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Mars and Venus Interaction with the Solar Wind by Using a Spherical Hybrid Model

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Outline

1. Motivation

2. HYB-model
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    2.2 Basic hybrid equation
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4. Summary and perspectives

Motivation

Question: How flowing plasma interacts with

The Moon : *no intrinsic B*, *no atmosphere*

Mercury : intrinsic B, *no atmosphere*

Venus : *no intrinsic B*, atmosphere

Mars : *no intrinsic B*, atmosphere

Titan : *no intrinsic B*, atmosphere

Tool: Global Quasi-Neutral Hybrid model

HYB: The FMI hybrid code

HYB is a 3-D Cloud-In-Cell Quasi-Neutral Hybrid code

- Semi-kinetic plasma matter: particle ions, massless electron fluid.
- Leapfrog algorithm to integrate the eq's forward in time.
  - Boris-Buneman integrator for the Lorentz force.
  - Divergence-free Faraday propagation (Yee lattice).
- Spatial Cartesian grid for the field quantities (hierarchically refinable) .
- Finite sized ion clouds (macroparticles) with volume weighting.
  - Simulation macroparticle is a finite sized particle cloud
  - Cloud size = local grid cell size.
- Developed for the planetary plasma interactions.

Object-oriented C++ programming

Runs on a single CPU

Basic Hybrid equations

Ions

$$m_i \frac{d\mathbf{v}_i}{dt} = q_i(\mathbf{E} + \mathbf{v}_i \times \mathbf{B})$$

$$\frac{d\mathbf{x}_i}{dt} = \mathbf{v}_i$$

Maxwell's eq's

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$(\nabla \cdot \mathbf{B} = 0)$$

$$(\nabla \cdot \mathbf{E} = \frac{\rho_q}{\epsilon_0})$$

Electrons

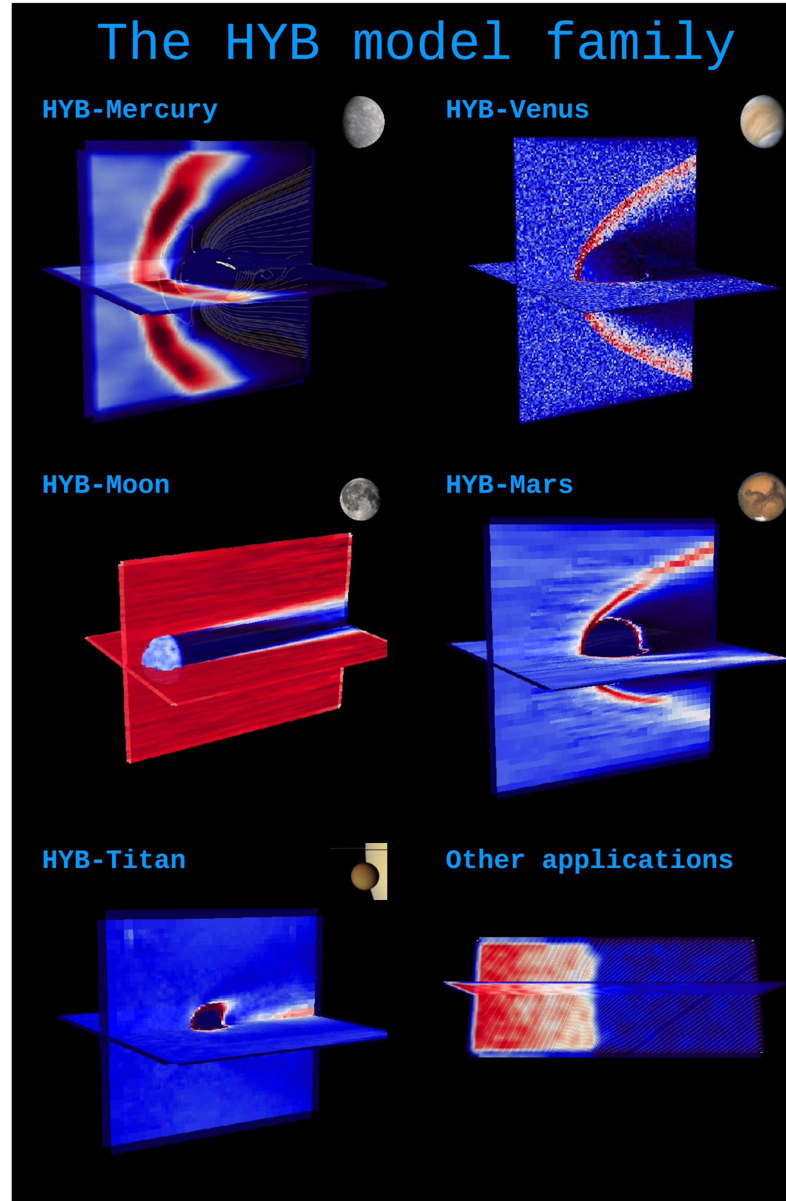
$$\mathbf{E} + \mathbf{U}_e \times \mathbf{B} = \eta_a \mathbf{J} + \frac{\nabla p_e}{q_e n_e}$$

$$p_e = n_e k_B T_e$$

$$\rho_q = \underbrace{\sum_i q_i n_i}_{\text{ion charge density in a grid cell}} + q_e n_e = 0$$

$$\mathbf{J} = \underbrace{\sum_i q_i n_i \mathbf{V}_i}_{\text{ion current}} + \underbrace{q_e n_e \mathbf{U}_e}_{\text{electron current}}$$

Typically $10^5 \ldots 10^6$ grid cells and $10^6 \ldots 10^8$ computational particles, 400 000 cells (30 particles/cell).



Solving the equations

0) Initial state for the magnetic field and the particles + parameters

magnetic field: $\mathbf{B}$

ions: $\mathbf{x}_i, \mathbf{v}_i$

parameters: η_a, T_e

1) Current density

$$\mathbf{J} = \mu_0^{-1}\nabla \times \mathbf{B}$$

2) Charge density of the electron fluid

$$q_\text{e} n_\text{e} = -\sum_i q_i n_i$$

3) Velocity field of the electron fluid

$$\mathbf{U}_\text{e} = \frac{\mathbf{J}}{q_\text{e} n_\text{e}} - \frac{\sum_i q_i n_i \mathbf{V}_i}{q_\text{e} n_\text{e}}$$

5) Propagation of the magnetic field

$$\mathbf{E}_\text{Faraday} = -\mathbf{U}_\text{e} \times \mathbf{B} + \underbrace{\eta_a \mathbf{J}}_{\text{field diffusion}}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}_\text{Faraday}$$

