Simulation of solar system plasma environments

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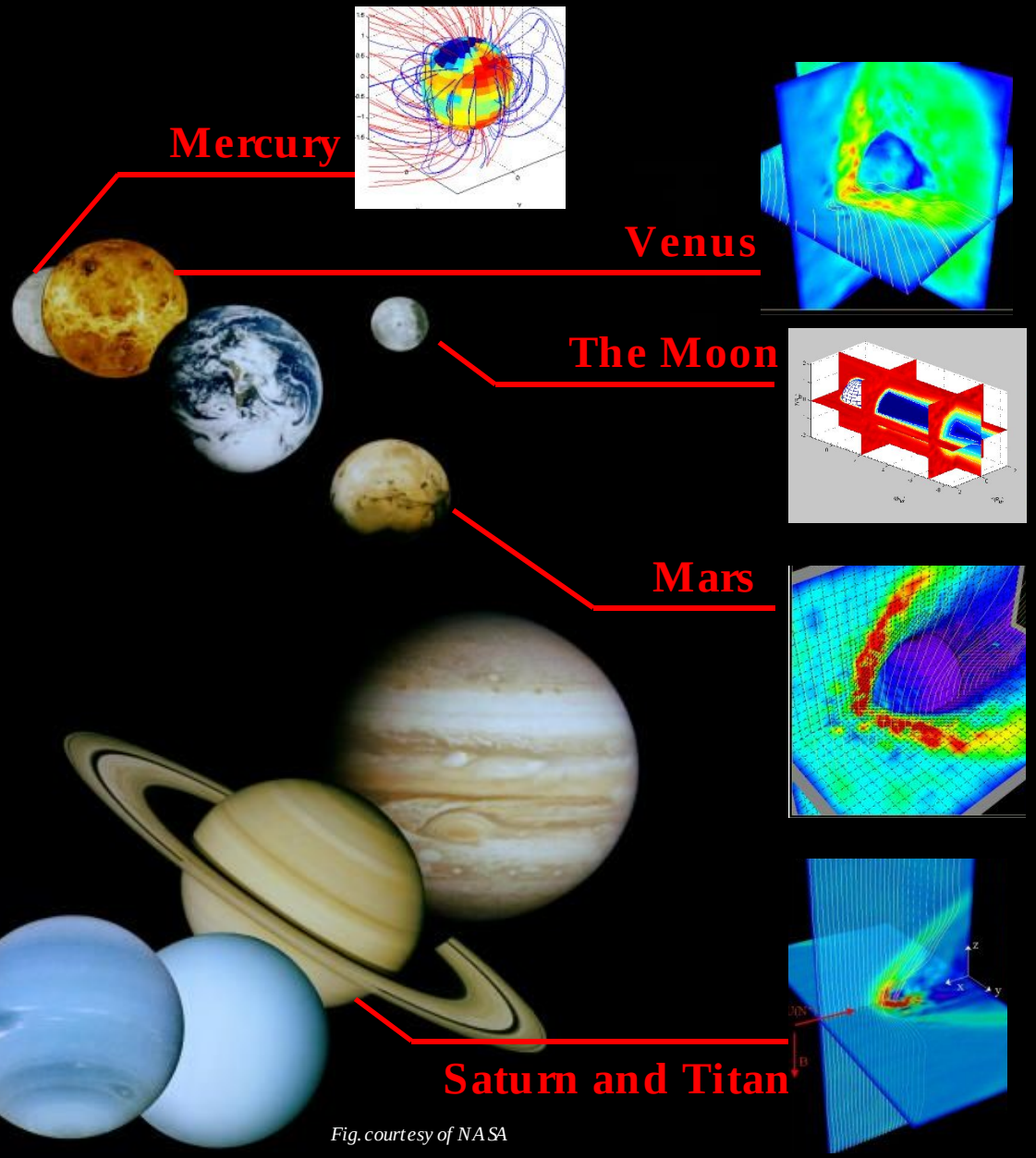
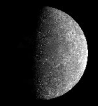


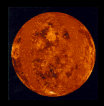
Fig. courtesy of NASA

Introduction

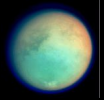
- **Question: How flowing plasma interacts with**


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

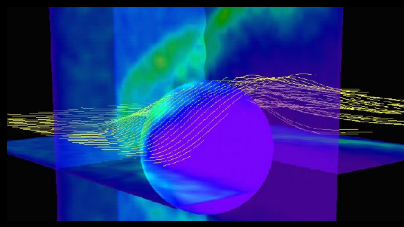

Mercury : Intrinsic B, *no atmosphere*


Venus : *no intrinsic B*, atmosphere


Mars : *no intrinsic B*, atmosphere

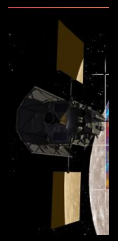

Titan : *no intrinsic B*, atmosphere

- **Tool: Global Quasi-Neutral Hybrid model**



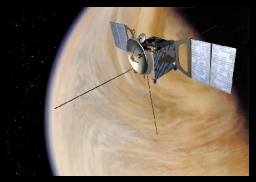
- **Concluding remarks**

New missions, New data

BepiColombo **Arrival: ~ 2014**

Messenger **Arrival: 2008(flyby), 2011**

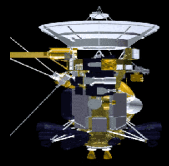


Venus Express **Arrived: April 2006**

Smart-1 **2005 ->**

***Chandrayaan-1*,…**

Mars Express **Arrived Dec. 2003**

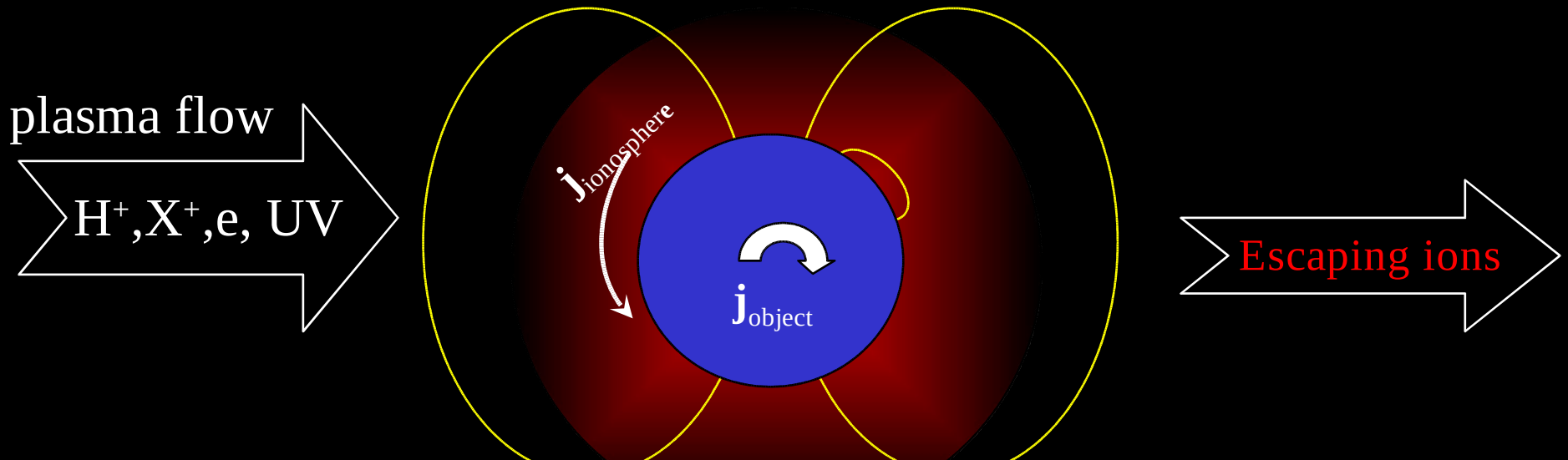


Cassini/Huygens **Arrived: 2004**

Flowing plasma - solar system body interaction

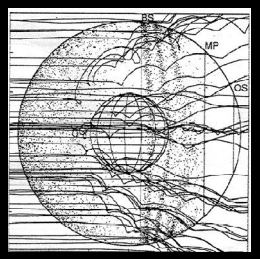
Components

Space:	**Source (photons, charged particles, E)**
	Sink (planetary ions and neutrals)
Intrinsic magnetic field:	**Dipole/magnetic anomalies?**
Atmosphere:	**ions, ionosphere, ionospheric currents?**
Interior:	**Conductor/insulator ?**

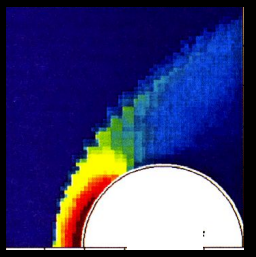


Global simulations

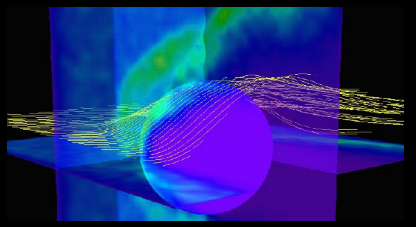
- Test particle simulations
  - Given **E** and **B** => not self-consistent



- Fluid models
  - Gas dynamic (GD) models [not self-consistent]
  - 1-D, 2-D, 3-D single/ multifluid MHD models:
    + self-consistent
    - assumes Maxwellian f(**v**), **U**(X^+) = **U**(Y^+)



- Quasi-neutral hybrid models
  + self-consistent, finite gyro effects included
  - computationally expensive



