Interaction of the Solar Wind with Weak Obstacles: Simulation Method and a Tour of Applications

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Outline

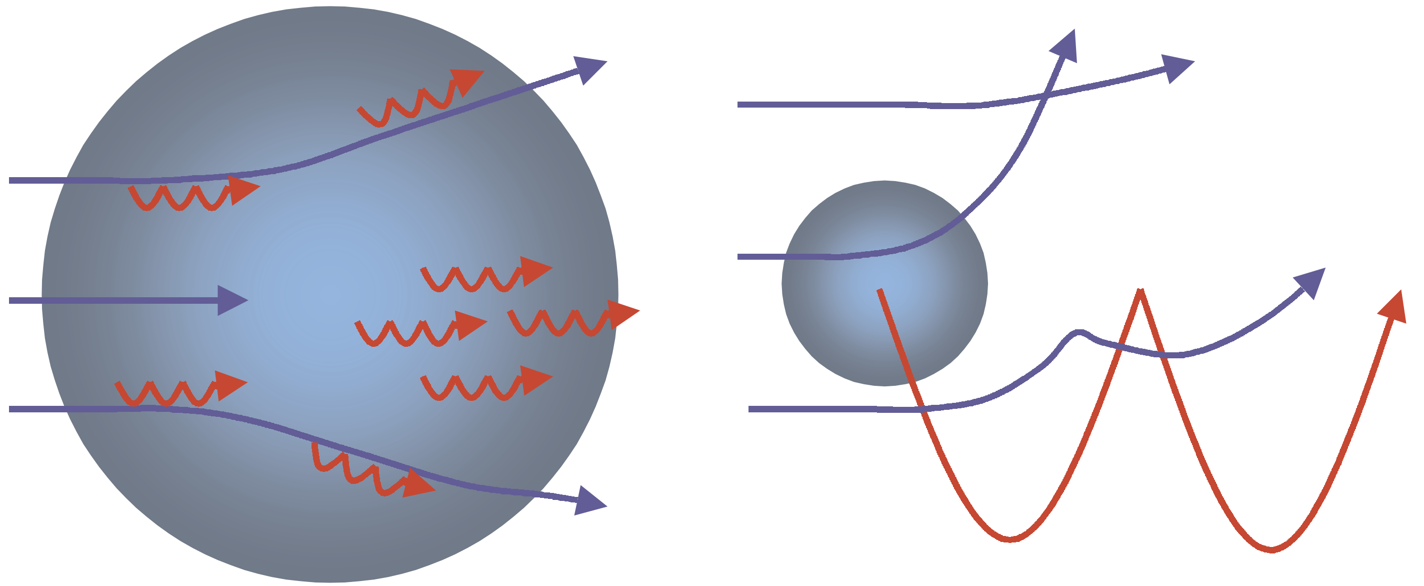
Background and scales

Simulation technique

3D simulation results for

- Mars
- Weak Comets
- Titan
- Asteroids
- Extrasolar Planets

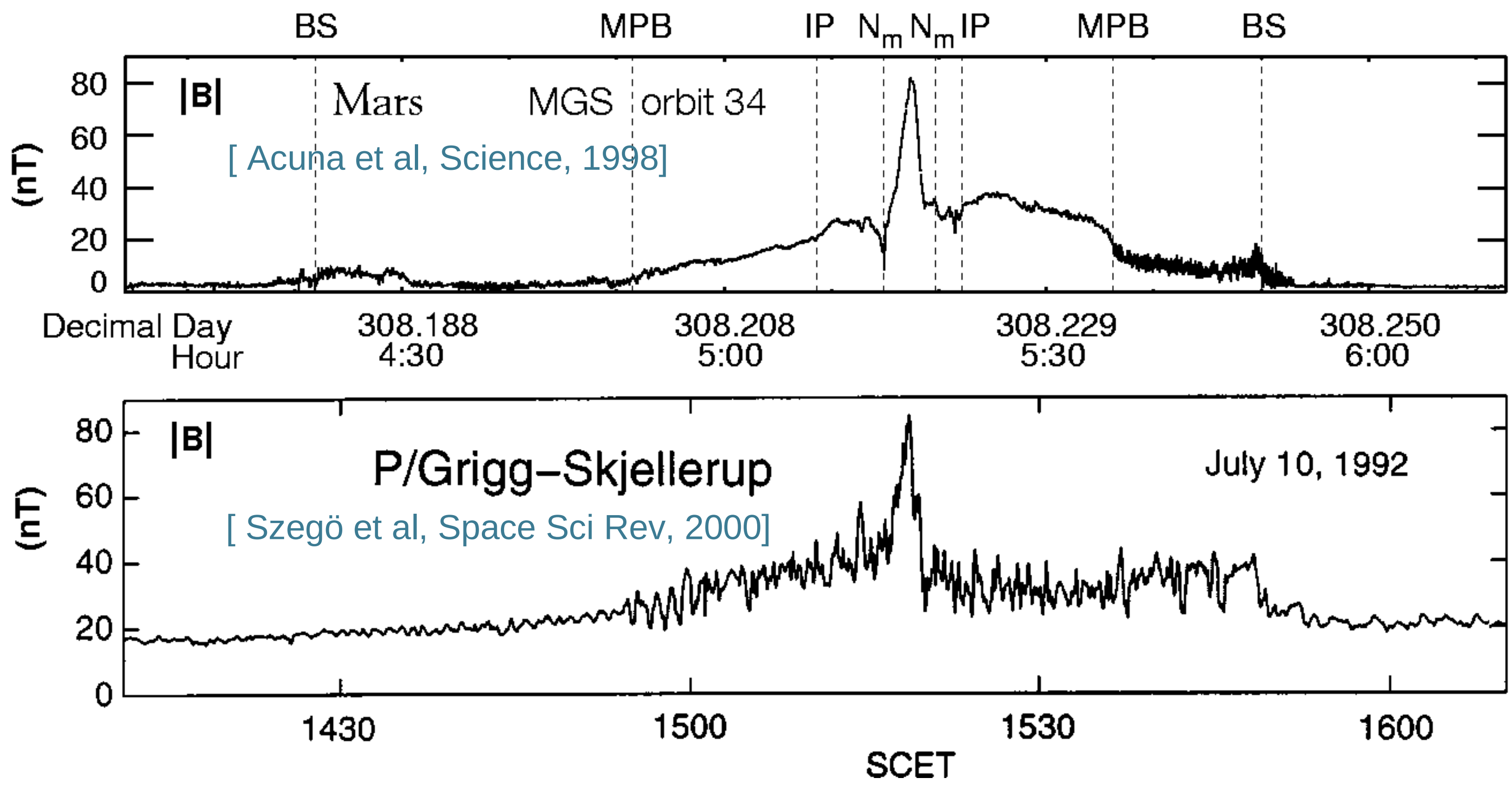
Strong vs. Weak Obstacles



Strong: Jupiter, Earth,
Halley

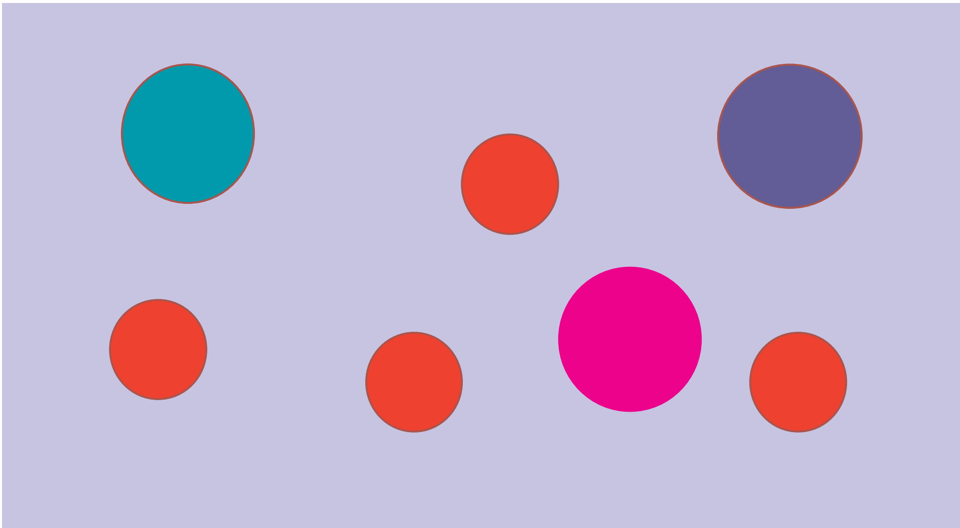
Weak: Mars, Titan,
Asteroids,
Churyumov-Gerasimenko

Mars vs. Weak Comets



Simulation Technique

(Hybrid model)



Electrons as fluid

Ions as particles:
Protons, Oxygen,
Water, Nitrogen,
...

