approx 350\text{-}500$ km/s
- ☐ Exosphere / atmosphere : O, H et CO_2
- ☐ Charged / neutral species coupling
  - photoionisation et electronic impact ionisation
  - charge exchanges
  - no dissociation, only simple ionisation
- ☐ Ionospheric chemistry

	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	$CO_2^+ + e \longrightarrow CO + O$	$3.88e^{-7}(300/T_e)^{0.5}$	$7.52e^{+9}$

Coupling between neutral and charged species

□ Neutral environment

- We fix the neutral density of the specie « X » in function of *r*

  $n_X \equiv n_X(\mathbf{r})$

□ Photoionisation

- Production rate : $q_X^{photo}(\mathbf{r}) = n_X.\nu_X^{photo}$

With

$$\nu_X = \int_\lambda \boldsymbol{I}_\infty(\lambda)\exp(-\tau(\mathbf{r},\chi,\lambda))\sigma_X(\lambda)\boldsymbol{d}\lambda$$

□ Electronic impact ionization

- Production rate : $q_X^{impact}(\mathbf{r}) = n_X.\nu_X^{impact}$

With

$$\nu_X^{impact} = \int_0^\infty \boldsymbol{v}\sigma(\boldsymbol{v})\boldsymbol{f}(\boldsymbol{v})4\pi\boldsymbol{v}^2\boldsymbol{dv}$$

□ Charge exchange reactions

- Production rate : $q_X^{CE}(\mathbf{r}) \propto n_X n_{SW}^e V_{SW} \sigma_{(X,M+)}$

Simulation characteristics

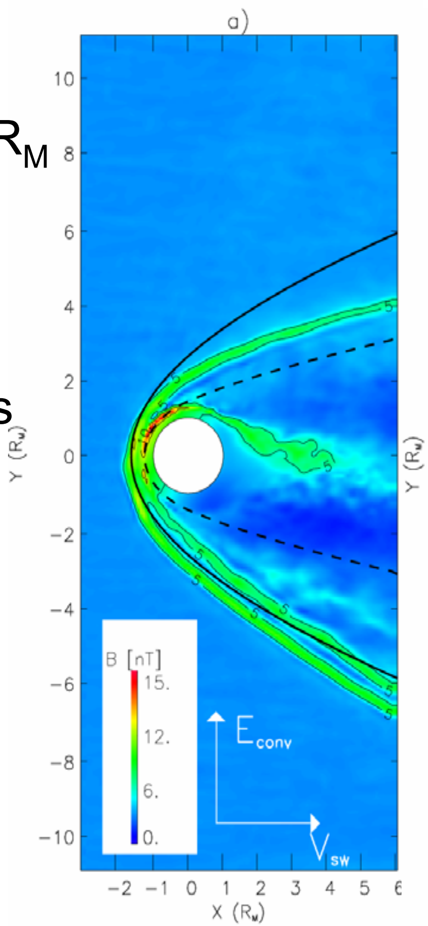
Algorithm : Matthews A.P., JCP, 1994
Programming language : Fortran 77/90 ~~Parallel~~ / sequential
Max memory used ~ 16 Go RAM $\Rightarrow$ 55×10^6 particles

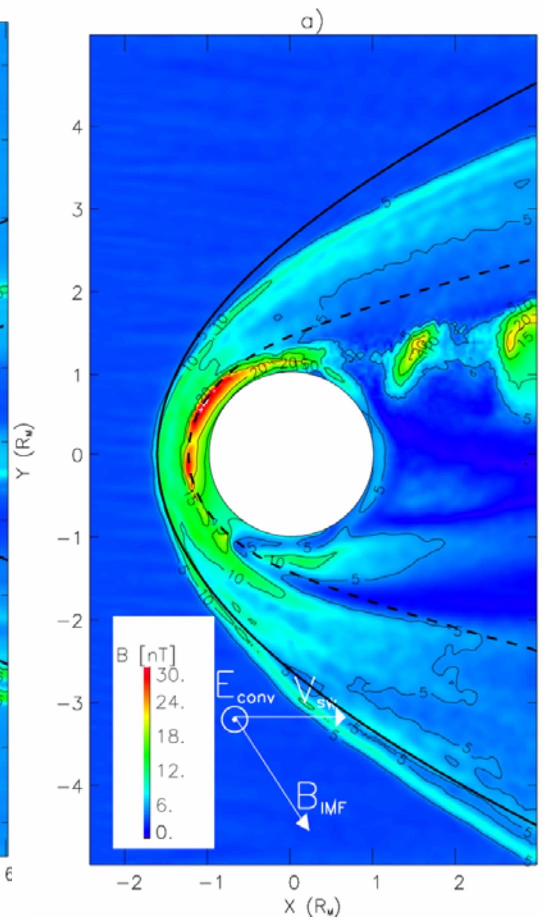
$-3\ R_M \leq X \leq 6\ R_M$
$-11\ R_M \leq Y,Z \leq 11\ R_M$