Quasi-Neutral Hybrid (QNH) model

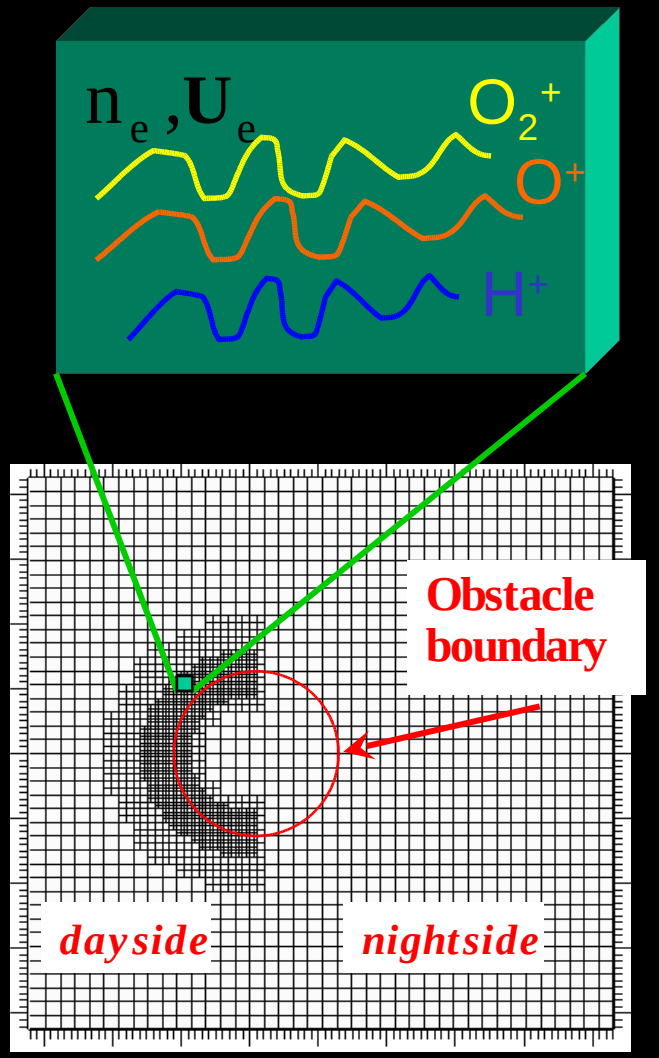
- Quasineutrality: $n_{electron} = \Sigma n_{ion}$
- Hybrid: H^+, O^+, O_2^+ etc. ions are *particles*, Electrons form a massless *fluid*
- Self-consistent model
- Dynamics:
  - Ions are accelerated by the Lorentz force
  - **B** propagated by the Faraday's law

- Hierarchically refined cubic grid *An example of the grid*
- Ion splitting and joining:

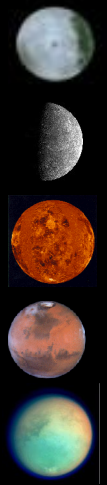
  splitting: **A** → $A_1 + A_2$

  joining: $\mathbf{B_1} + \mathbf{B_2} + \mathbf{B_3}$ → $B_1 + B_2$

  (note: conserves E and ***p****)*



QNH model family



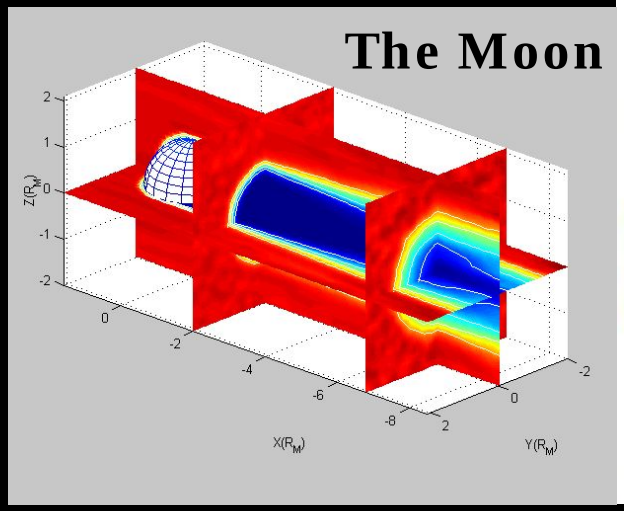
The Moon (Smart-1)

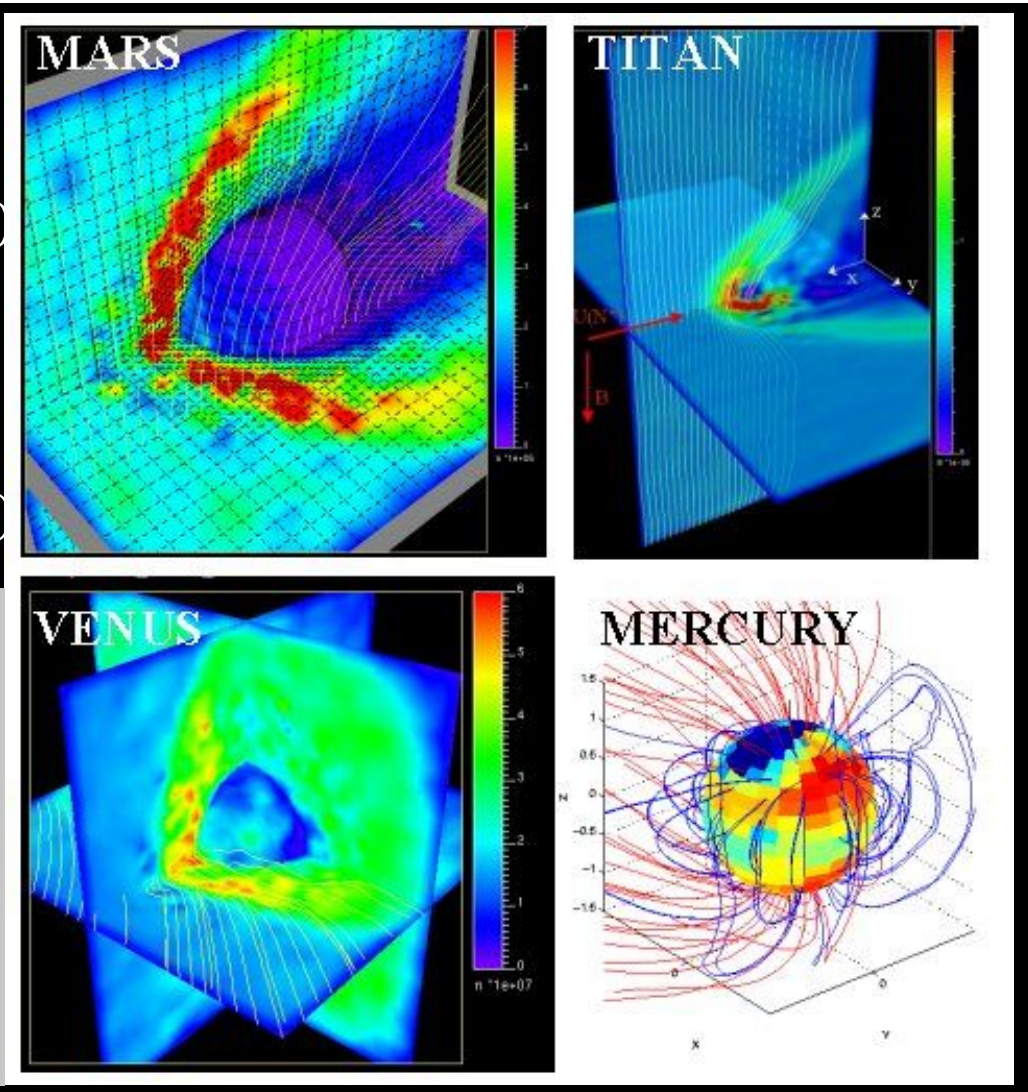
Mercury (BepiColombo)

Venus (Venus Express)

Mars (Mars Express)

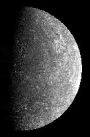
Titan (Cassini/ Huygens)





QNH model family (cont.)