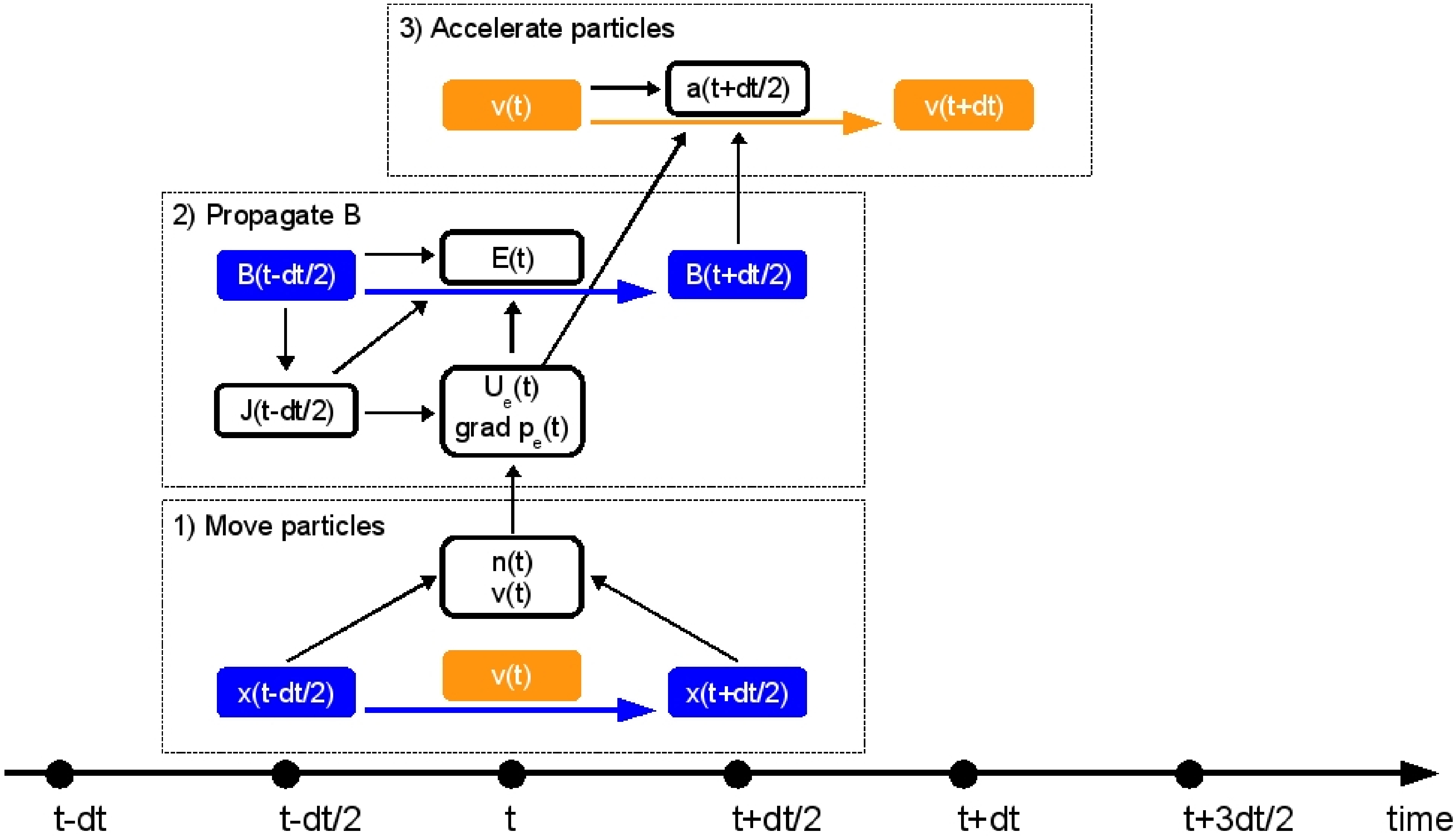
6) Propagation of the particles

$$\mathbf{E}_\text{Lorentz} = -\mathbf{U}_\text{e} \times \mathbf{B} + \frac{\nabla p_\text{e}}{q_\text{e} n_\text{e}}$$

$$\frac{d\mathbf{v}_i}{dt} = \frac{q_i}{m_i}(\mathbf{E}_\text{Lorentz} + \mathbf{v}_i \times \mathbf{B})$$

$$\frac{d\mathbf{x}_i}{dt} = \mathbf{v}_i$$

Leapfrog algorithm



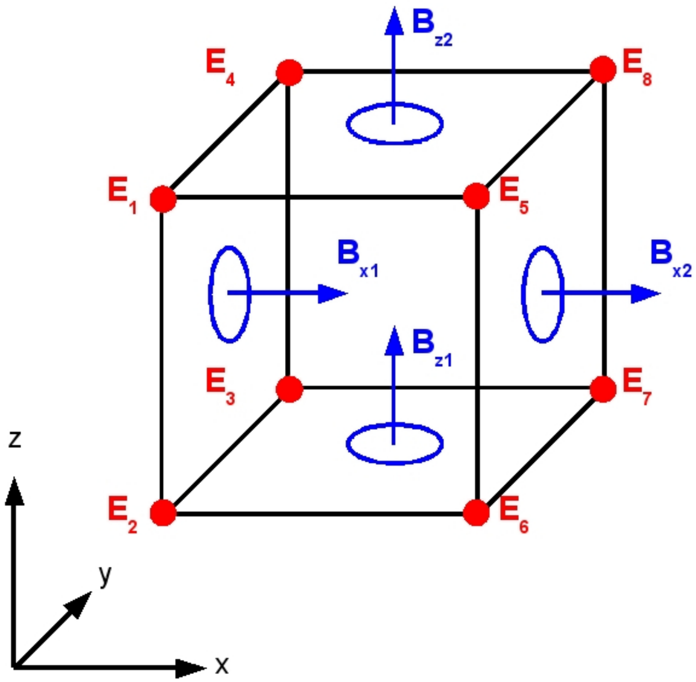
Divergenceless gridded B

B stored as fluxes on six cell faces, E calculated at cell nodes.

Fluxes propagated by taking a line integral of curl(E) using a linear approximation between the nodes.

This construction gives a stationary divergence of the magnetic field in a cell, i.e. initially divergence-free B stays that way.

Linear interpolations between cells, faces and nodes.