Basic Equations

Eq. of motion for ions:

$$\frac{d\underline{x}_s}{dt} = \underline{v}_s \qquad \frac{d\underline{v}_s}{dt} = \frac{q_s}{m_s}\left(\underline{E} + \underline{v}_s \times \underline{B}\right) - \nu_{ns} n_n \left(\underline{v}_s - \underline{u}_n\right)$$

Electron fluid:

$$n_e m_e \frac{d\underline{u}_e}{dt} = -n_e e \underline{E} + \underline{J}_e \times \underline{B} - \nabla p_{e,\mathrm{sw}} - \nabla p_{e,\mathrm{hi}}$$

Ohm's law:

$$\underline{E} = -\frac{\underline{J}_i \times \underline{B}}{\rho_c} + \frac{\mathrm{curl}\,\underline{B} \times \underline{B}}{\mu_0 \rho_c} - \frac{\nabla p_{e,\mathrm{sw}} + \nabla p_{e,\mathrm{hi}}}{\rho_c}$$

Adiabatic equation:

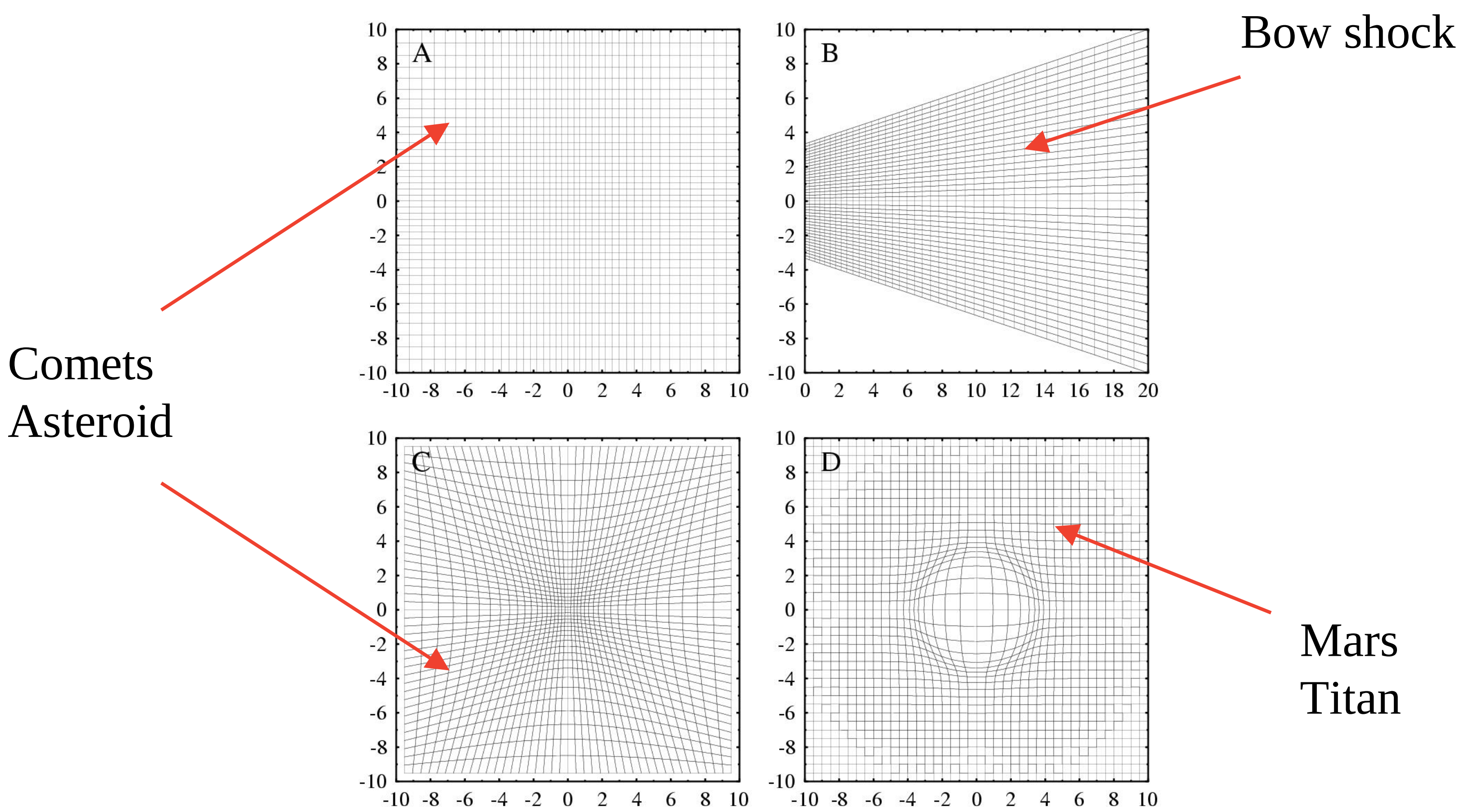
$$p_{e,\mathrm{sw}} = \beta_{e,\mathrm{sw}} \left(\frac{n_{\mathrm{sw}}}{n_0}\right)^{\kappa} \qquad p_{e,\mathrm{hi}} = \beta_{e,\mathrm{hi}} \left(\frac{n_{\mathrm{hi}}}{n_0}\right)^{\kappa}$$

Faraday's law:

$$\frac{\partial \underline{B}}{\partial t} = \mathrm{curl}\,\frac{\underline{J}_i \times \underline{B}}{\rho_c} - \mathrm{curl}\,\frac{\mathrm{curl}\,\underline{B} \times \underline{B}}{\mu_0 \rho_c}$$

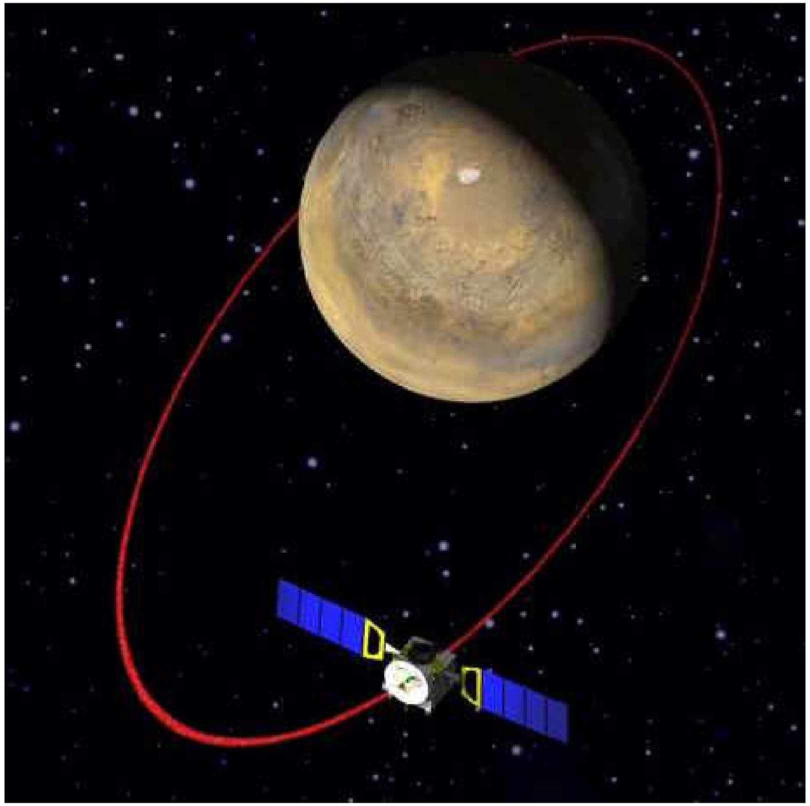
[Bagdonat and Motschmann, JCP, 2002]

Curvilinear Grids (3D)