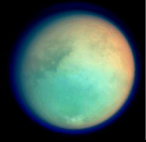
The Moon



Mercury

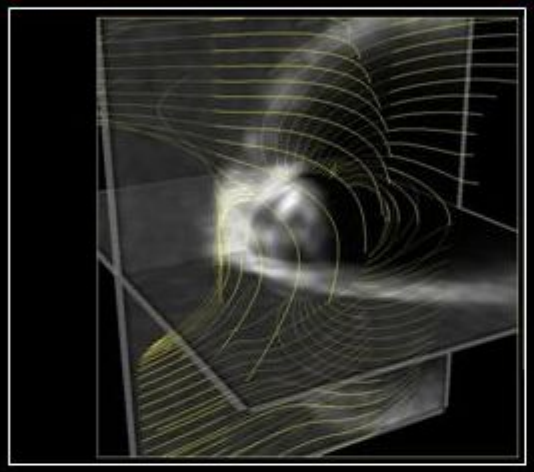
Venus

Mars

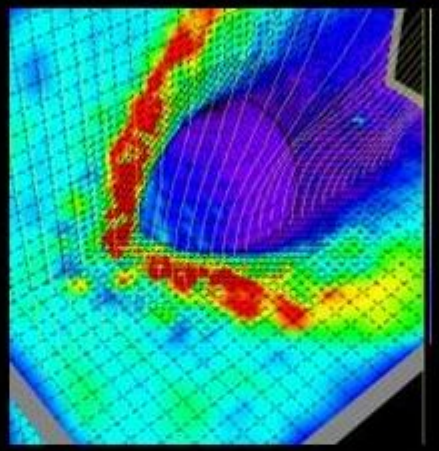


Titan

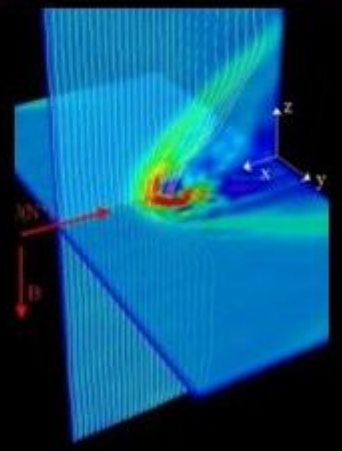
Exoplanet *(CoRoT, Kepler)*

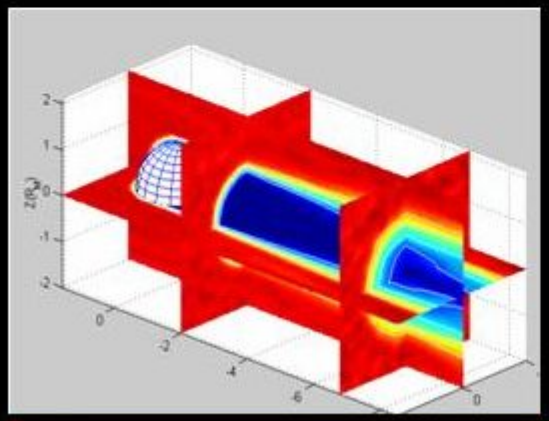


Mars *(Mars Express)*

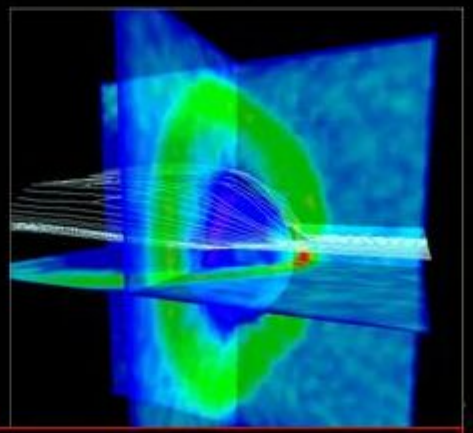


Titan *(Cassini/Huygens)*

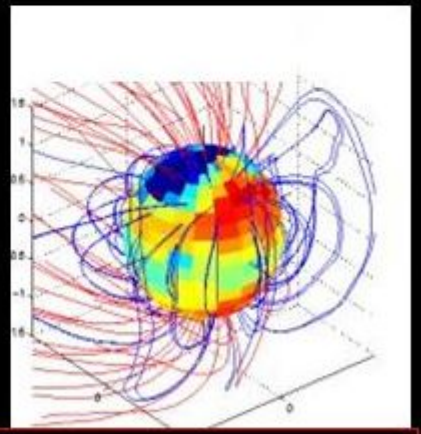




The Moon *(Smart-1)*



Venus *(Venus Express)*

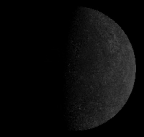


Mercury *(Bepi Colombo)*

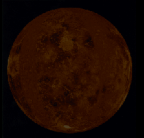
Kallio/2006

No global $B_{intrinsic}$ & no atmosphere: The Moon

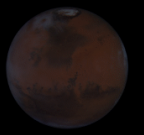
The Moon



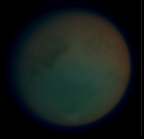
Mercury



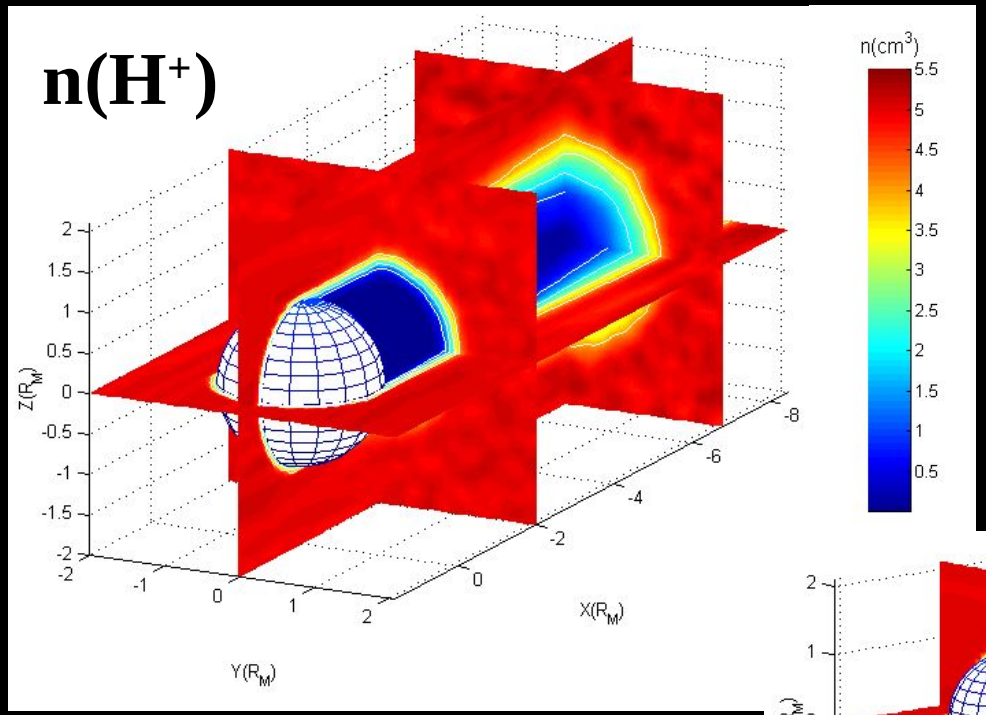
Venus



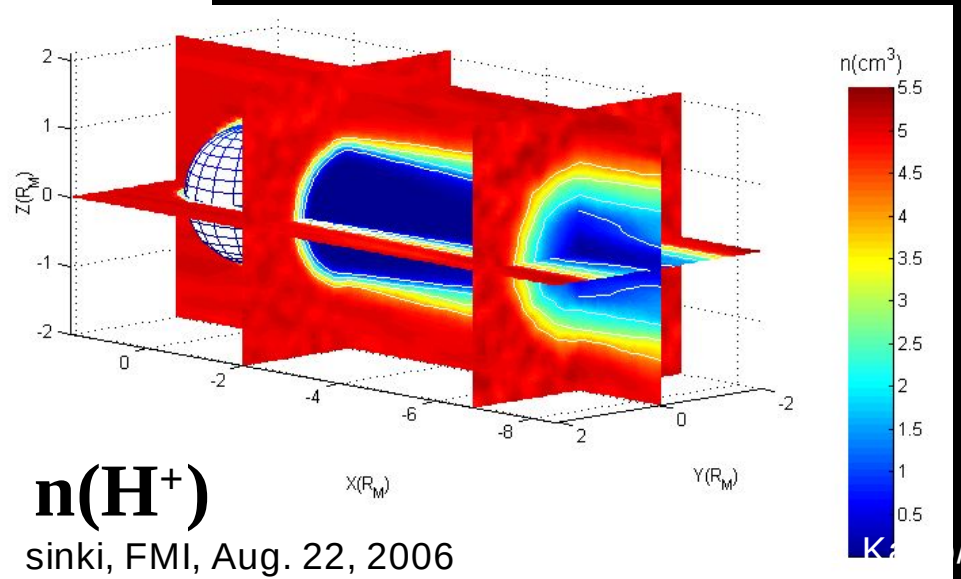
Mars



Titan



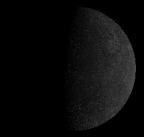
The Moon in the solar wind



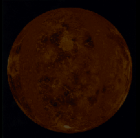
QNH model info
- **no atmosphere**
- **insulating object**
- **absorbing obstacle**