Yee lattice

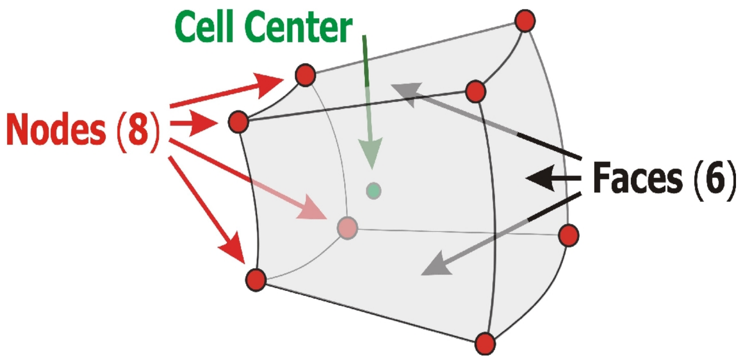
$$\frac{\partial \phi}{\partial t} = -\oint_{\partial S} \mathrm{d}\mathbf{l} \cdot \mathbf{E}$$

$$\frac{\partial}{\partial t}(\nabla \cdot \mathbf{B})_{\mathrm{cell}} = 0$$

$$(\nabla \cdot \mathbf{B})_{\mathrm{cell}} = (\phi_{1x} - \phi_{2x}) + (\phi_{1y} - \phi_{2y}) + (\phi_{1z} - \phi_{2z})$$

Spherical grid

Spherical cell



Why we need Spherical coordinates

1. Better grid resolution
(Natural Grid Refinement)

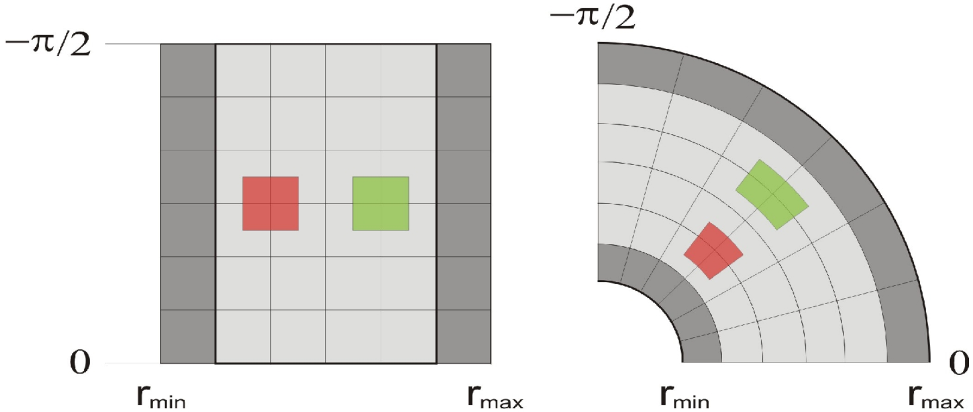
2. Boundary conditions
(Natural Boundary Conditions)

3. Self – consistent ionosphere
(for Venus ~ 20km)

Interpolations between spherical grid elements

CN - cell to node
NC - node to cell
FC - face to cell
NF - node to face
EN - edge to node

Macroparticle in Cartesian and spherical grids



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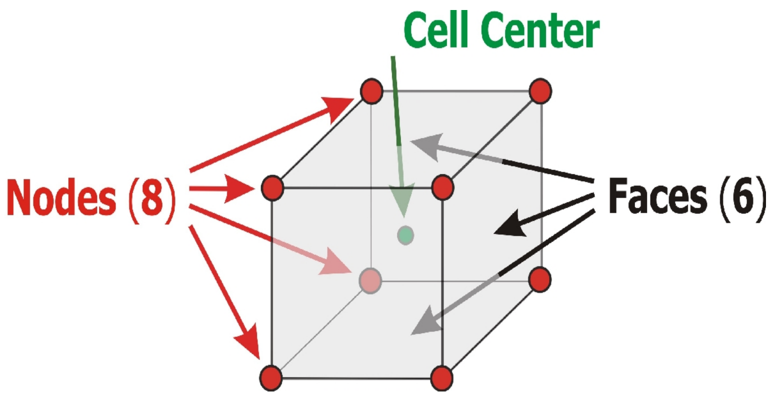
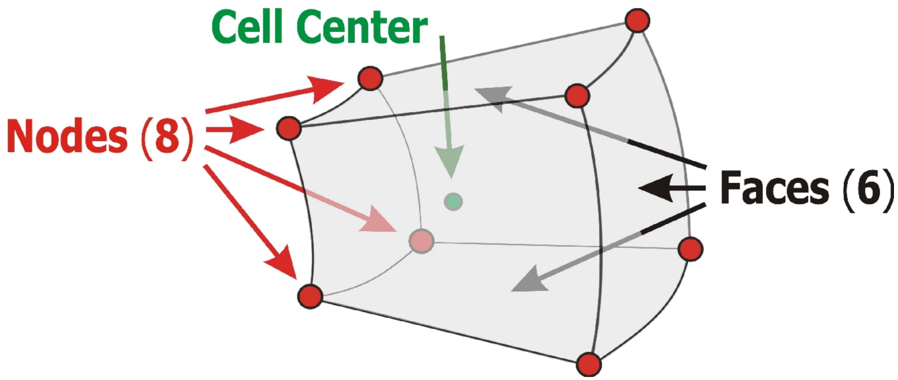
Cartesian vs Spherical





−	**Spherical Worlds** Planetary worlds are spherical	+
−	**Grid Resolution** In SC the grid size decreases automatically near the obstacle	+
−	**Obstacle Boundary Conditions** In SC the planetary surface overlaps r-constant surface of the grid	+
+	**Interpolation** In CC interpolations between the grid elements are simpler	−
+	**Boundary Conditions** In CC it is easier to set the external boundary conditions	−
+	**Pole Problems** In SC there are two singularity – poles	−

Solar wind – Venus interaction

Input parameters

Initial Magnetic Field: $B_x = 0$, $B_y = 10nT$, $B_z = 0$

Particle populations:
(Similar as in Jarvinen at al, 2009)

0 .Solar Wind Population
H+, $n = 1.5 \cdot 10^6\ m^{-3}$, $T = 10^5$ K.

1 .Solar Wind Population
H+, $n = 14 \cdot 10^6\ m^{-3}$, $T = 10^5$ K, $V_z = 4.3 \cdot 10^5$ m/s.