$\Delta x \approx 300$ km
$\Delta t = 0.3$ s

0 $\Rightarrow$ 1000 time steps
« stationnary sol. »
tested up to 3000 time steps

Restitution time :
~7 days





$-2.5\ R_M \leq X \leq 3\ R_M$
$-5.5\ R_M \leq Y,Z \leq 5.5\ R_M$

$\Delta x \approx 130$ km
$\Delta t = 0.15$ s

0 $\Rightarrow$ 2000 time steps
« stationnary sol. »

Restitution time :
~7-8 days

More « realistical » simulations

☐ Estimates the contribution of sputtering to the formation of the neutral corona and the oxygen escape

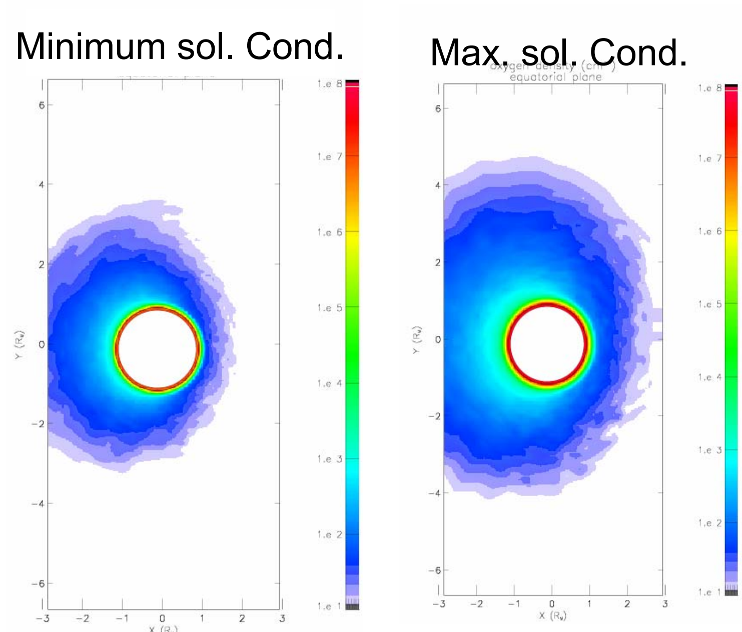
3D Monte-Carlo (1)
⇒Exospheric O corona
(Diss. Recomb. O_2^+)

3D hybrid
⇒Global descr. of
Planetary plasma env.

3D test-particle
⇒ Ion impacting fluxes

3D Monte-Carlo (2)
⇒ sputtering contribution

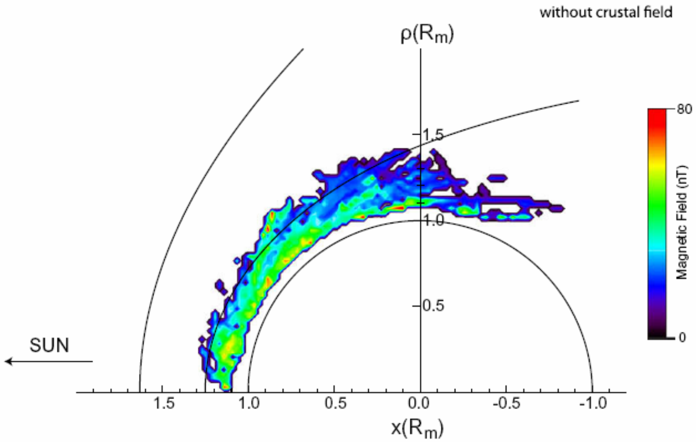
Chaufray et al, JGR, 2007



It underlined the difficulty of extrapolating the present measured loss rates to the past Mars' history without a better theroretical knowledge.