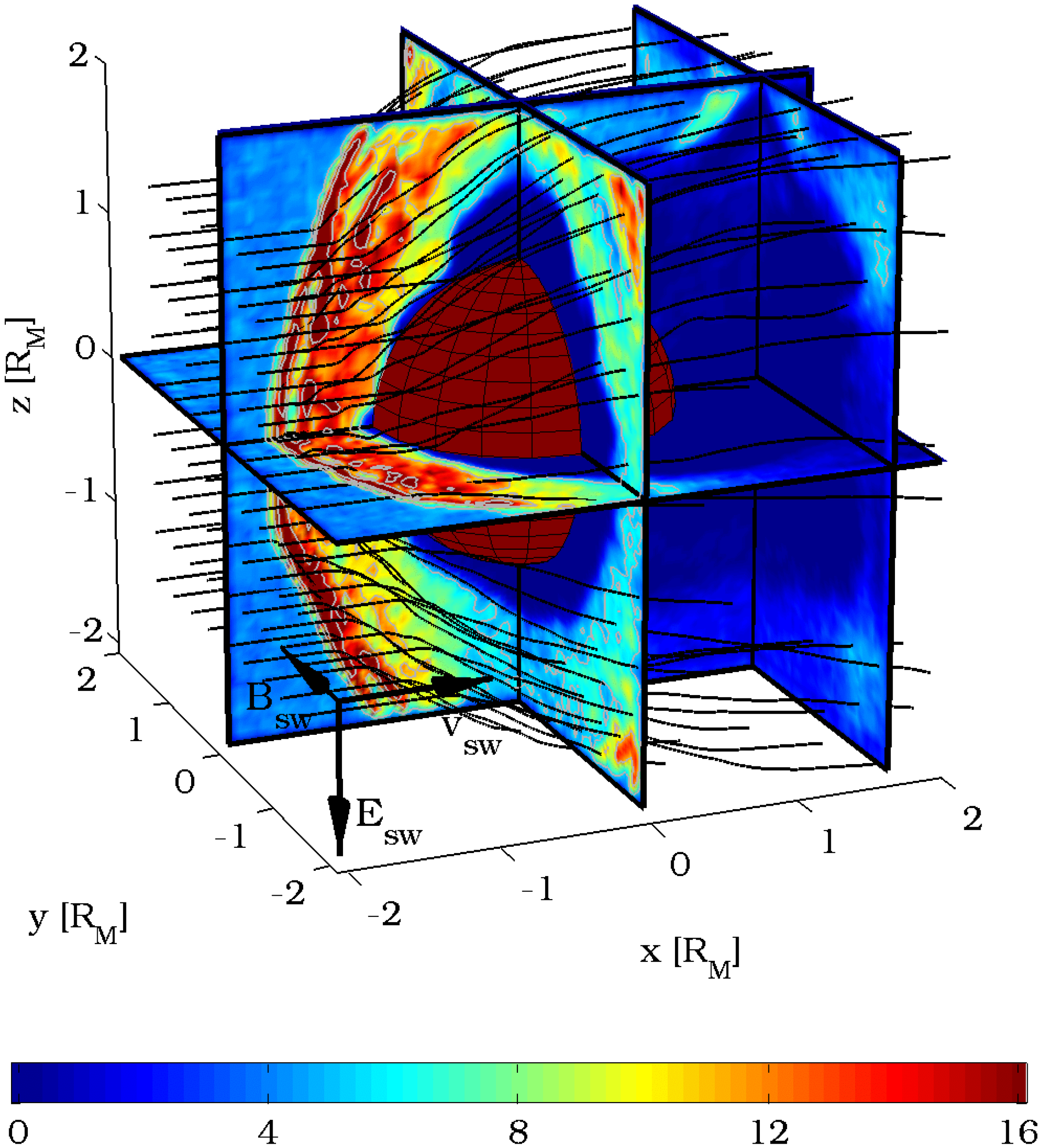


Simulation of Mars

1989 Phobos
1997 - Mars Global Surveyor
2003 - Mars-Express



Mars



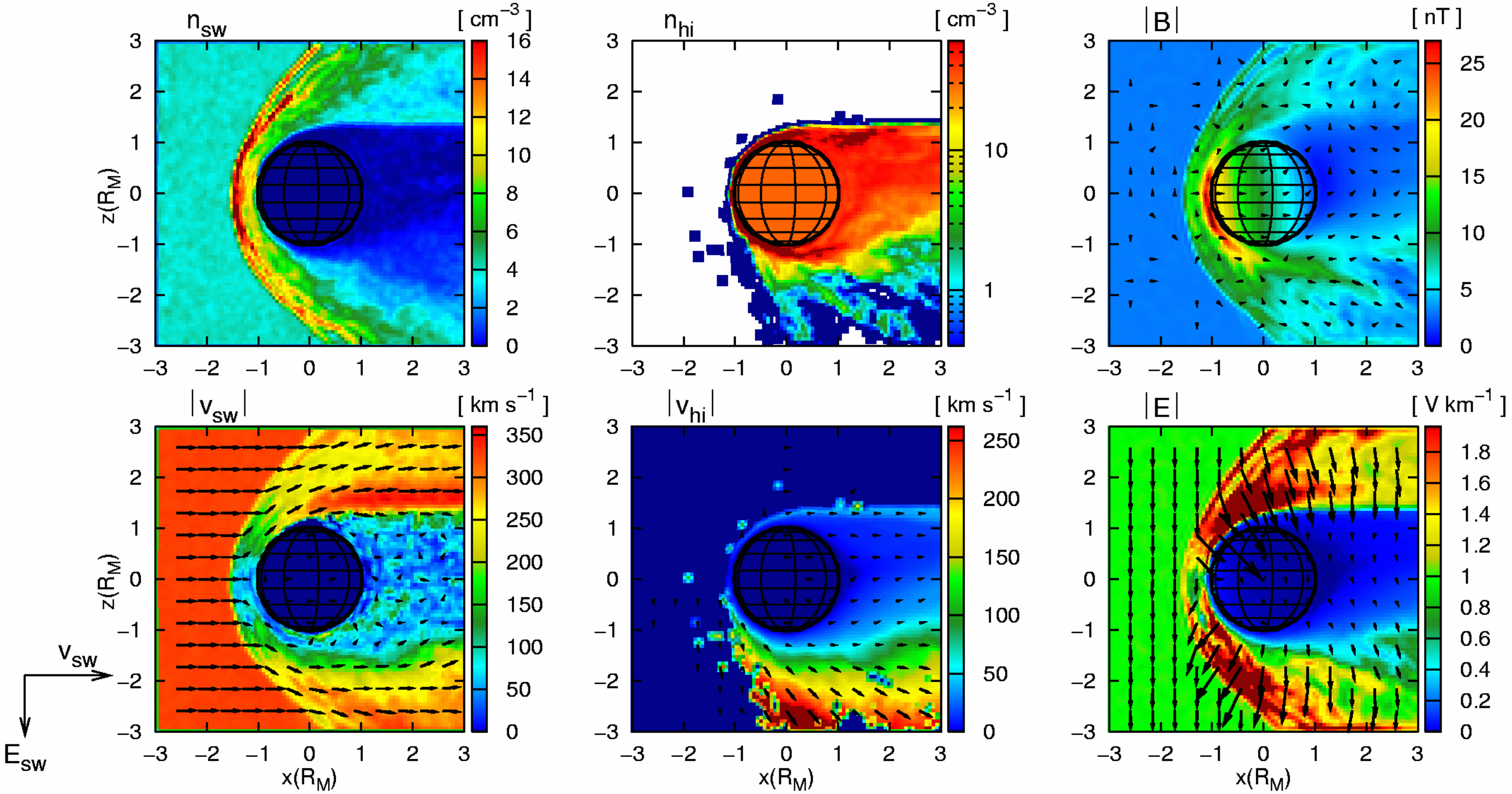
[Boesswetter et al, Ann. Geophys., 2004]

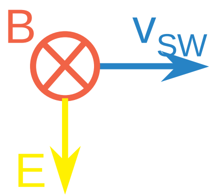
Solar wind density n_{sw} [cm^{-3}]

Polar Plane, T_e = 0.3 eV

t = 1392.1 s

[Bößwetter, Bagdonat, Motschmann; 2004]