2. Ionospheric Population
O+, Emission rate = $2.0 \cdot 10^{25}\ s^{-1}$, T = 2000 K.

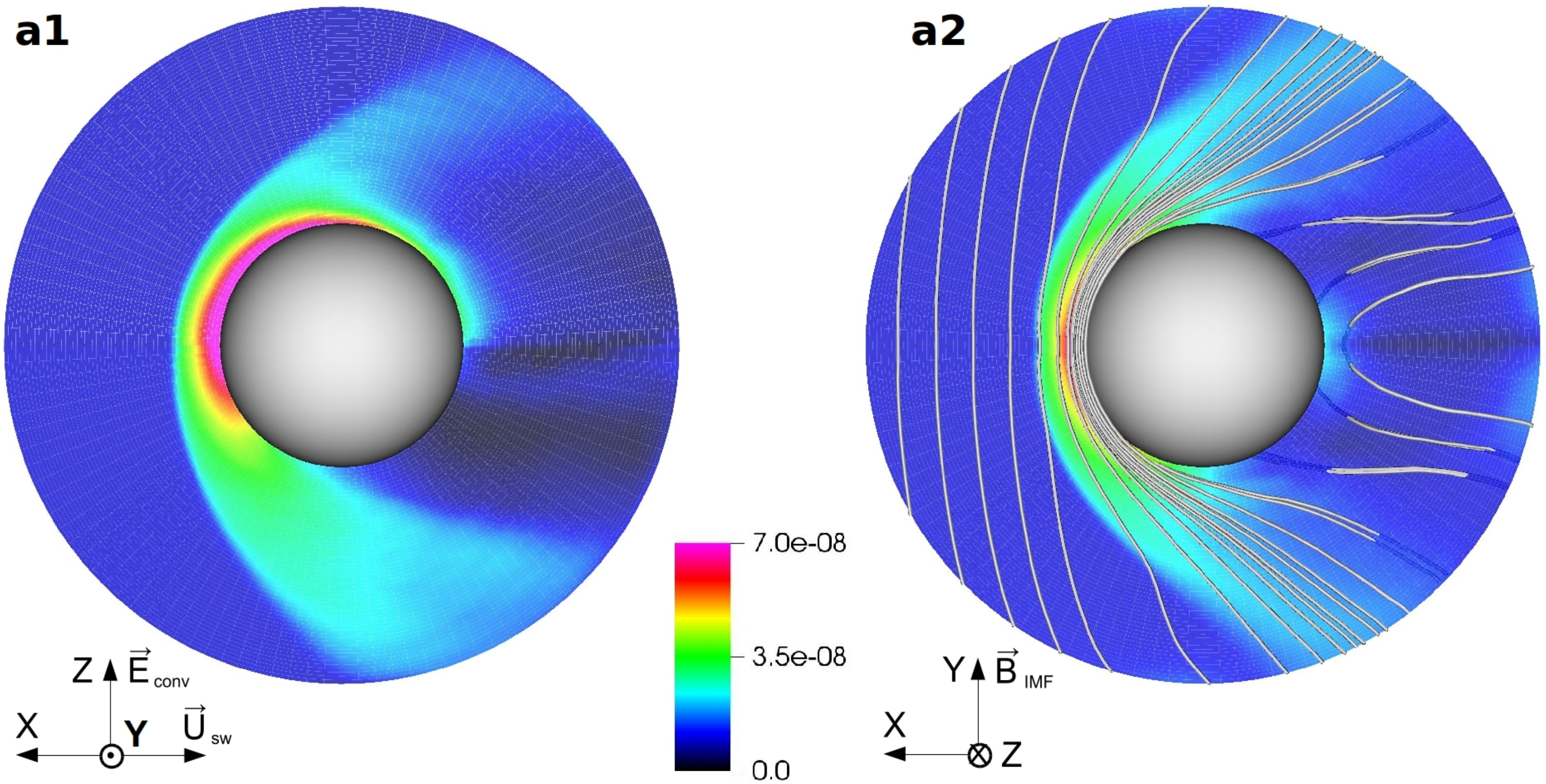
3. Exospheric Populations
H+, Emission rate = $2.0 \cdot 10^{23}\ s^{-1}$, T = 6000 K.
O+, Emission rate = $4.0 \cdot 10^{24}\ s^{-1}$, T = 5600 K.
H+, Emission rate = $6.2 \cdot 10^{24}\ s^{-1}$, T = 200 K.

MacroParticles: particles/cell=30.

Grid stucture: Spherical
dr = 202 km, $d\theta = 3.0^o$, $d\varphi = 6.0^o$

Solar Wind - Venus Interaction. Steady state regime (400s)

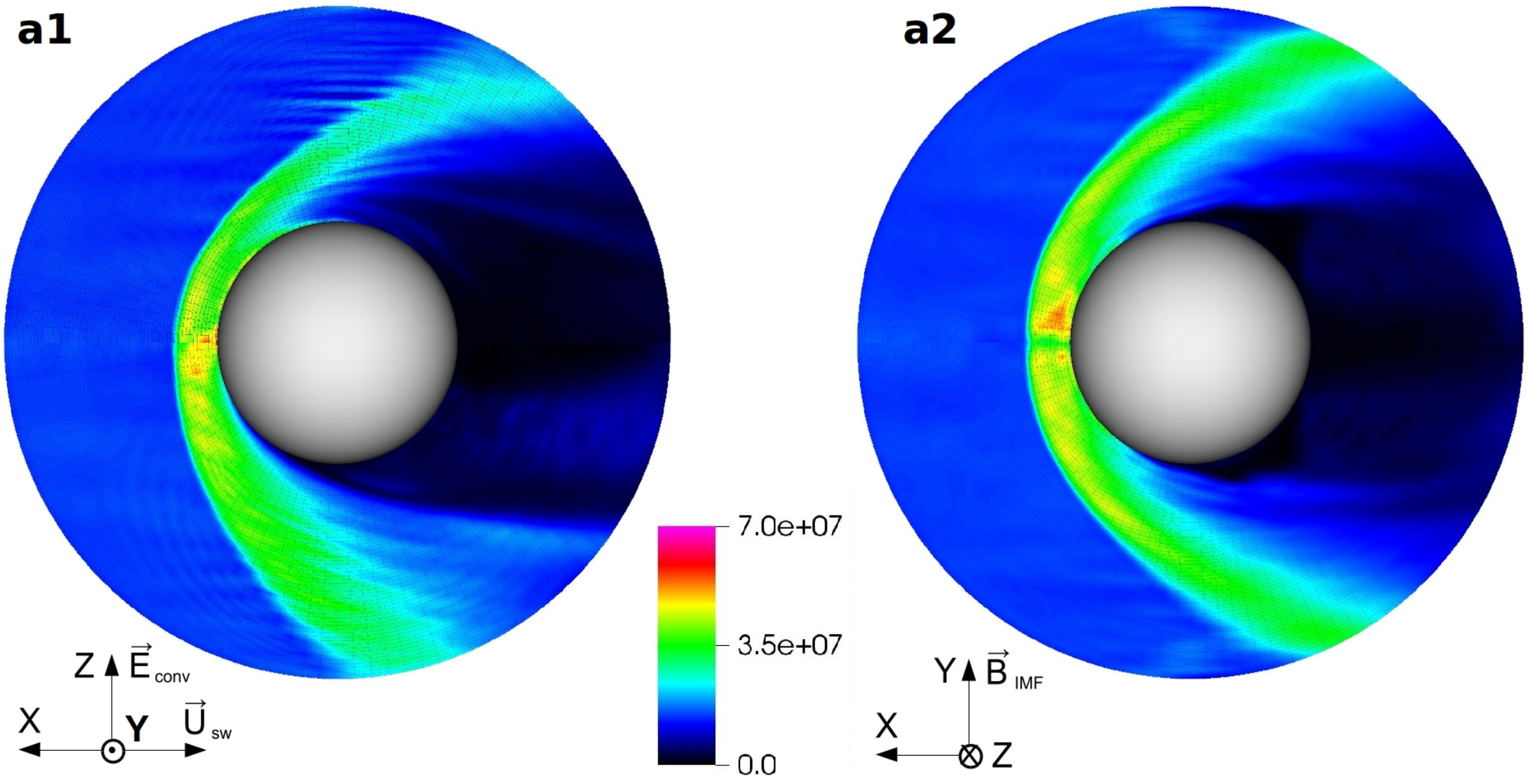
Magnetic field, B [T]



S. Dyadechkin, E. Kallio and R. Jarvinen. *A new 3D spherical hybrid model for solar wind interaction studies*. JGR. Submitted.