challenges

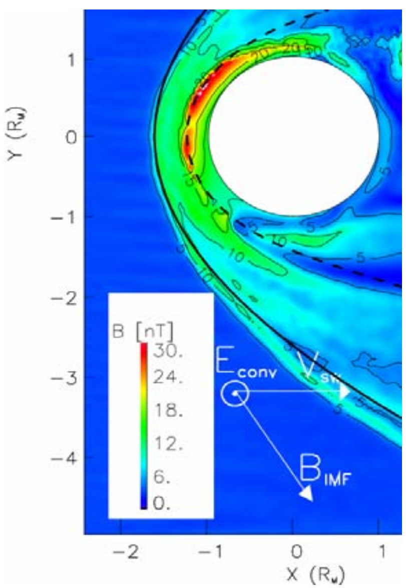
Akalin et al, Icarus, 2009

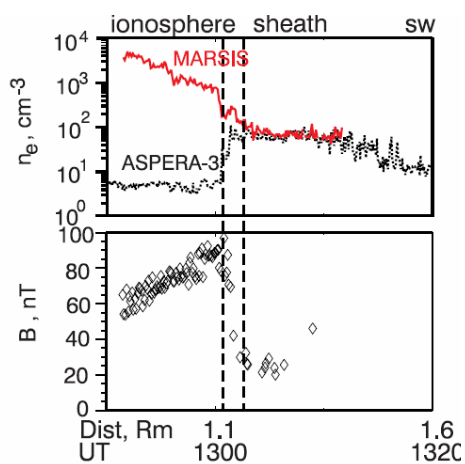


Formation of the MPB :

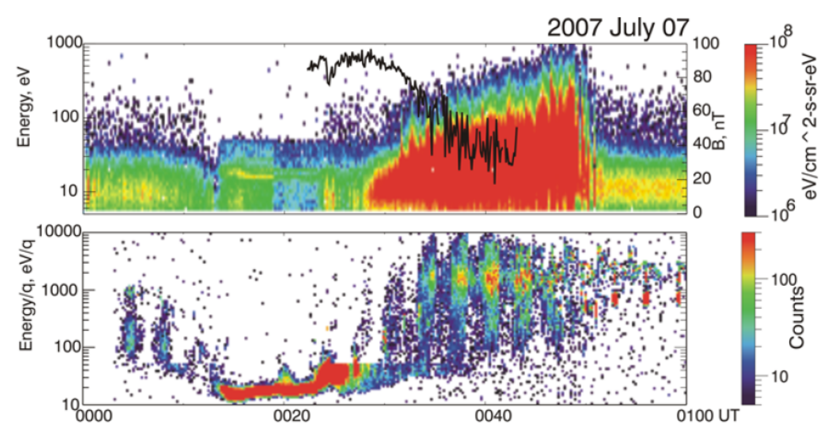
Max of magnetic field in MPR, without crustal field contribution :
-Observations (MGS, MeX/MARSIS) : 80-100 nT
-Simulations (hybrid) : 30-40 nT (max. □ when Δx □)

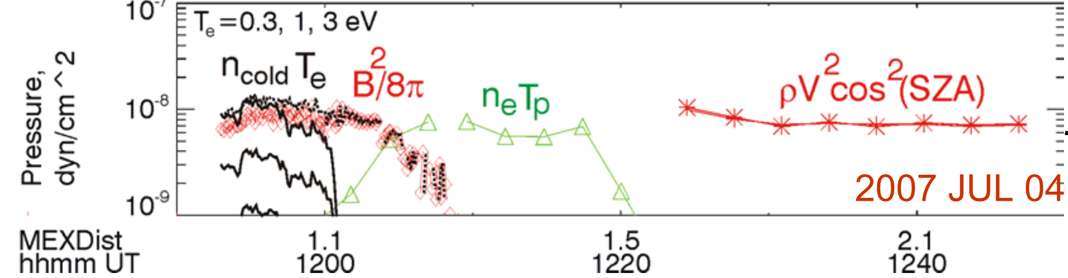
Other discrepancy : no gradual increase of B seen in the simulation