Lunar wake: Magnetic field

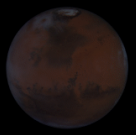
The Moon



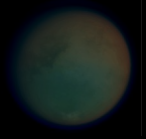
Mercury



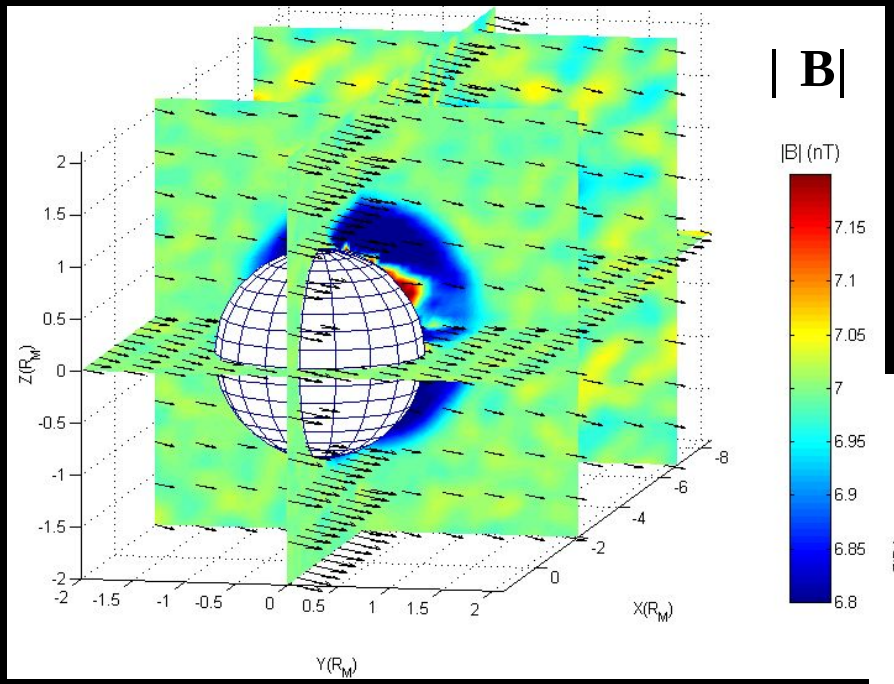
Venus



Mars

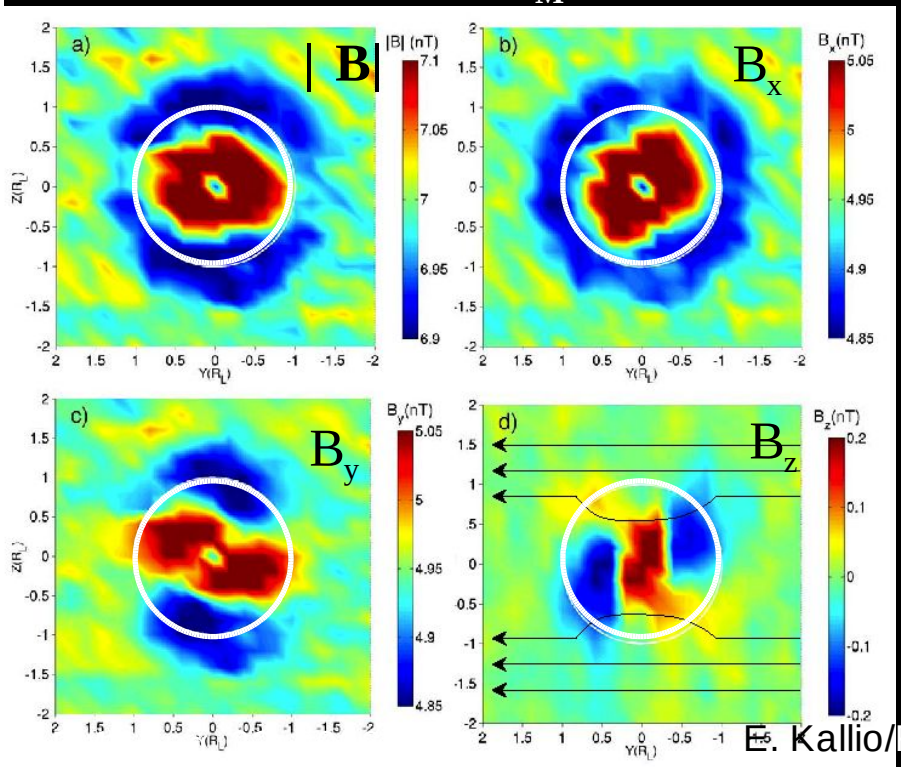


Titan



The Moon in the solar wind

X = -6.8 R_M



QNH model info:
- **no atmosphere**
- **insulating object**
- **absorbing obstacle**

Global $B_{intrinsic}$ & no atmosphere: Mercury

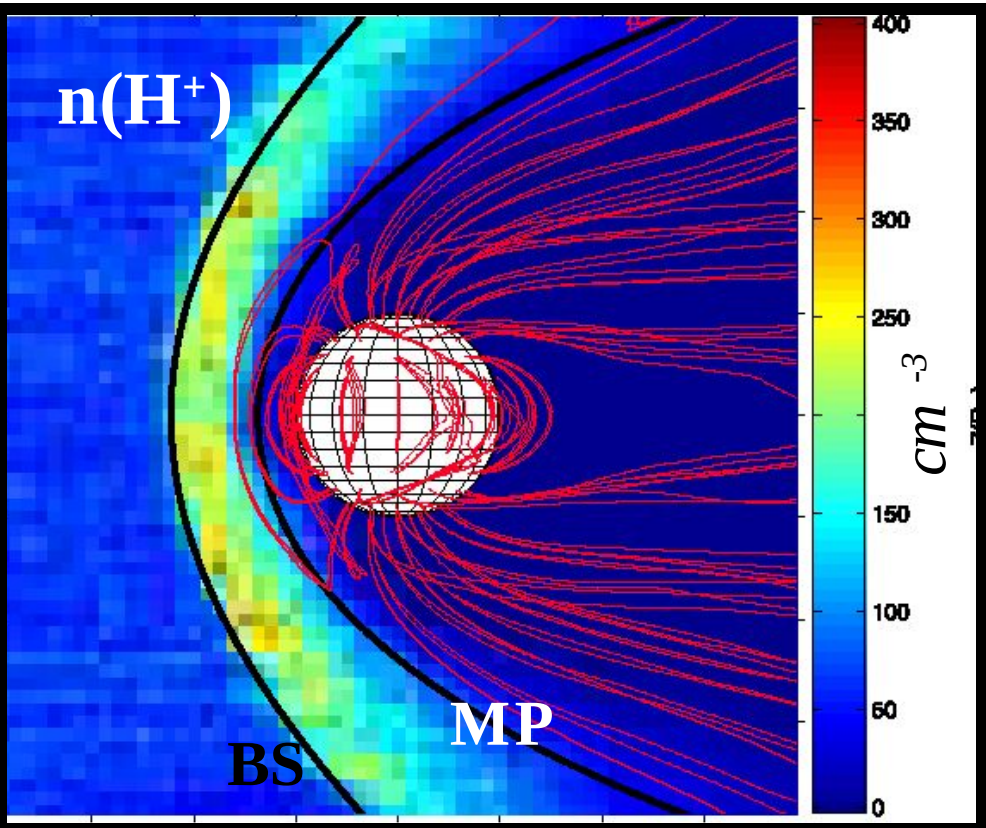
The Moon

Mercury

Venus

Mars

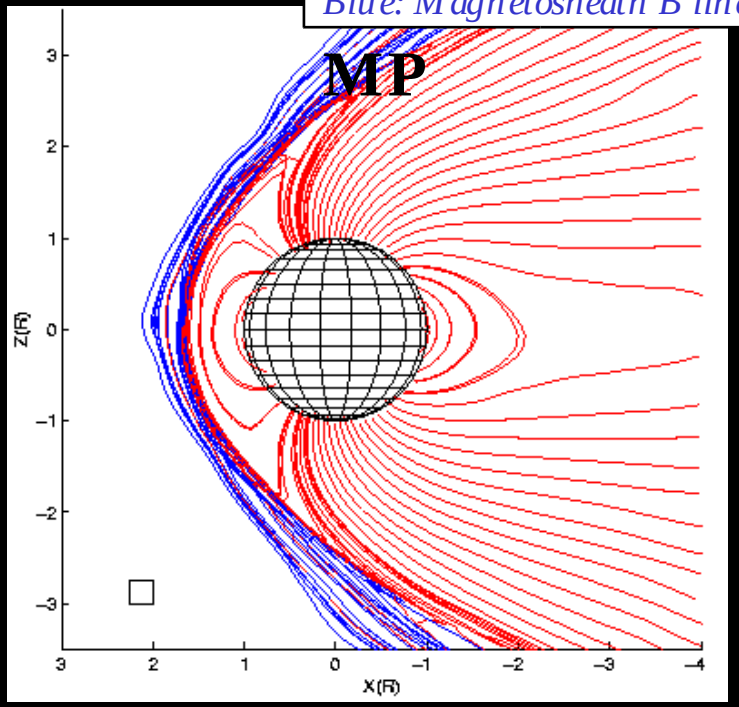
Titan



QNH model info:
- **both insulating and conducting objects tested**
- **absorbing obstacle**

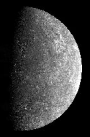
***IMF North**: Bsw = [0, 0, 10] nT;*
n_{sw} = 76 cm $^{-3}$ (~perihelion);
U_{sw} = 430 km s^{-1}
300 nT at the magnetic equator, no tilt

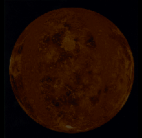
Red: Mercurybound B lines
Blue: Magnetosheath B lines