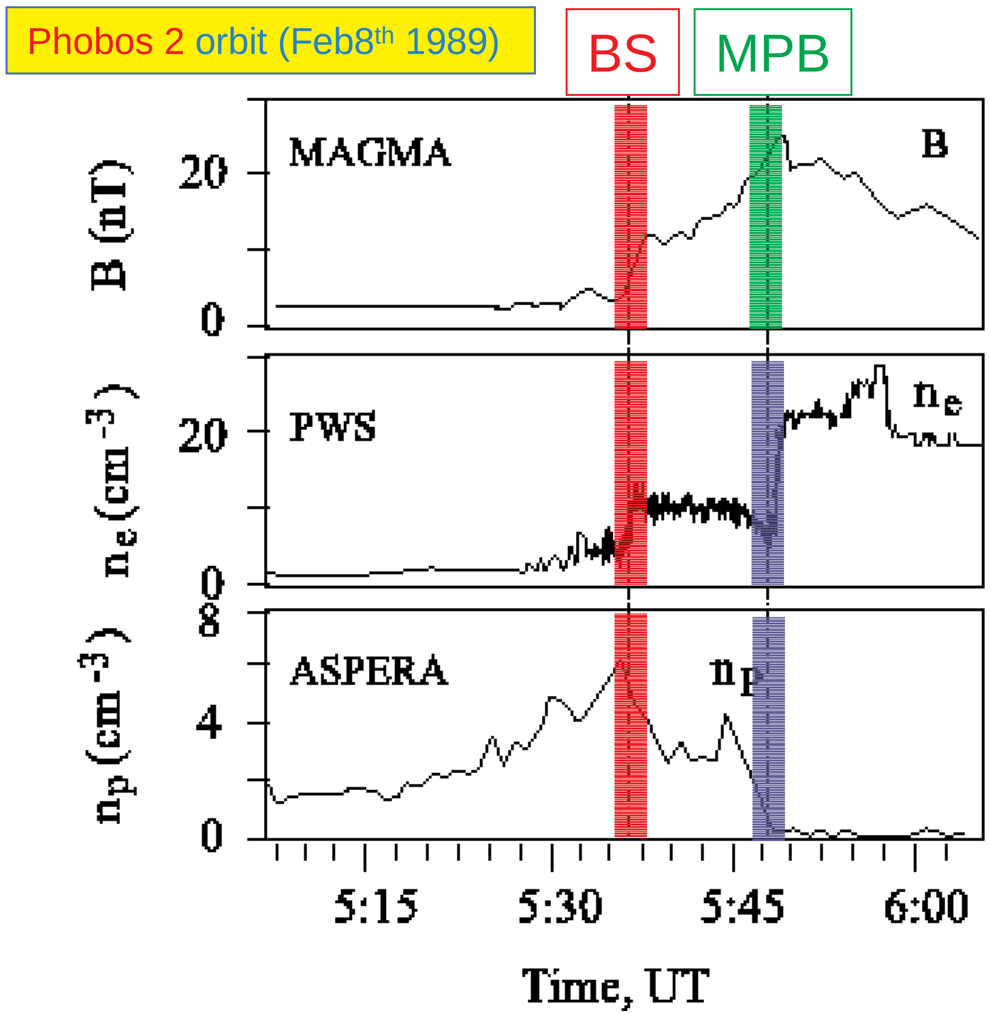


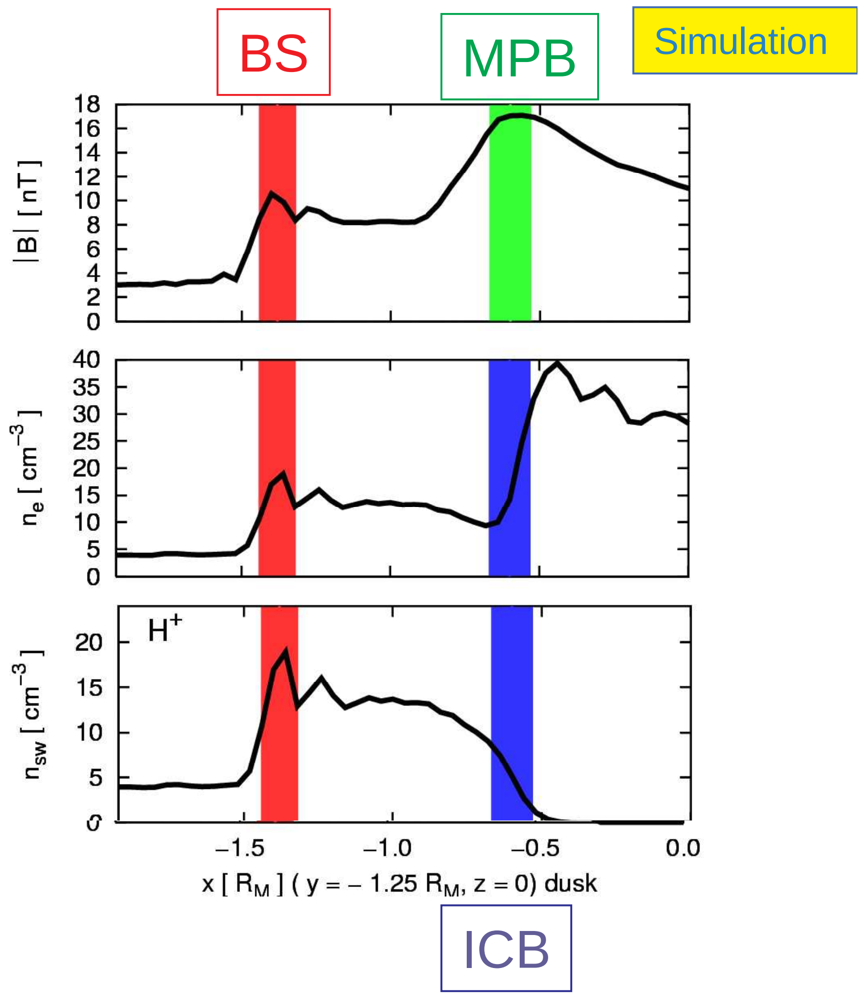


Total ion production rate: $5.37 \cdot 10^{25}\ s^{-1}$
Ionization frequency: $2 \cdot 10^{-7}\ s^{-1}$
Background magnetic field: 3 nT

Solar wind density: 4 cm^{-3}
Alfvén Mach number: 10
Ion inertial length: c/ω_{pi}=114 km

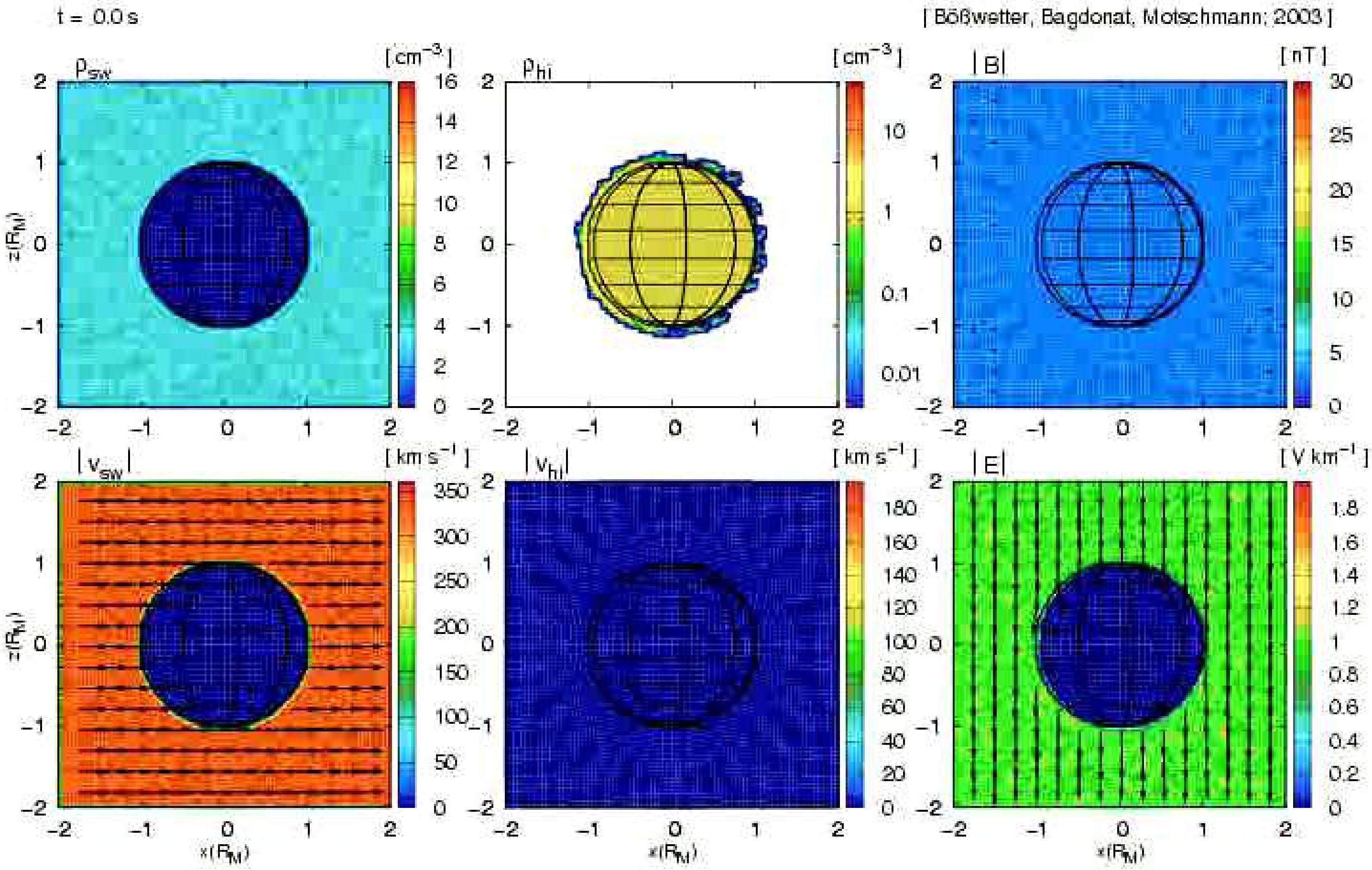
Comparison of observation and simulation