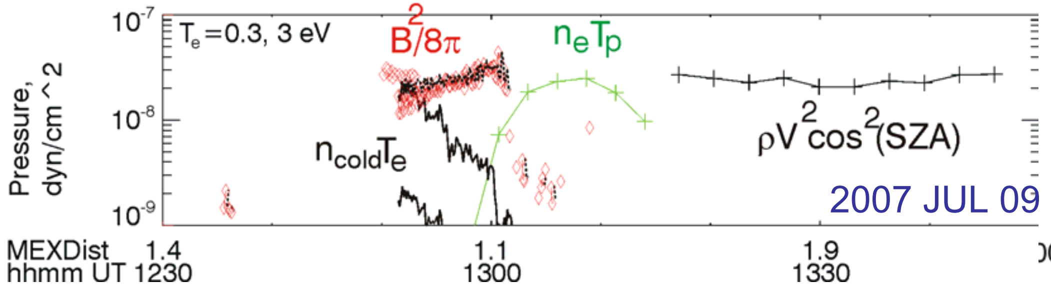


Dubinin et al, 2008a

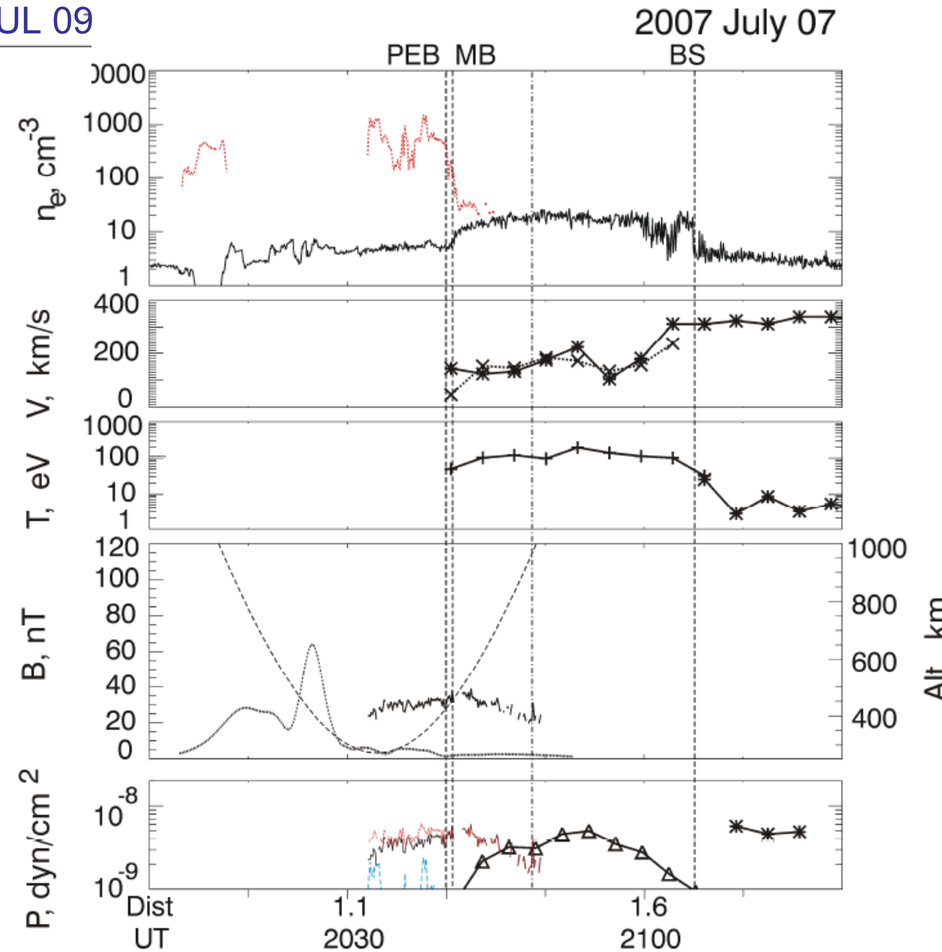




□Abrupt change at 'MPB' jump of B (>70nT), mixture of SW and planetary ions



□ Pressure balance observed across the different boundaries



□Smaller ram pressure

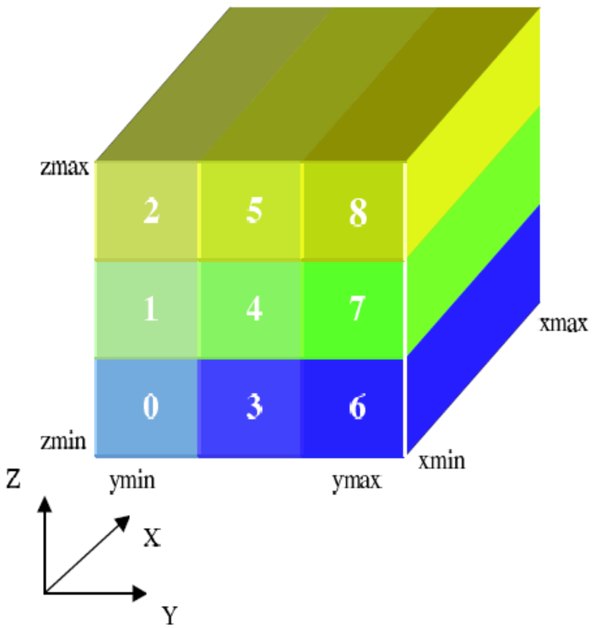
□Pile-up of the magnetic field weaker

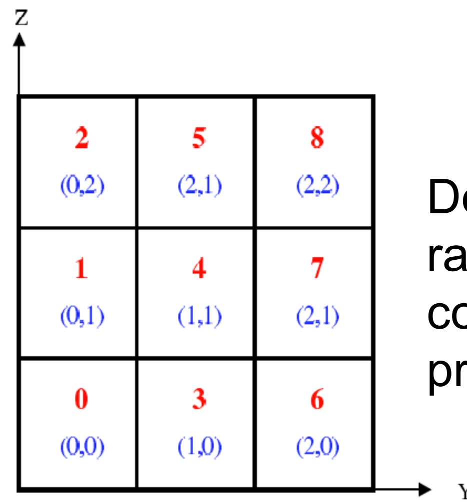
□Boundary of the dense and cold plasma is sharp and coincides with the boundary of SW stoppage