Solar Wind - Venus Interaction. Steady state regime (400s)

H+ number density, n [m^{-3}]



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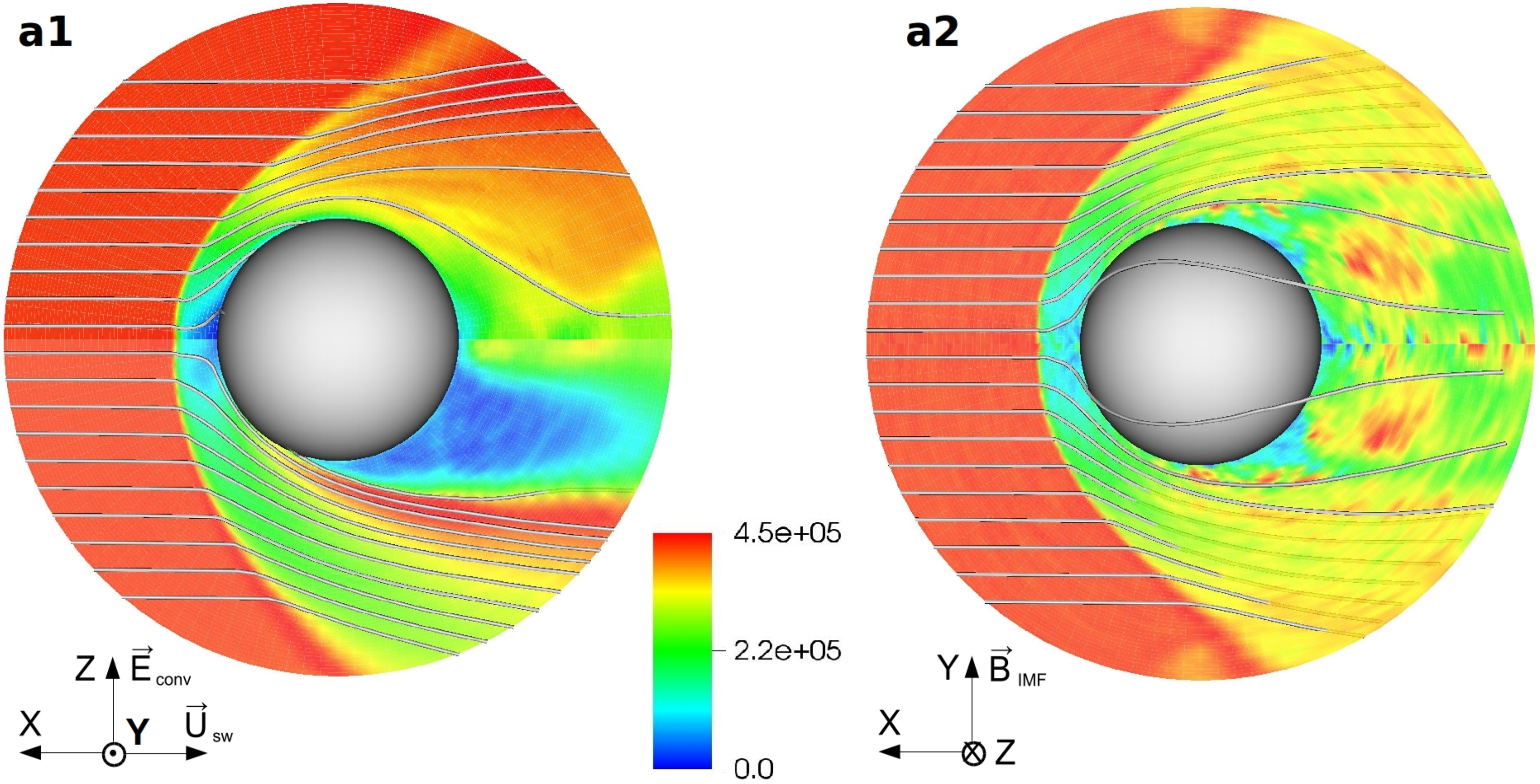
Solar Wind - Venus Interaction. Steady state regime (400s)

H+ bulk velocity, V [m/s]



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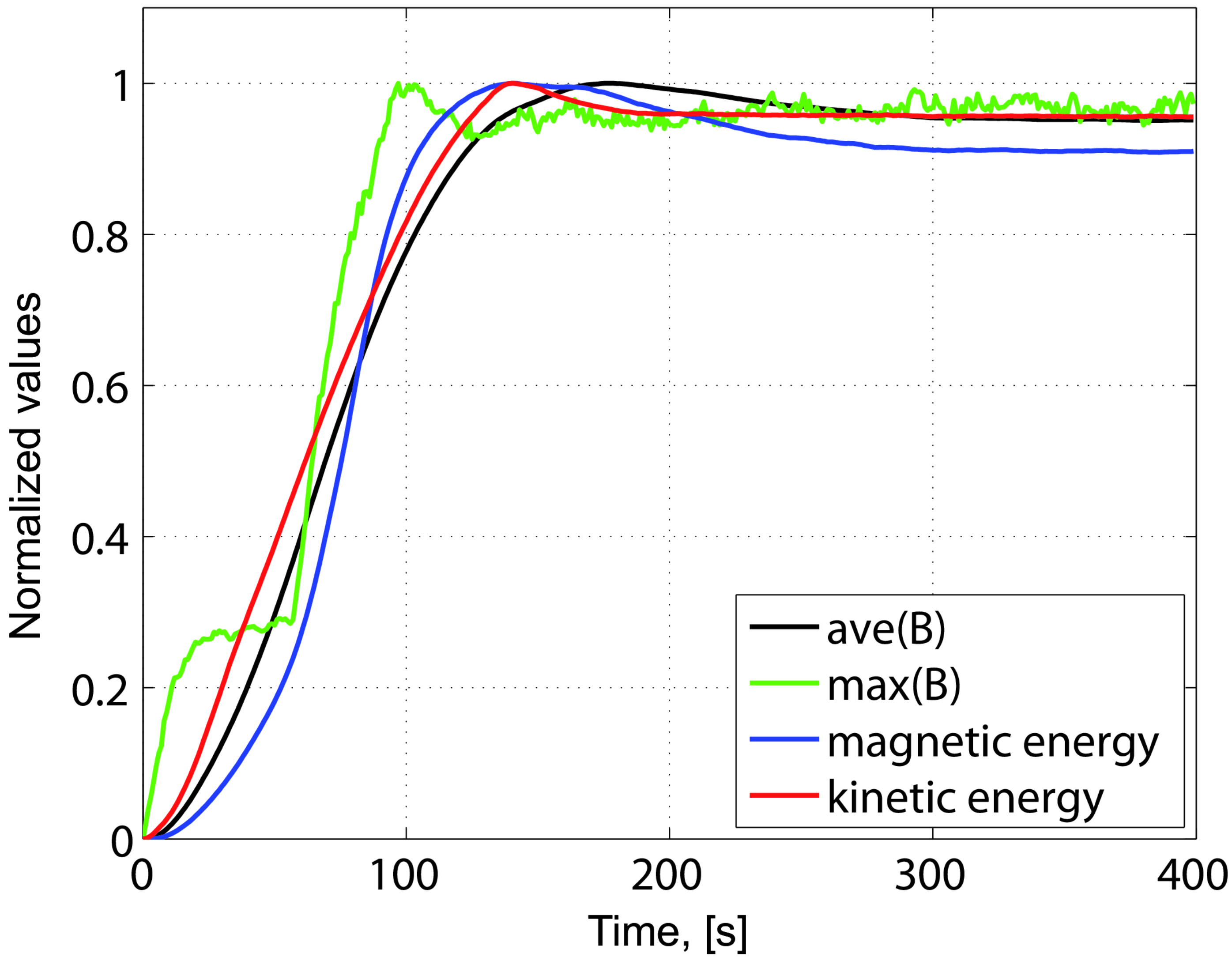
Solar Wind - Venus Interaction