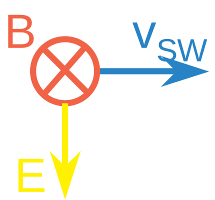




[Sauer and Dubinin, 2000]

Polar Plane, T_e = 2 eV





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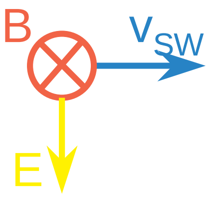
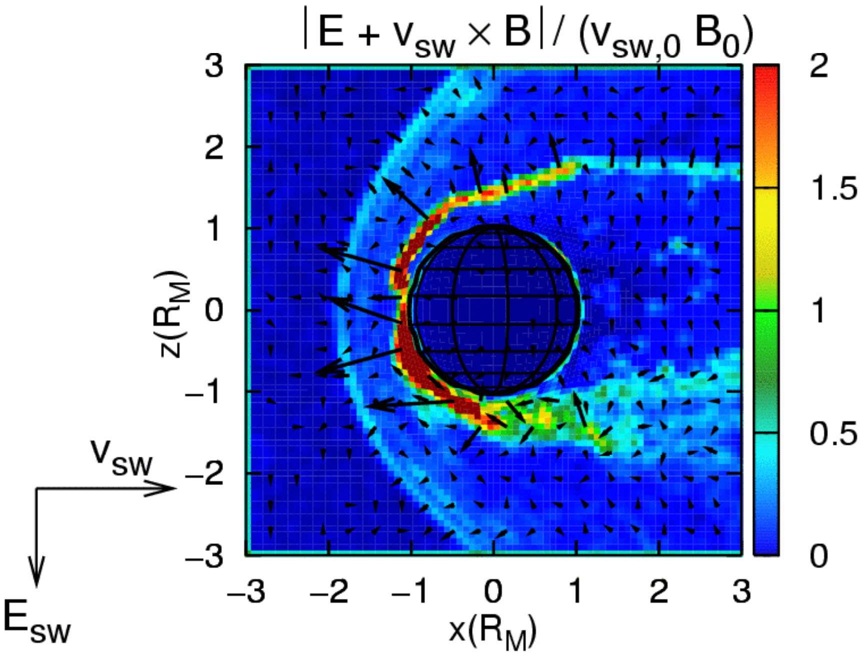
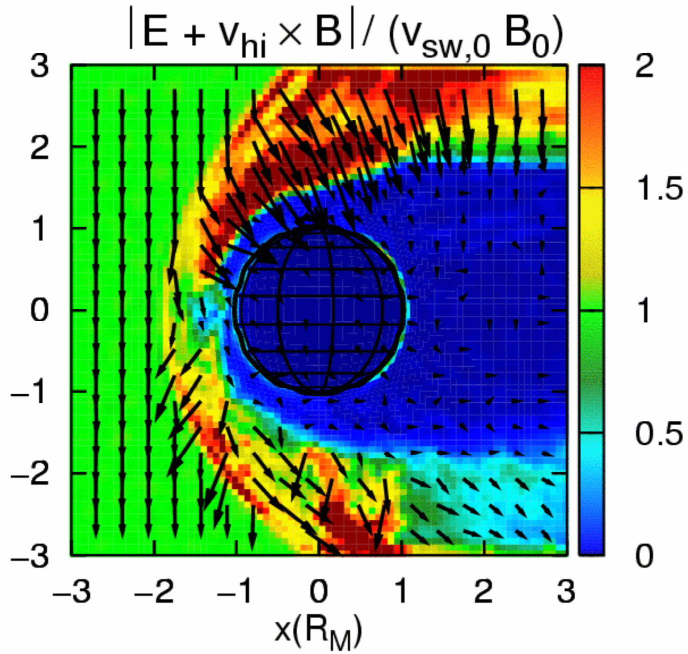
Formation of the ICB/MPB



Force on solar wind protons



Force on O^+ ions



Gradient of the electron pressure points **outward**
⇒ Reflection of SW protons

<u>Northern hemisphere:</u>
Electric field of the SW points **toward the planet**

Simulation of Comet Churyumov-Gerasimenko

3.25 AU .....2.5 AU

Simulation of CG at 3.25AU

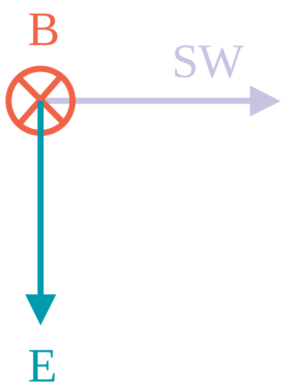
$Q_n=10^{24}s^{-1}$

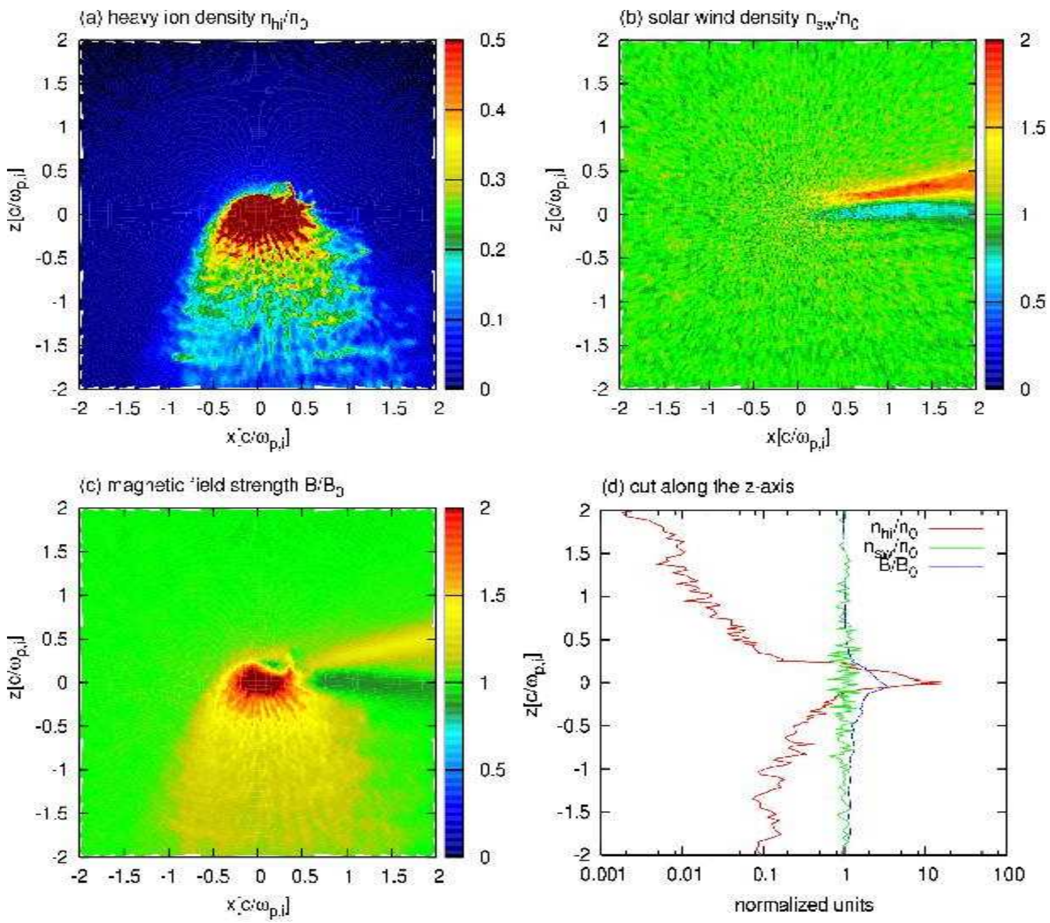
$B_0=1.13nT$

$n_0=0,66cm^{-3}$

$M_{A0}=10$

$x_0=280km$





[Bagdonat et al, The new Rosetta Target, 2004]