□Magnetic field does not change across the boundary

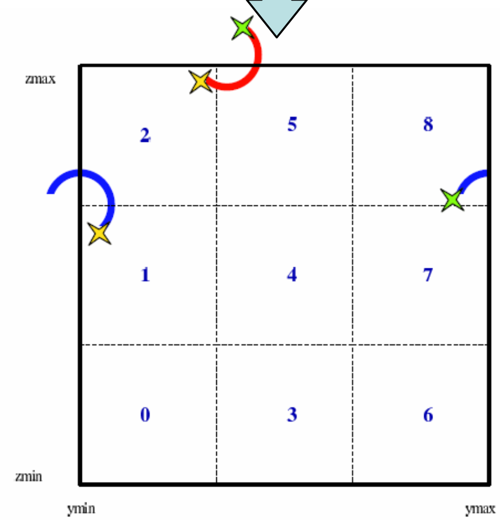
Dubinin et al, 2008b

Towards parallel computing





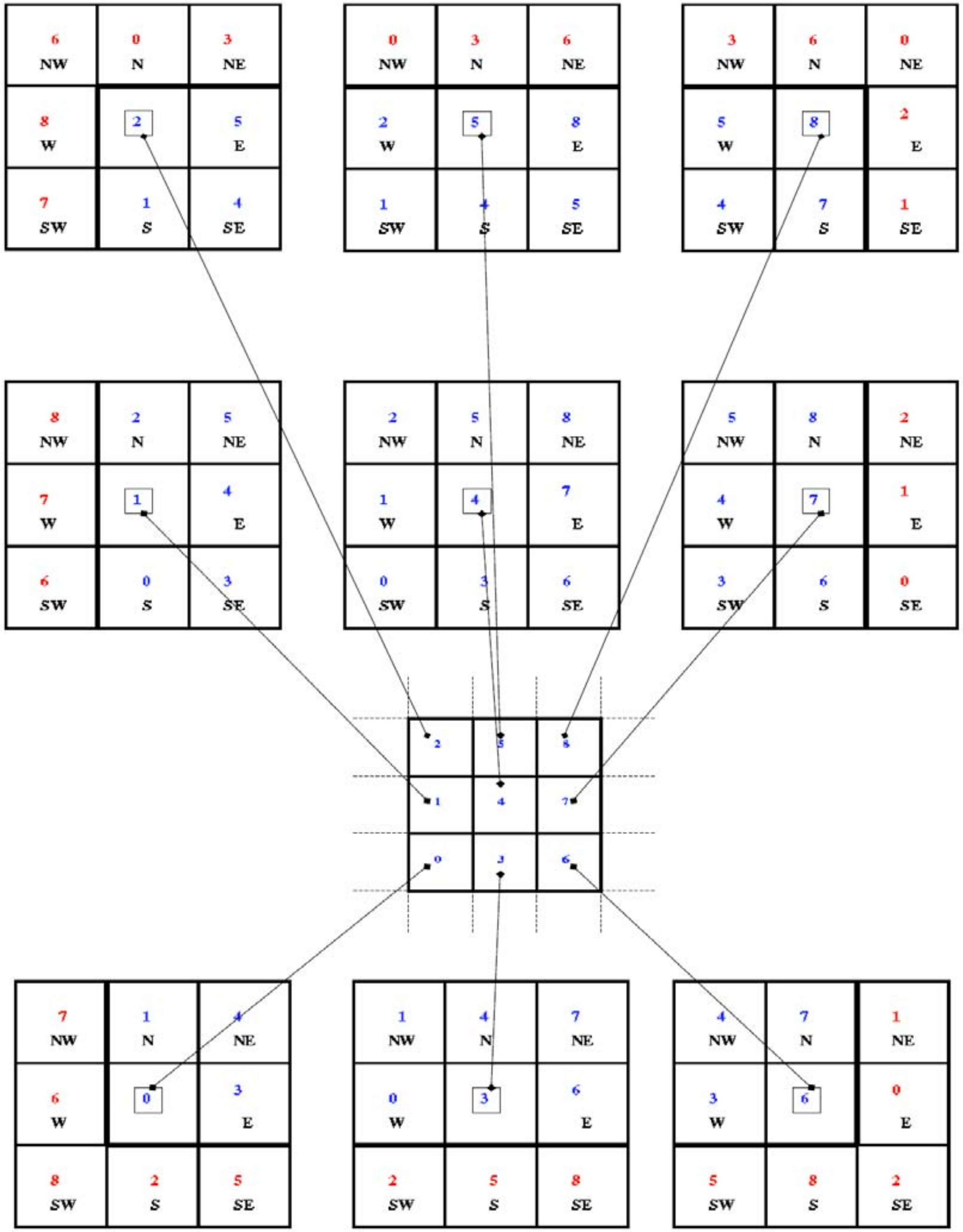
Definition of the rank and coordinates of the proccesses