Solar wind – Mars interaction

Input parameters

Initial Magnetic Field: $B_x = 0$, $B_y = 4.7$nT, $B_z = 0$

Particle populations:
0 .Solar Wind Population
H+, $n = 3.1\cdot10^5\ m^{-3}$, $T = 10^5$ K.

1 .Solar Wind Population
H+, $n = 3.1\cdot10^6\ m^{-3}$, $T = 10^5$ K, $V_z = 4.3\cdot10^5$ m/s.

2. Ionospheric Population
O+, Emission rate = $6.0\cdot10^{24}\ s^{-1}$, T = 2000 K.

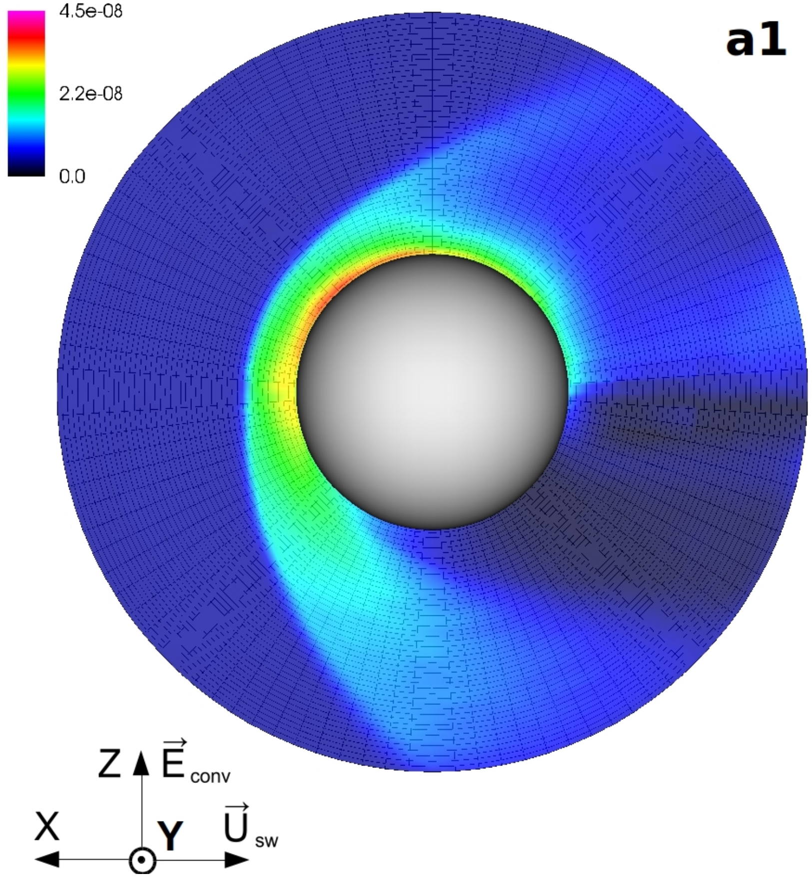
3. Exospheric Populations
H+, Emission rate = $6.28\cdot10^{22}\ s^{-1}$, T = 6000 K.
O+, Emission rate = $1.28\cdot10^{24}\ s^{-1}$, T = 5600 K.
H+, Emission rate = $2.0\cdot10^{24}\ s^{-1}$, T = 200 K.

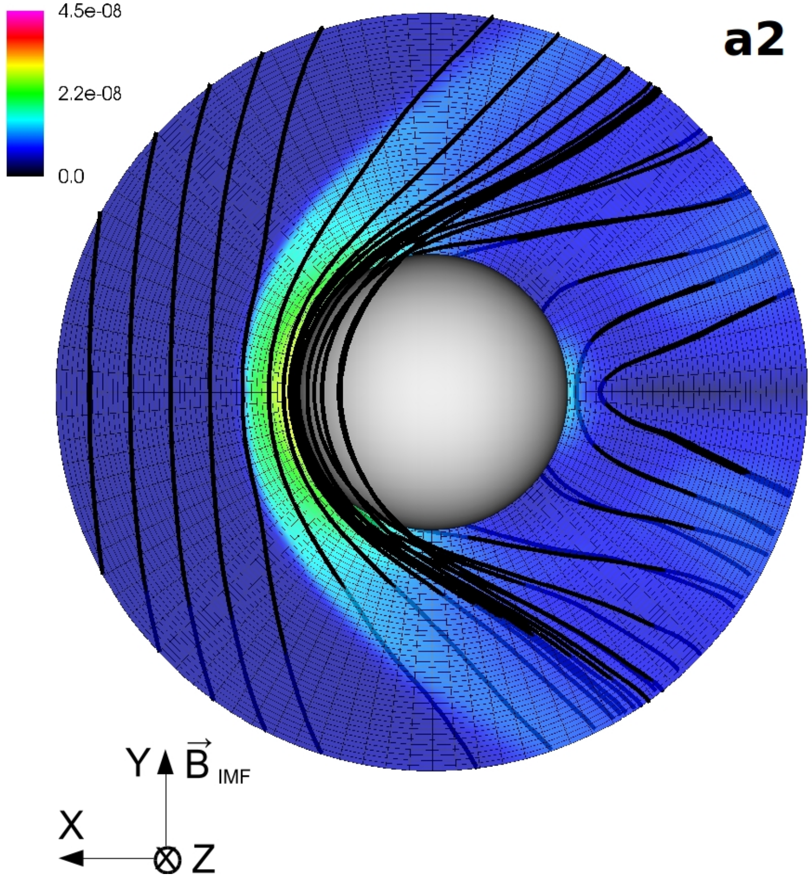
MacroParticles: particles/cell=30.