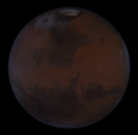


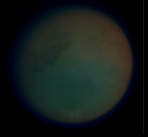
Particle flux of impacting H^+ ions


The Moon


Mercury


Venus


Mars

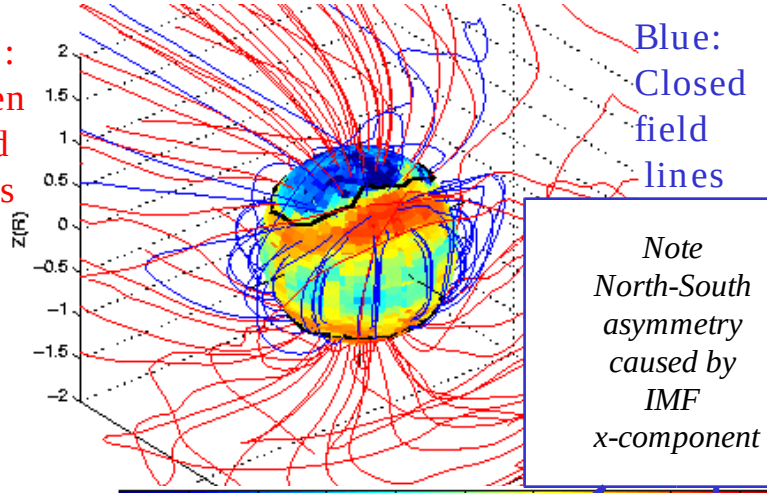

Titan

Parker-IMF: *Bsw = [32, 10, 0] nT*

Red: Open field lines

Blue: Closed field lines

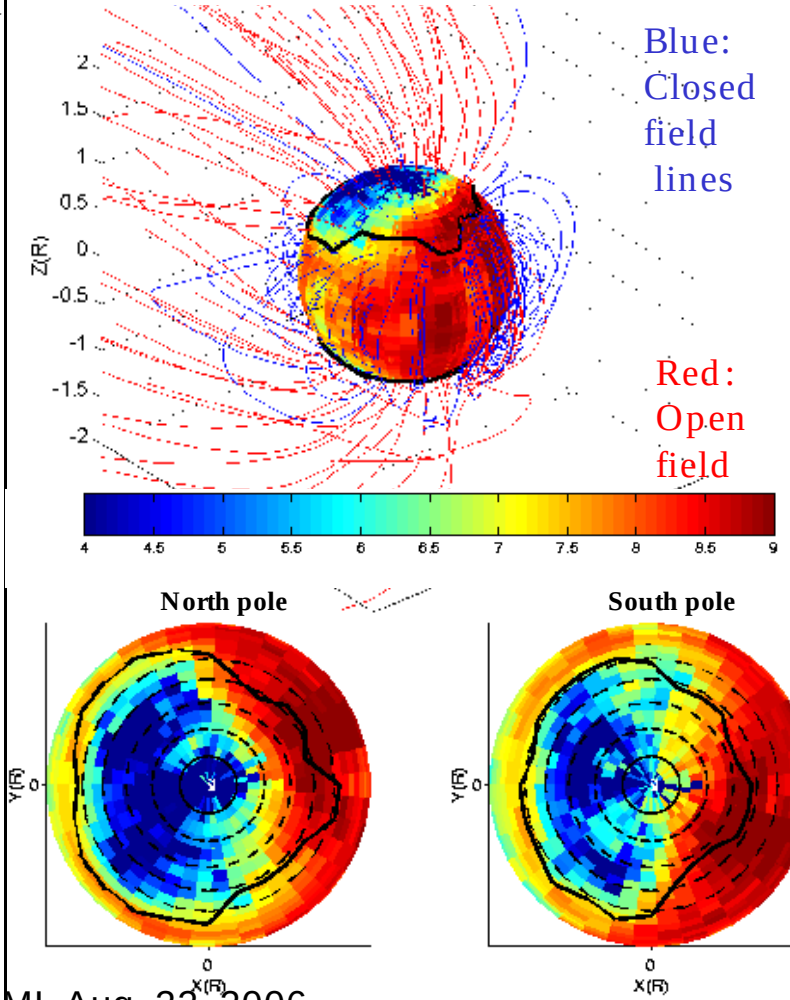
Note North-South asymmetry caused by IMF x-component



High Speed (*Vsw = 860 km/s, IMF*

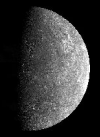
Blue: Closed field lines

Red: Open field

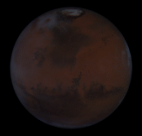


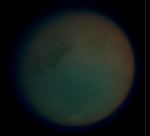
"Region-1 field-aligned currents"


The Moon

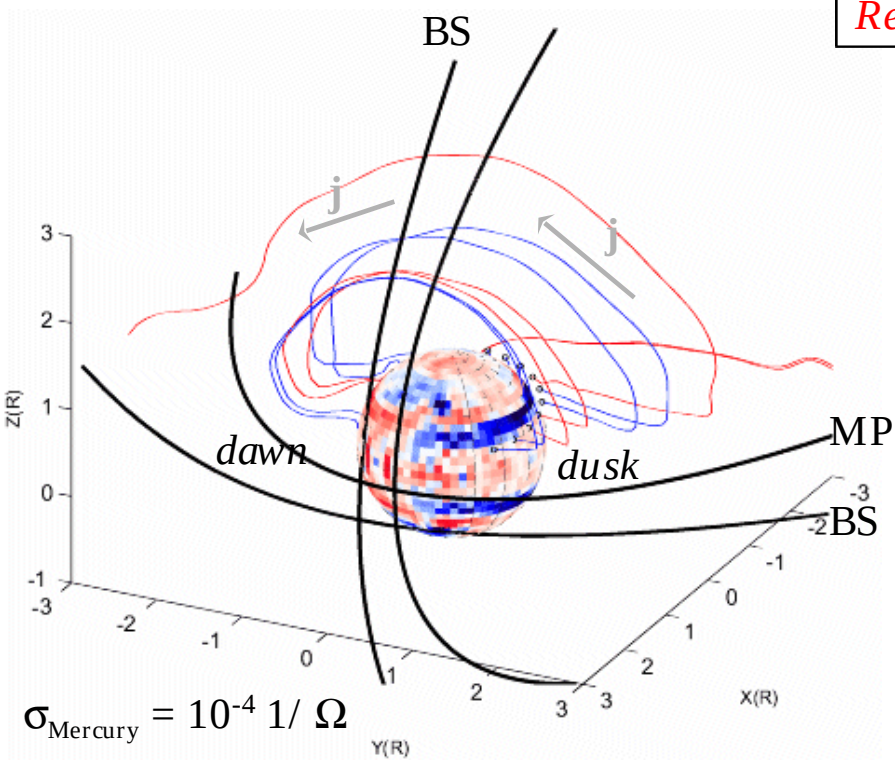

Mercury

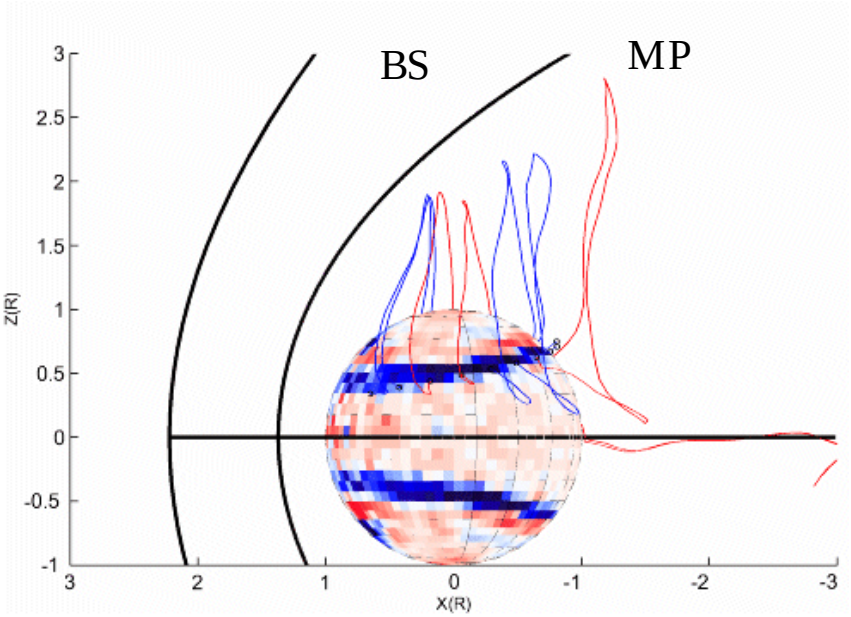

Venus


Mars


Titan

Blue line: *Current returns to the surface*
Red line: *Current does not return to the surface*





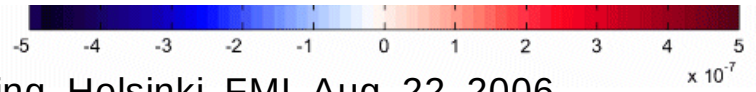
$\sigma_{Mercury} = 10^{-4}$ 1/ Ω m

Surface color map

$\mathbf{j} \cdot (-\bar{\mathbf{n}}^{\circ})$ *[A/m2]*

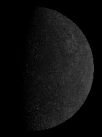
Blue color:
j *away the planet*

Red color:
j *toward the planet*

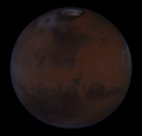


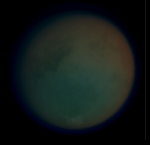
No global $B_{intrinsic}$ & atmosphere (I): Venus