Definition of boundary conditions
$\Rightarrow$
communicators

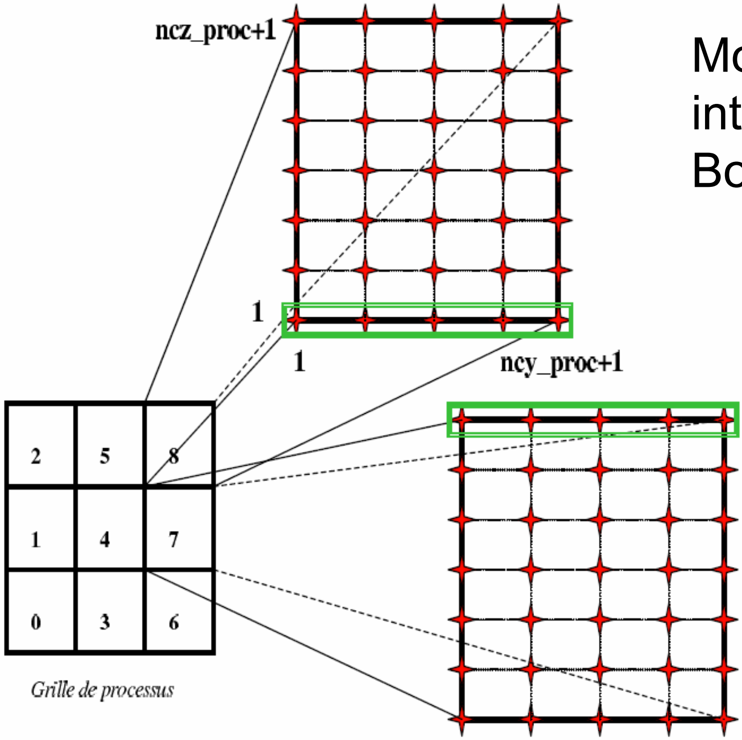
Grid topology
Division of the domain in sub-domains
1 sub-domain (mini-simulation) $\Rightarrow$ 1 process