Grid stucture: Spherical
dr = 136 km, $d\theta = 3.6^o$, $d\varphi = 7.2^o$

Solar Wind - Mars Interaction. Steady state regime (180 s)

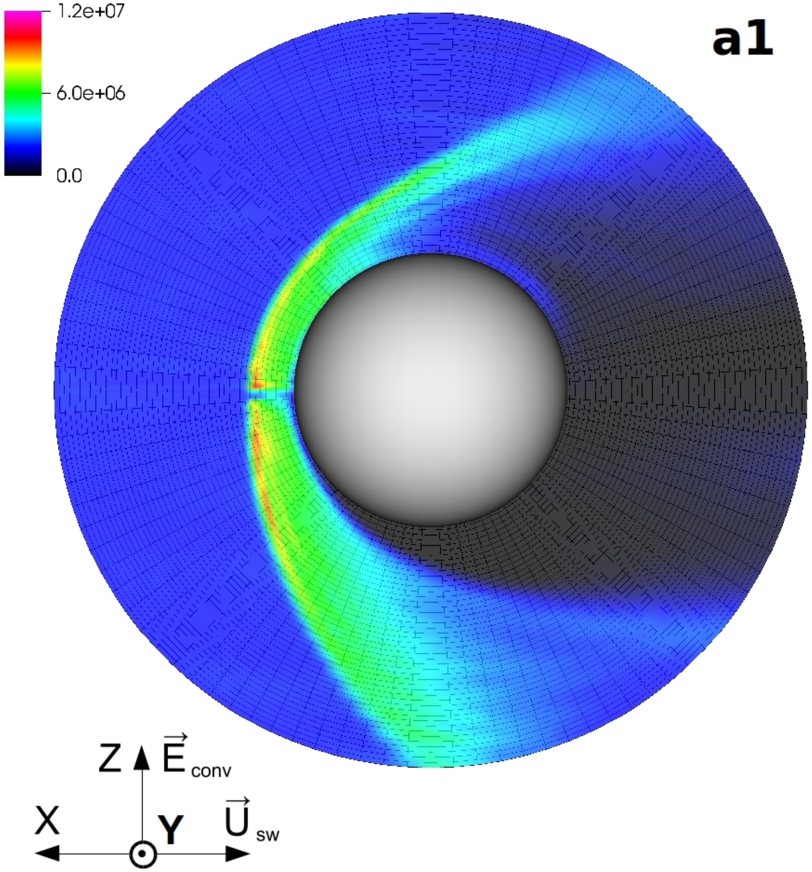
Magnetic field, B [T]

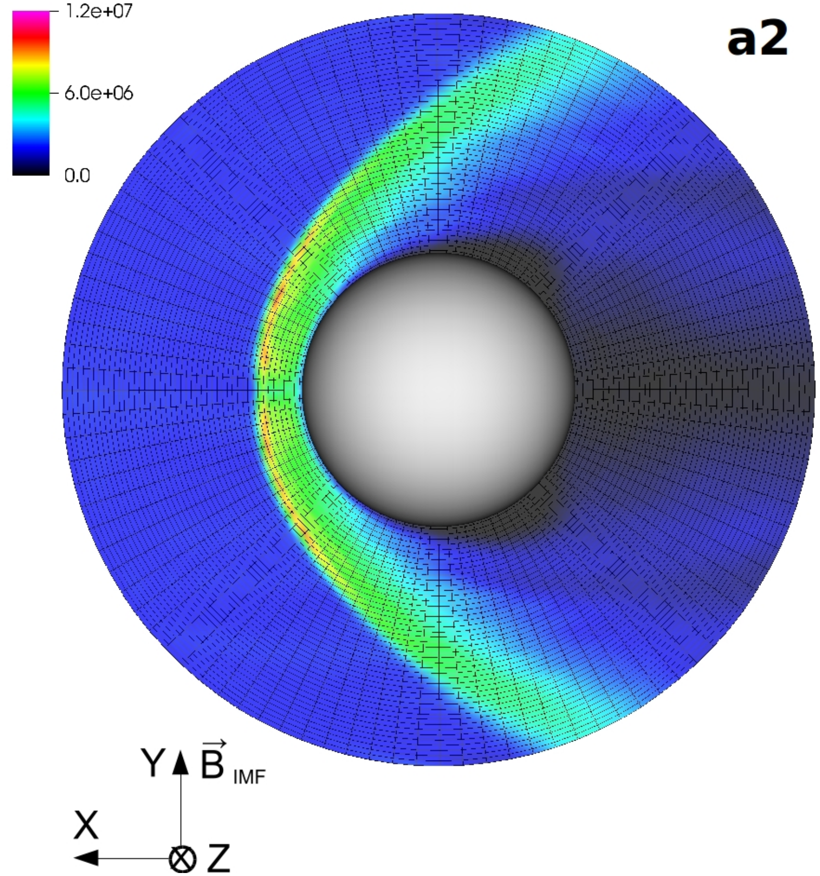




Solar Wind - Mars Interaction. Steady state regime (180 s)