Simulation of CG at 2.5AU

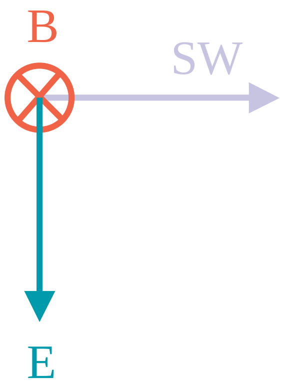
$Q_n = 1.9 \cdot 10^{26} s^{-1}$

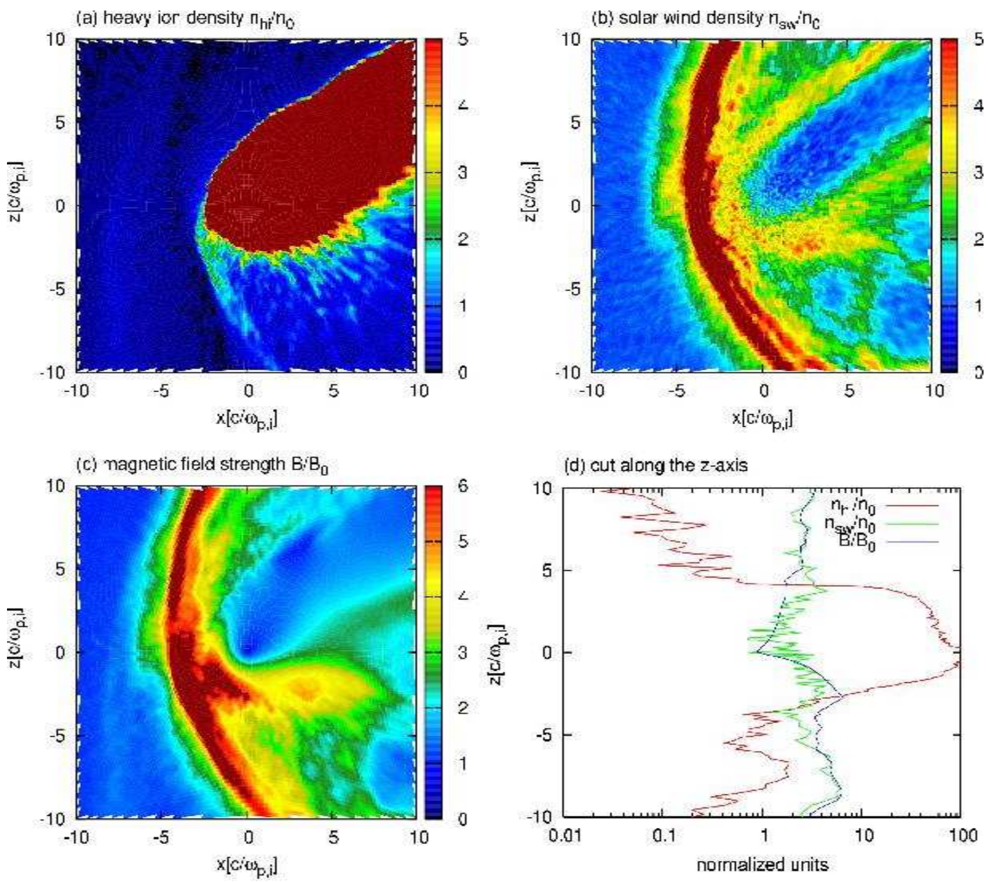
$B_0 = 1.5nT$

$n_0 = 1,1 cm^{-3}$

$M_{A0} = 10$

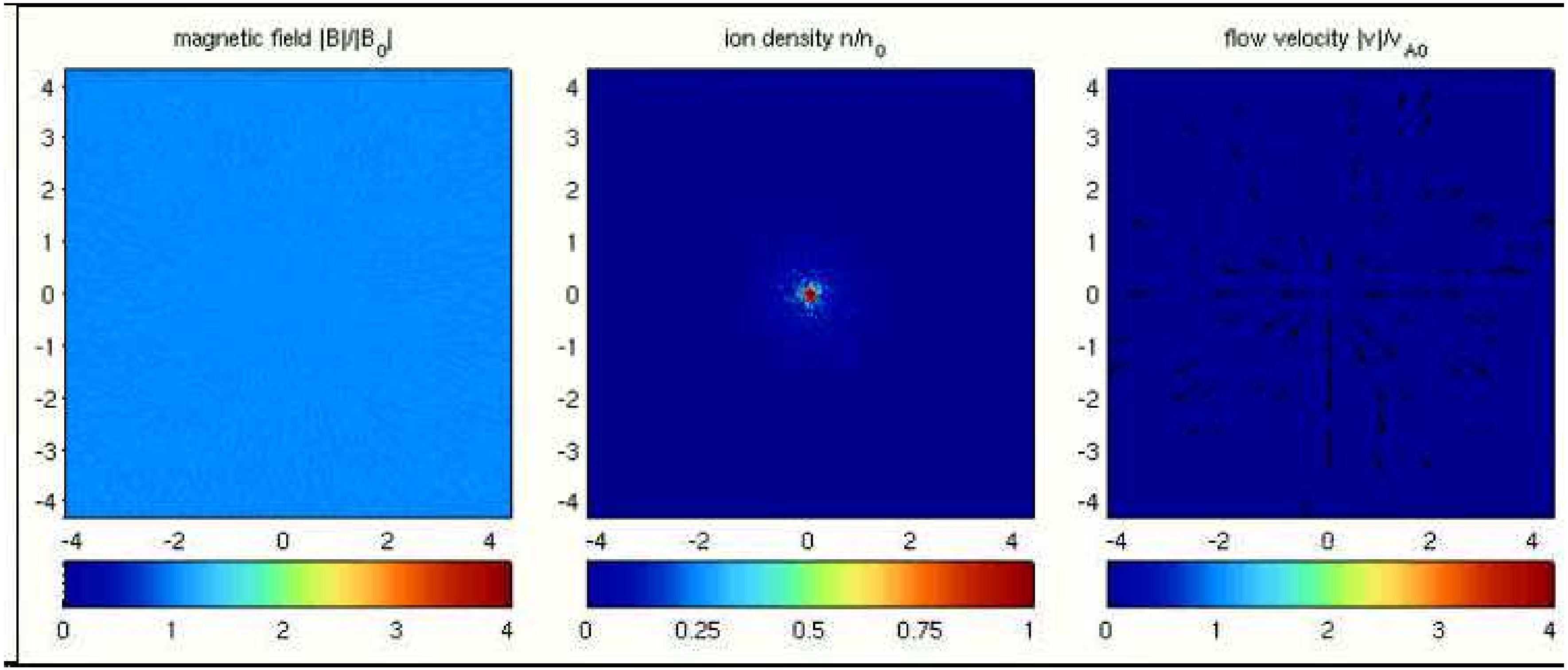
$x_0 = 220km$





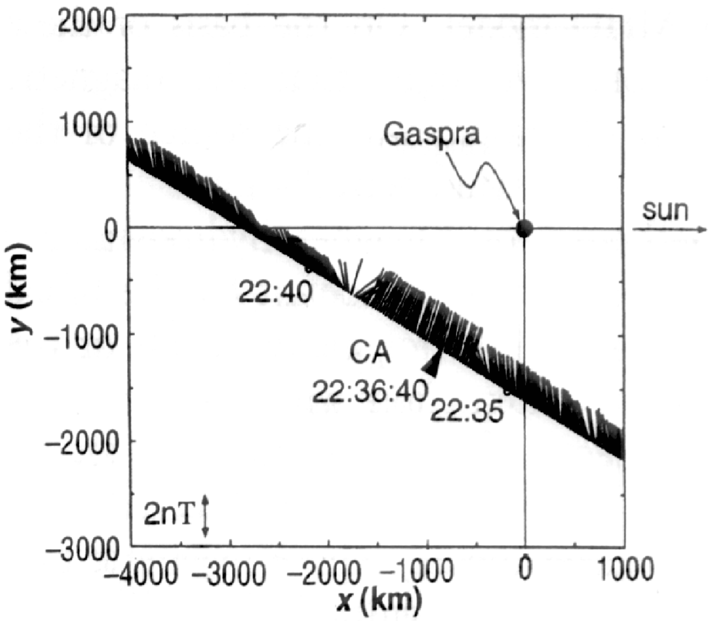
[Bagdonat et al, The new Rosetta Target, 2004]