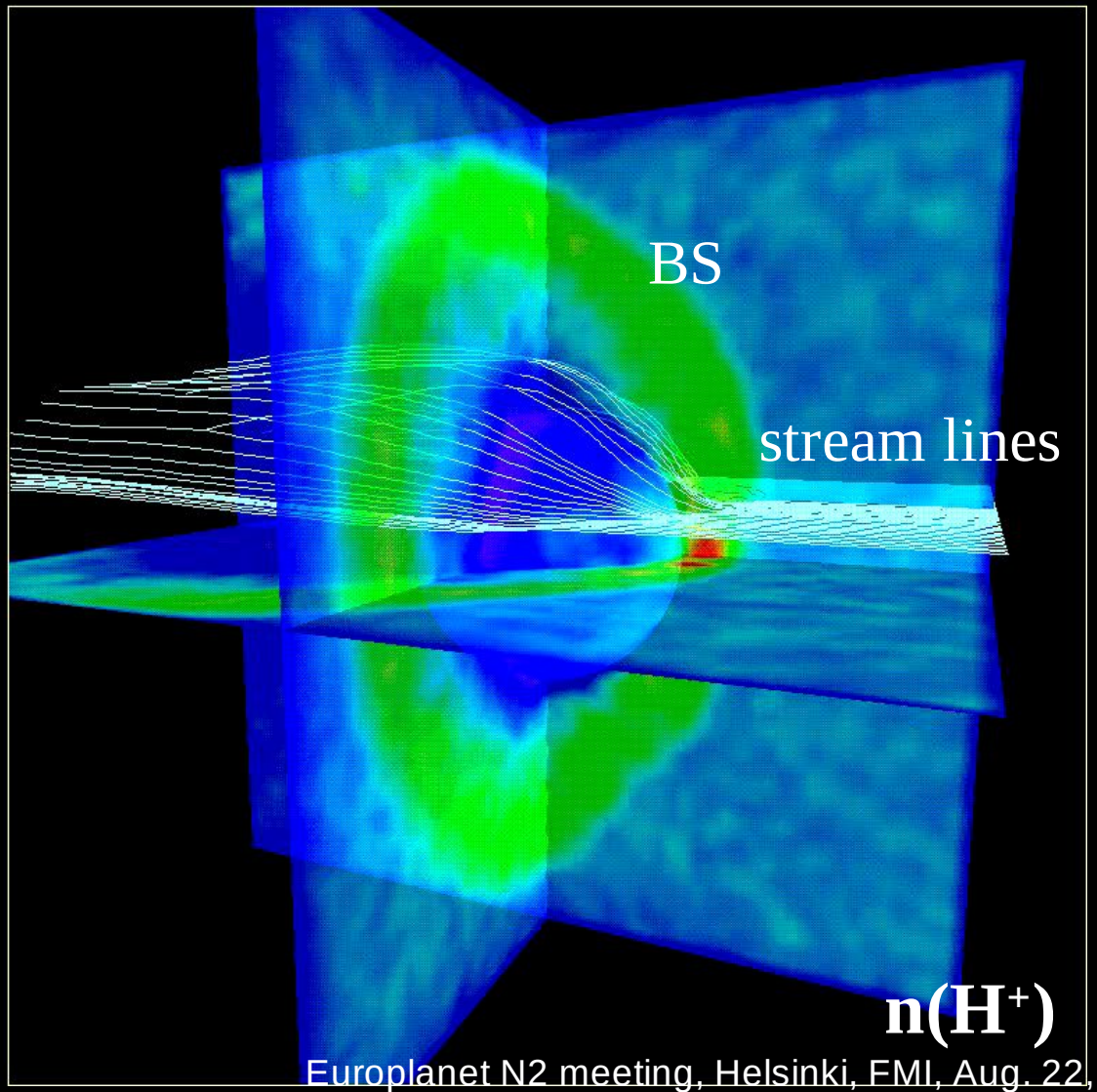

The Moon


Mercury


Venus

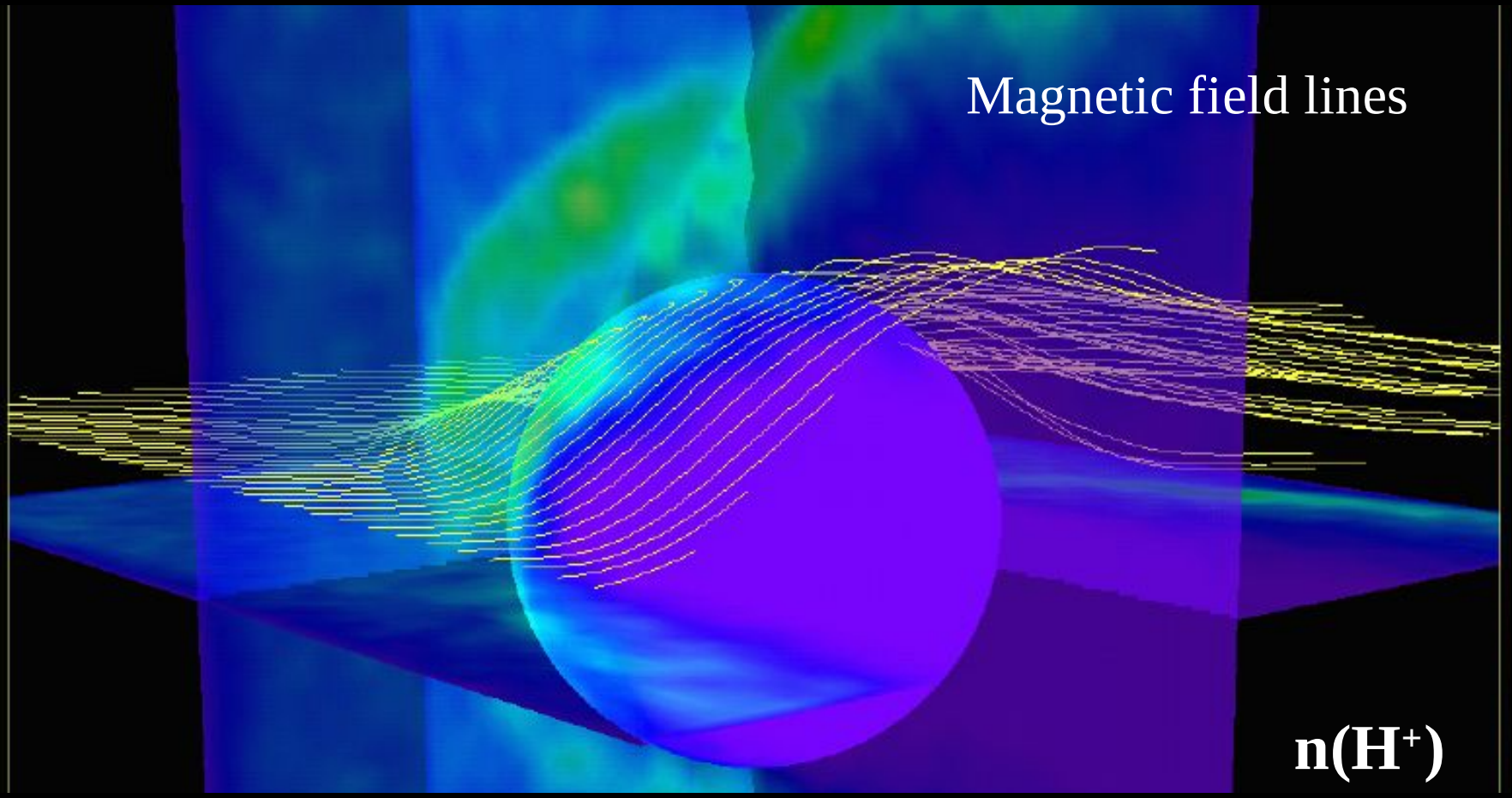

Mars


Titan



QNH model info:
- **an atmosphere**
- **Infinite conductivity within the obstacle**
- **absorbing obstacle**

Magnetic field lines



The Moon

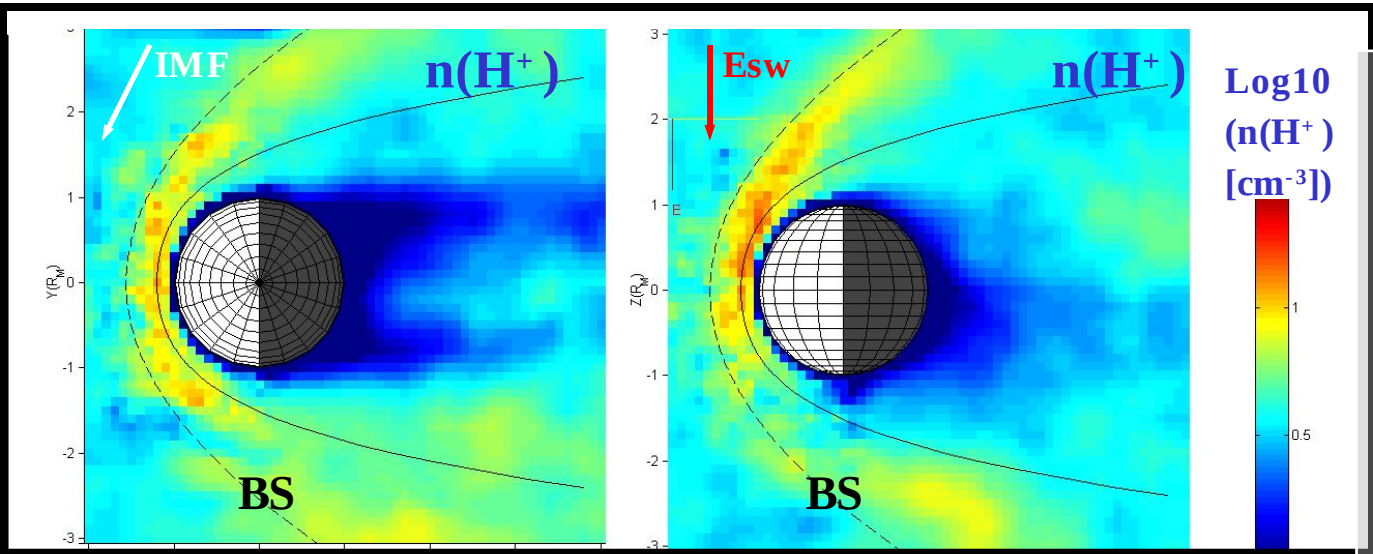
Mercury

Venus

Mars

Titan

Escaping planetary ions



QNH model info:
- **an atmosphere**
- **Infinite conductivity within the obstacle**
- **absorbing obstacle**
- **no magnetic anomalies**

• Three ion species:
H^+ (from SW and H corona)
O^+ (from O corona)
O_2^+ (from exopause)