1 processor administers 1 (or more) process(es)

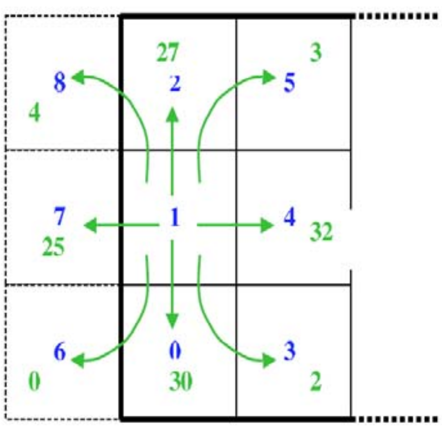


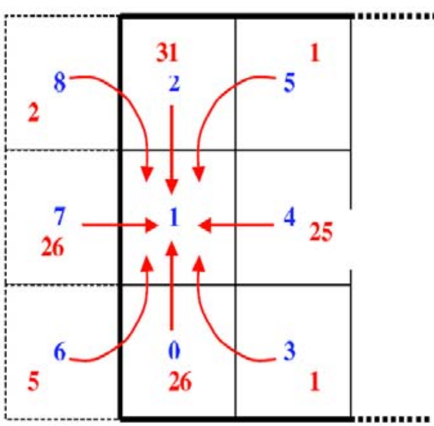
For each communicator :
Definition of neighborhood process

Communications involve particle, electromagnetic field and moment informations



Moment collection : contribution of particles at the interface of 2 processes
Boundary conditions.