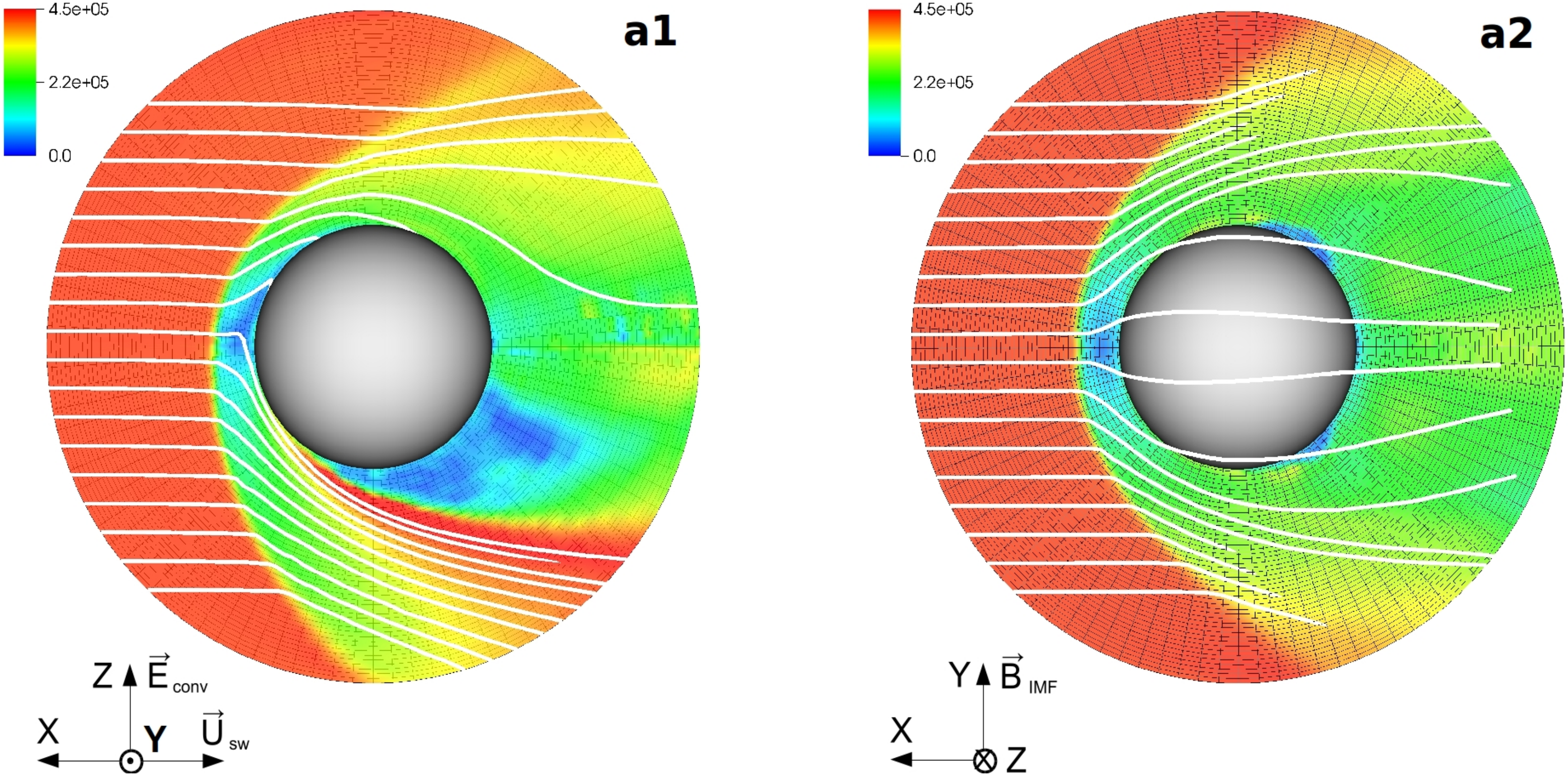
H+ number density, n [m^{-3}]



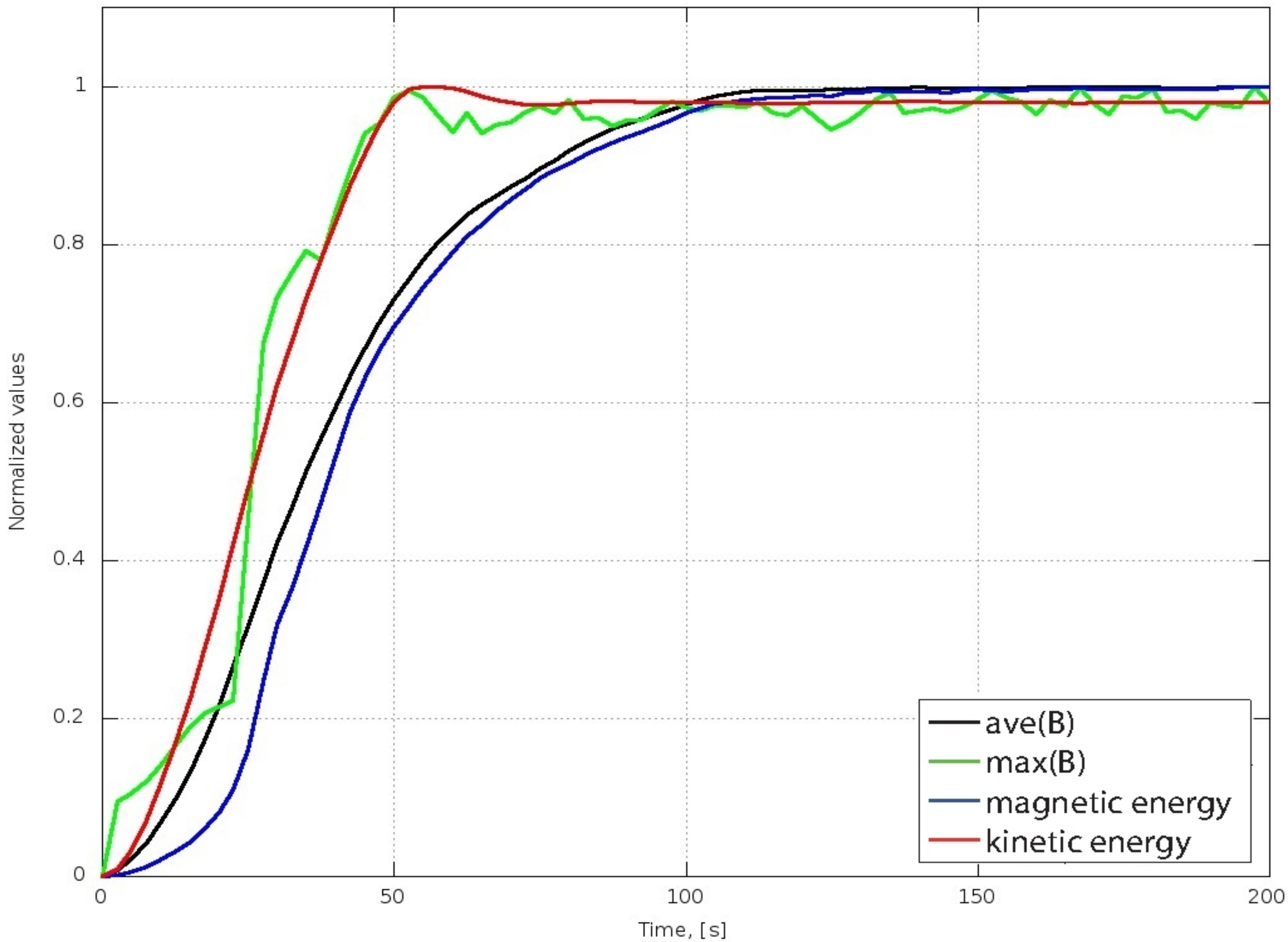


Solar Wind - Mars Interaction. Steady state regime (180 s)

H+ bulk velocity, V [m/s]



Solar Wind - Mars Interaction



Summary and Perspectives

Spherical HYB model is ready to use

Spherical HYB model has some advantages compared to Cartesian HYB
a. Better grid resolution
b. Natural inner boundary conditions

Perspectives

Self-consistance ionosphere.
(For Venus Δr ~ 20 km)

Nonuniform grid (Δr != const)

Magnetized objects (Mercury, Earth ...)

Testing, developing.