• Upstream parameters:
n_{sw} = 3 cm^{-3}
U_{sw} = [-450, 0, 0] km/ s
IMF = [cos(55°), -sin(55°), 0]nT

The Moon

Mercury

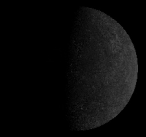
Venus

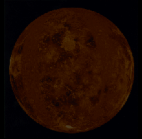
Mars

Titan

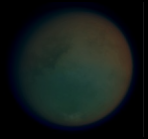
Magnetic field lines (I)

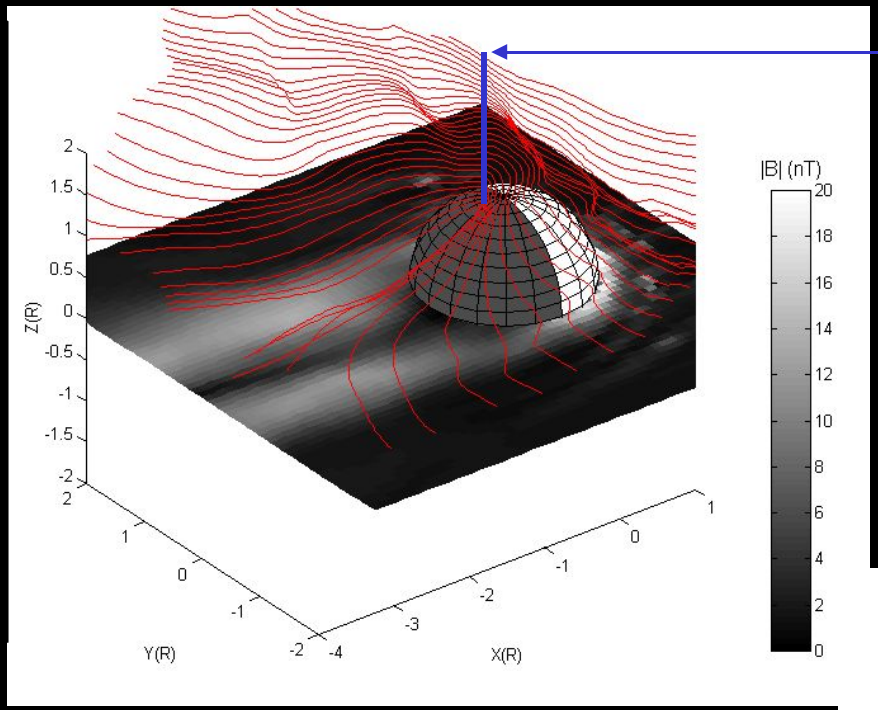

The Moon


Mercury

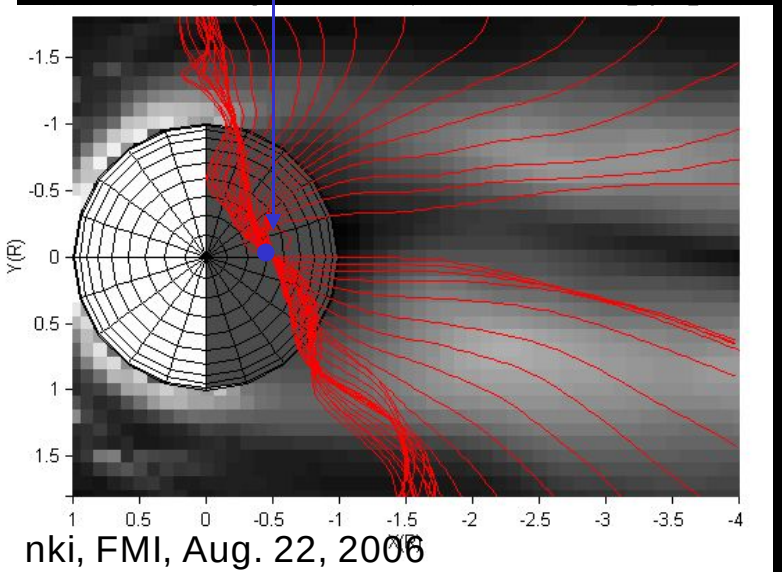

Venus


Mars


Titan

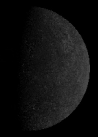


Magnetic field lines connected to the line between the points (-0.5, 0, 1) R_M and (-0.5, 0, 3) R_M

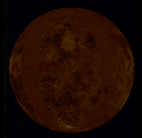


QNH model and data analysis (I): MEX

The Moon

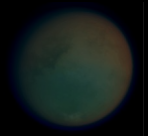


Mercury



Venus

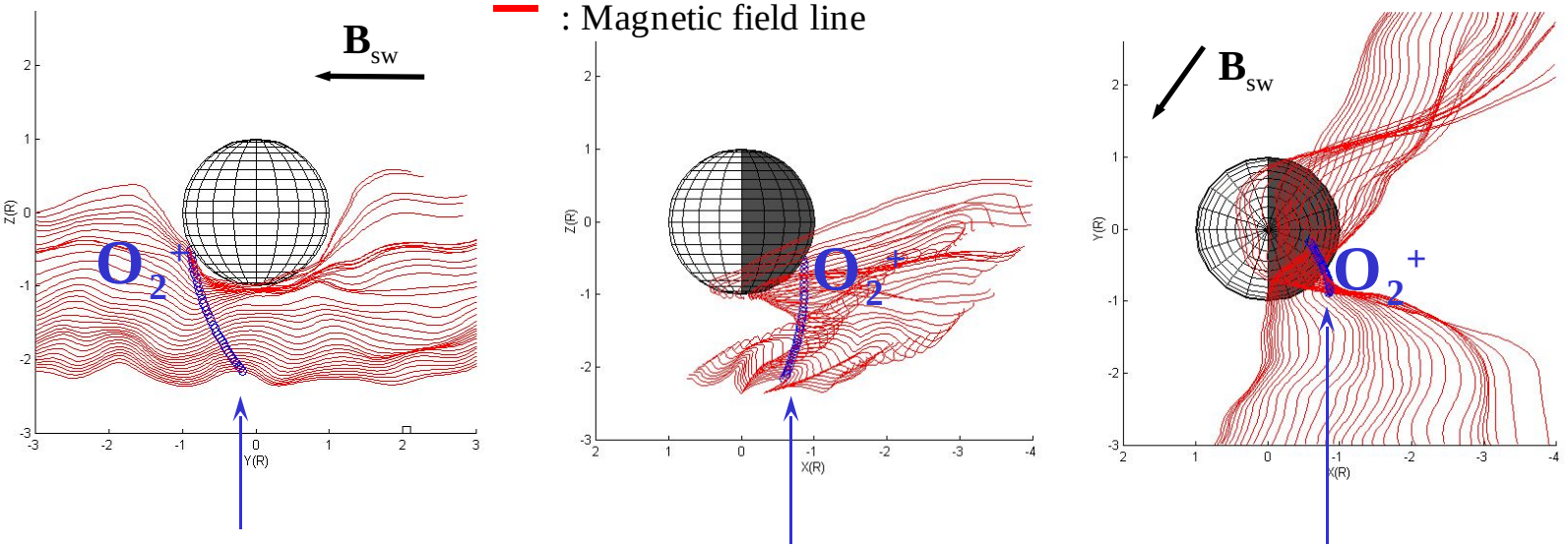
Mars



Titan

O: Starting point of the field line tracing

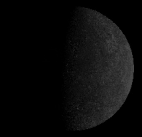
: Magnetic field line

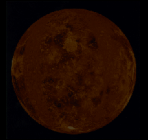


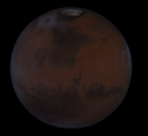
Orbit of Mars Express when it observed escaping planetary ions

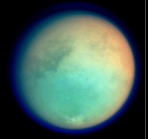
No global $B_{intrinsic}$ & atmosphere (III): Titan