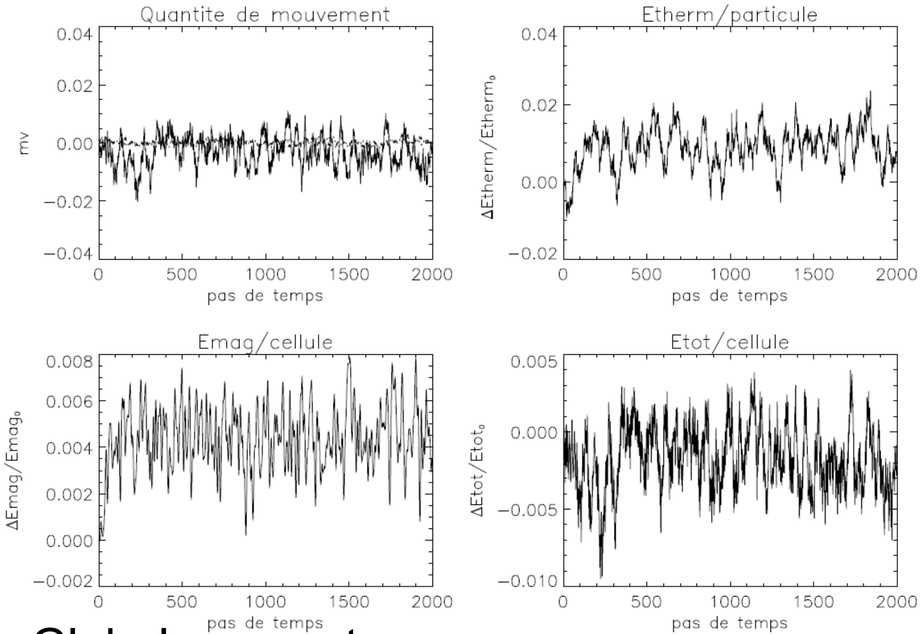


Particle administration

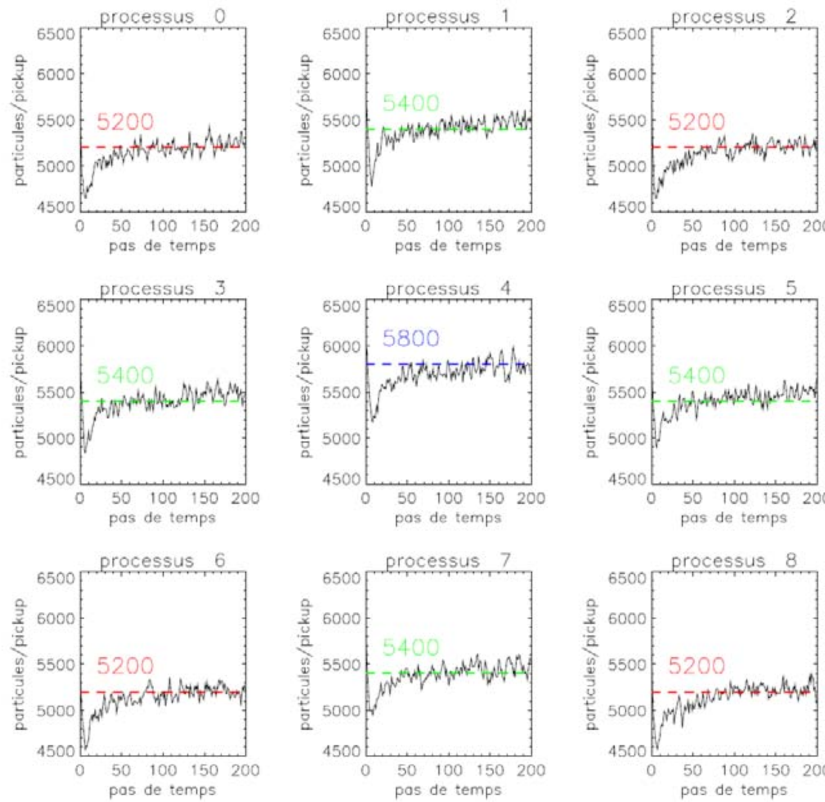
```
! On boucle sur le nombre d'information par particules a échanger
do j = 1,11
! On compacte les particules que l'on va envoyer vers le nord
mask(1 :nptot) = ((particule(3,1 :nptot)>zmax).and.((particule(2,1 :nptot)<=ymin)
&
.and.(particule(2,1 :nptot) <=ymax))).and.((particule(9,1 :nptot)==0) &
.and.((particule(1,1 :nptot) >= xmin).and.(particule(1,1 :nptot) <=xmax)))

p_out_N(j,1 :np_out(N)) = pack(particule(j,1 :nptot),mask(1 :nptot))
enddo
```

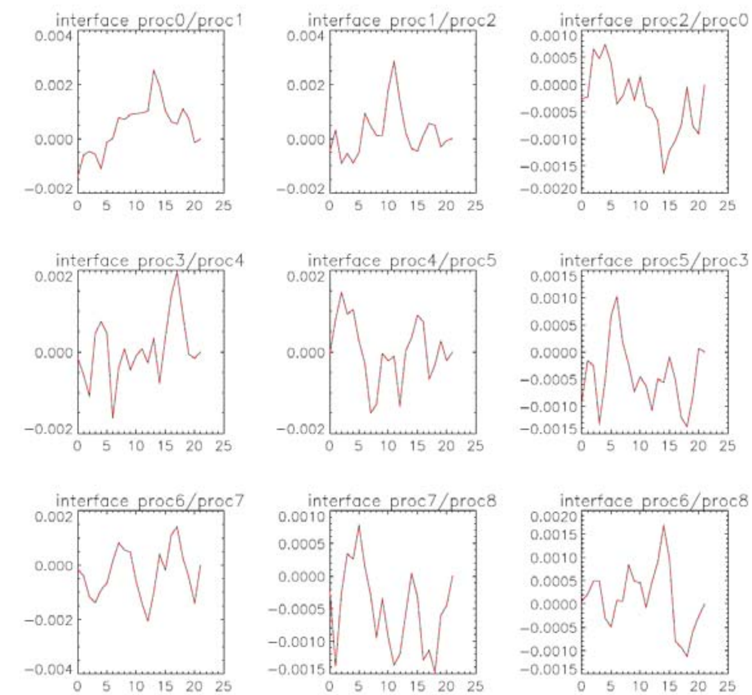
Test – quiet plasma (SW + pick-up)



Global parameters



Conservation of particles in the simulation



Check interfaces values (for Bx here)