Evolution of CG at 2.5AU



Simulation of a Magnetized Asteroid

1991: *Galileo* flyby of asteroid *Gaspra*

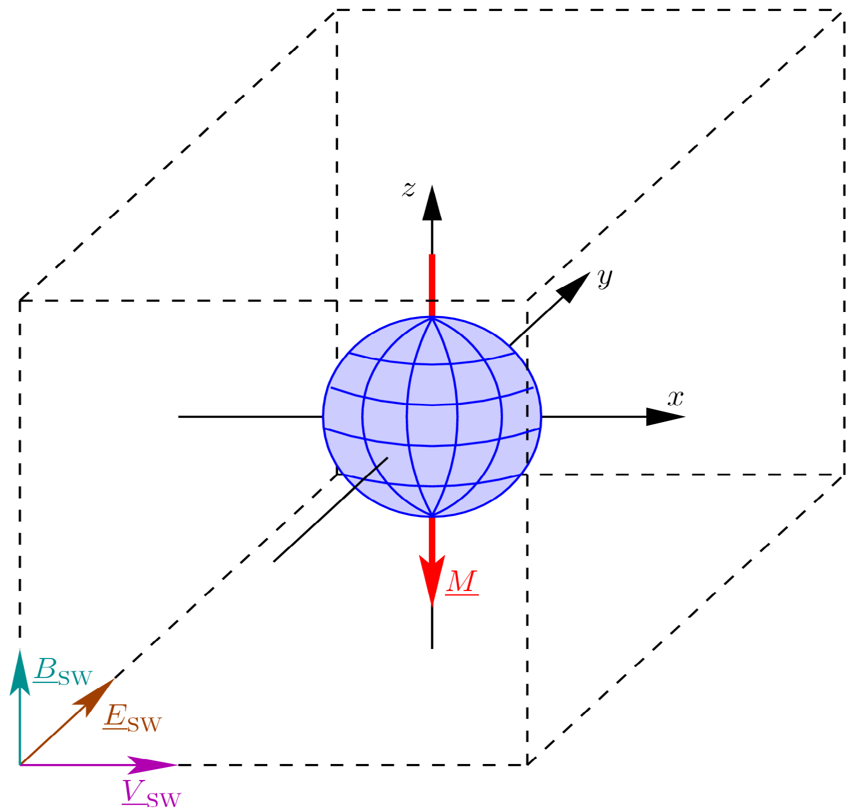


[Kivelson et al, Science, 1993]

2008: *Rosetta* flyby of asteroid *2867 Steins* (scheduled)

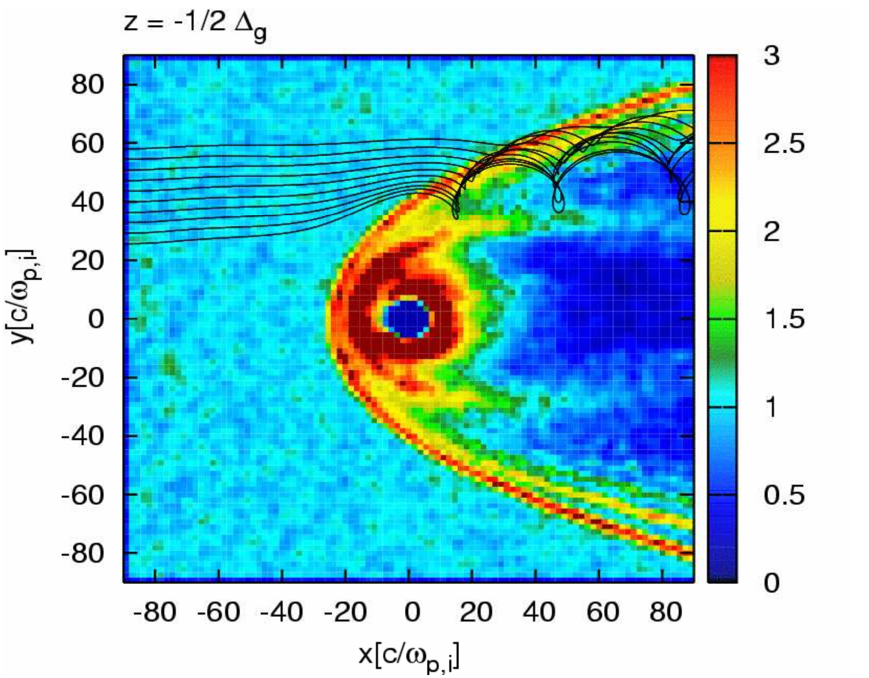
2010: *Rosetta* flyby of asteroid *21 Lutetia* (scheduled)

Simulation Frame

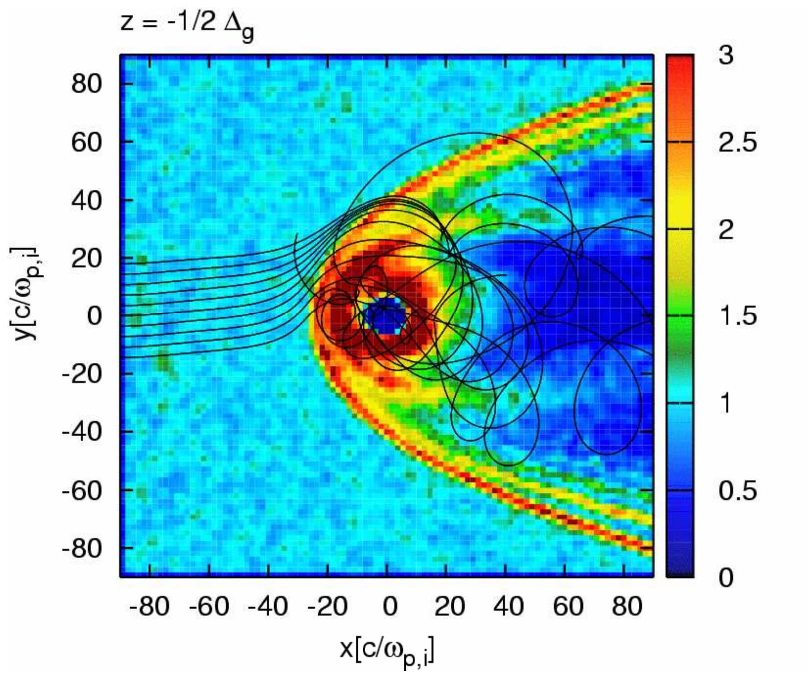


Magnetized Asteroid

Substructure of the boundary layer



Ring of trapped particles around the obstacle



$\underline{M} \parallel -\underline{e}_z$, & $\underline{B}_{SW} \parallel \underline{e}_z$

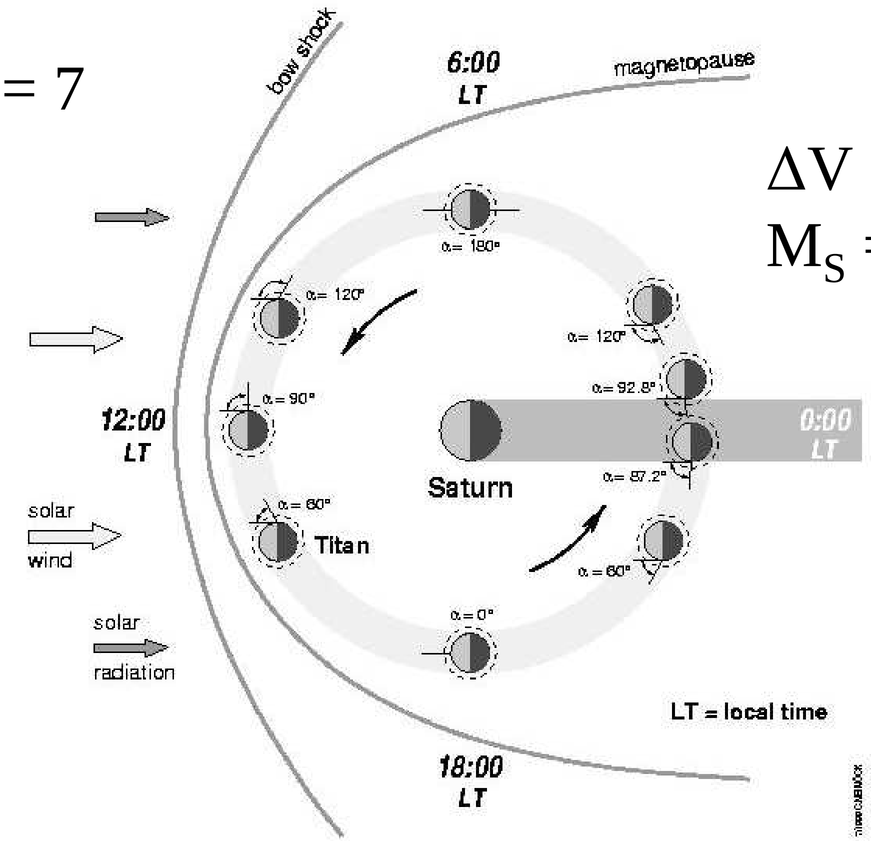
[Simon et al, DPG, 2005]

Titan at Saturn

$M_S = 7$

$\Delta V = 120$ km/s
$M_S = 0.57$

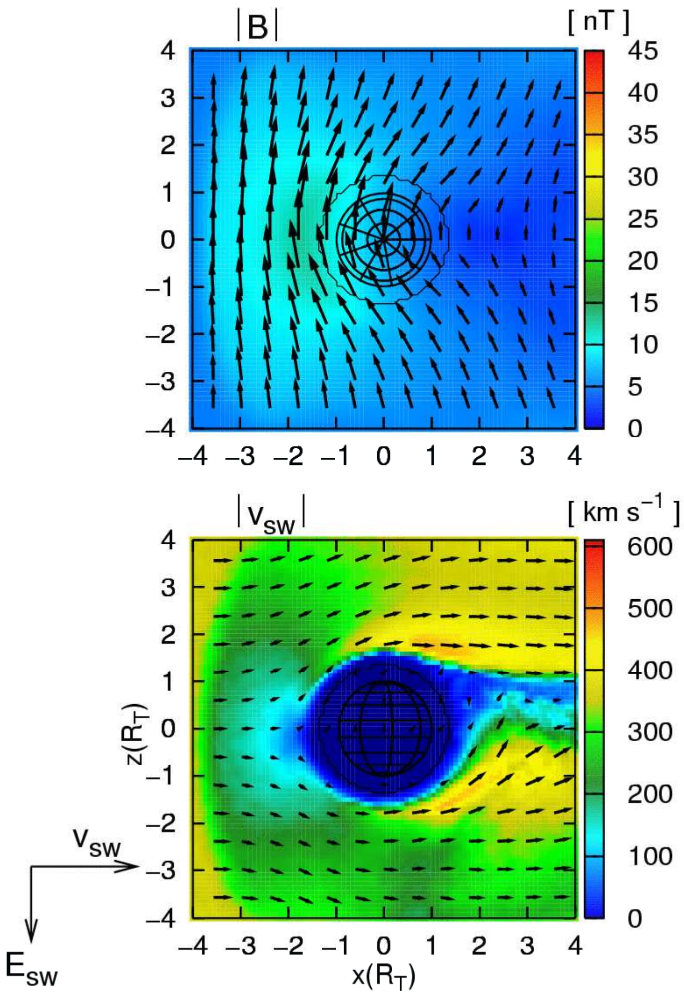
Standoff: 25 R_S
Orbit: 20 R_S

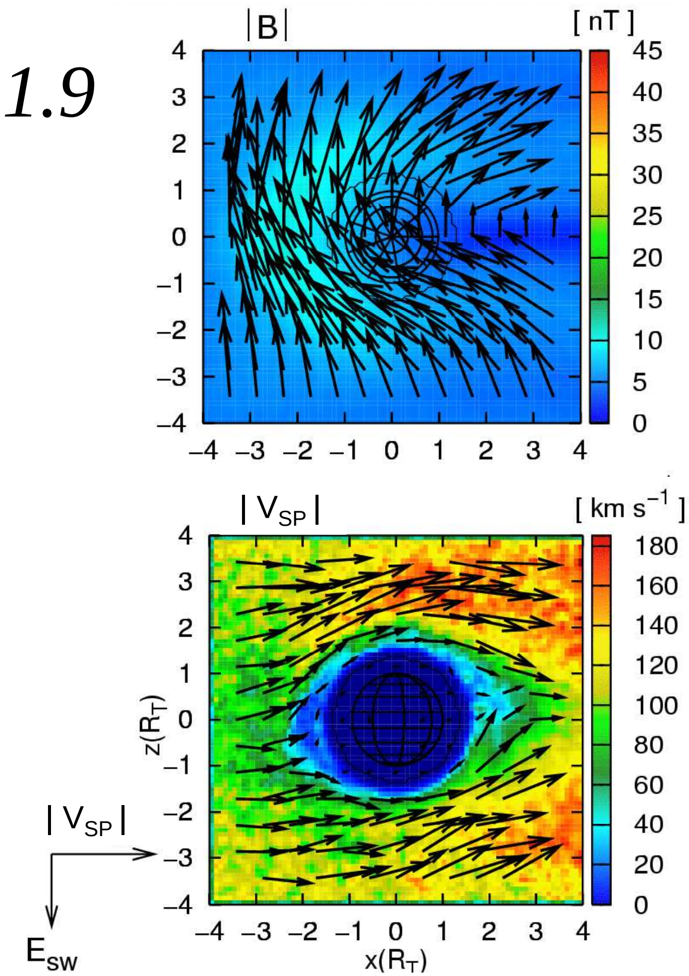


[http://www.uni-koeln.de]

Titan in SW (M_S = 7) *Titan in MS (M_S = 0.57)*

$M_A = 1.9$

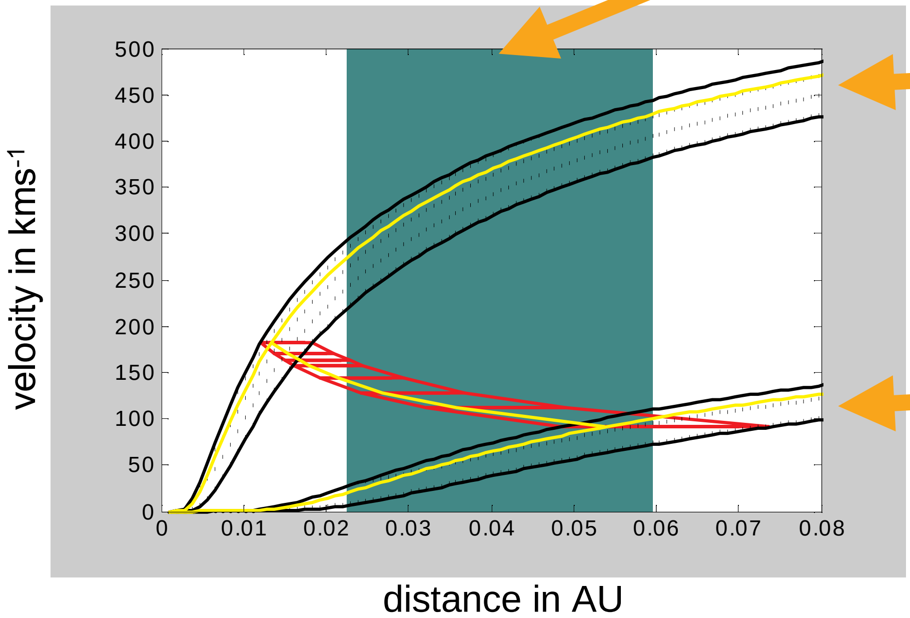




Extrasolar Planet in Stellar Wind

Stellar Wind Model:
[Weber&Davis, ApJ, 1967]

Planetary orbits



T=2.0 10^6 K

T=0.5 10^6 K

Velocities much lower with respect to 1 AU

Planets may be located within Alfvén radius

[Preusse et al, A&A, 2005]
[Lipatov et al, PSS, 2005]

Summary

- Weak obstacles: d <~ r_g
- Hybrid code is appropriate technique
- Successful application to Mars, CG, Titan, asteroids
- Mars: BS, ICB/MPB reproduced and interpreted
- CG: „classical“ boundaries emerge and separate at about 2.8AU, pronounced ion kinetic behaviour, distribution functions strongly non-thermal
- Titan: subsonic flow in MS, Mars-like in SW
- Asteroid: „quasi-magnetospheric“ structures
- Exoplanets: located in Alfven radius