The Moon

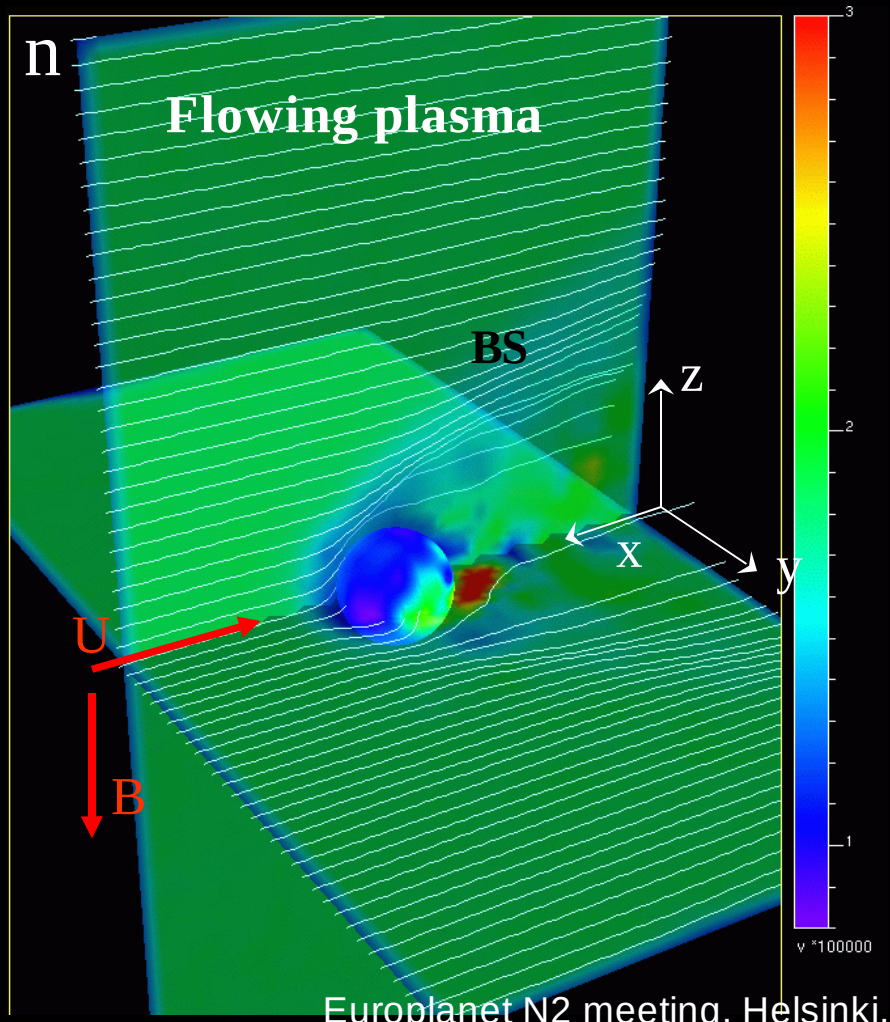

Mercury

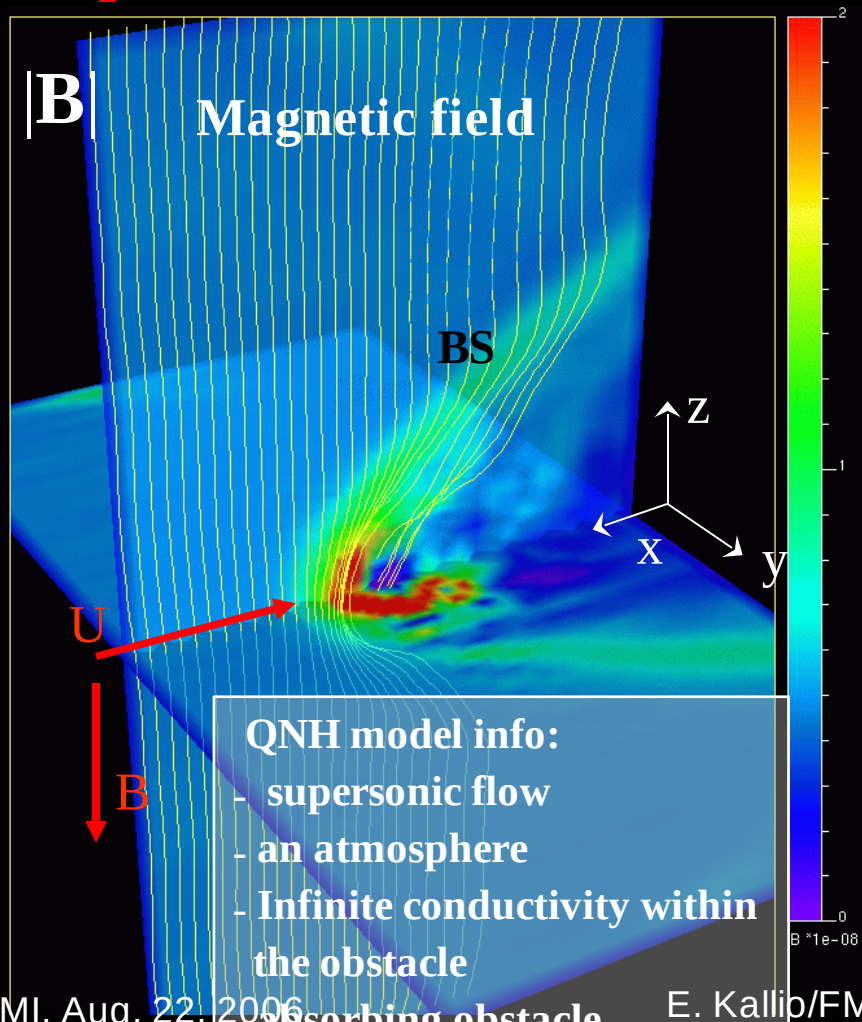

Venus


Mars


Titan

A test run: Titan in a supersonic flow

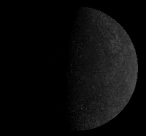




QNH model info:
- supersonic flow
- an atmosphere
- Infinite conductivity within the obstacle
- absorbing obstacle

Titan in a subsonic flow


The Moon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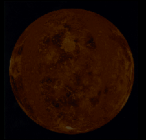
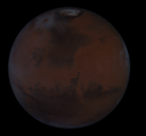
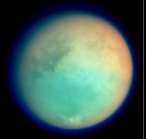
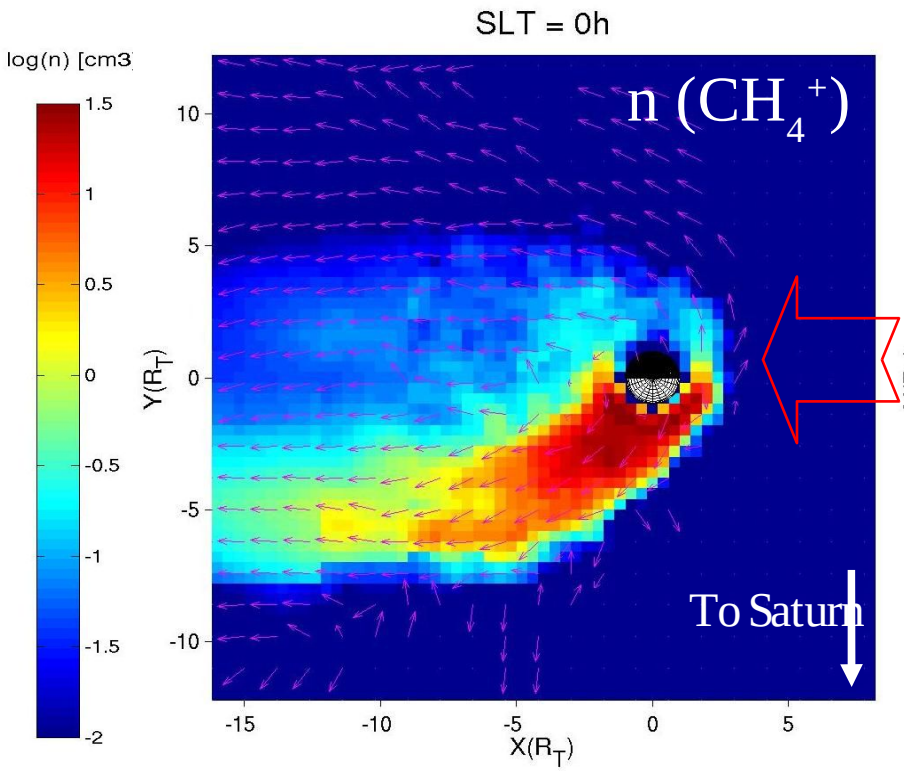
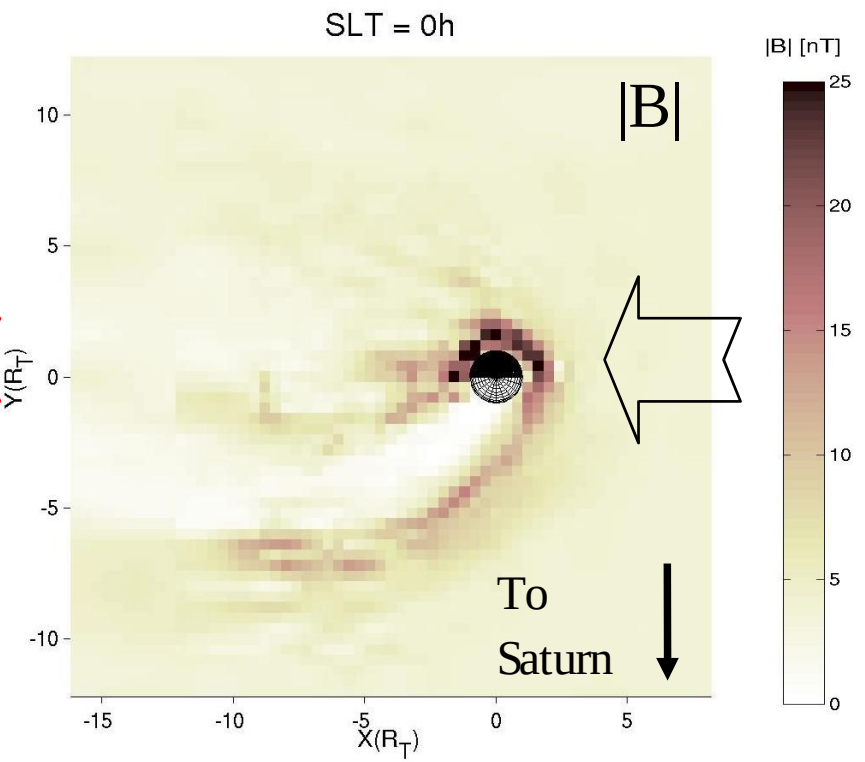

Venus


Mars


Titan



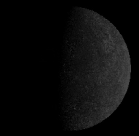


QNH model info:

- **subsonic flow; an atmosphere; infinite conductivity within the obstacle; absorbing obstacle**

QNH model and data analysis (II): Cassini


The Moon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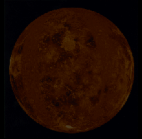
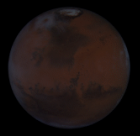

Venus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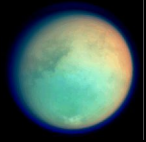
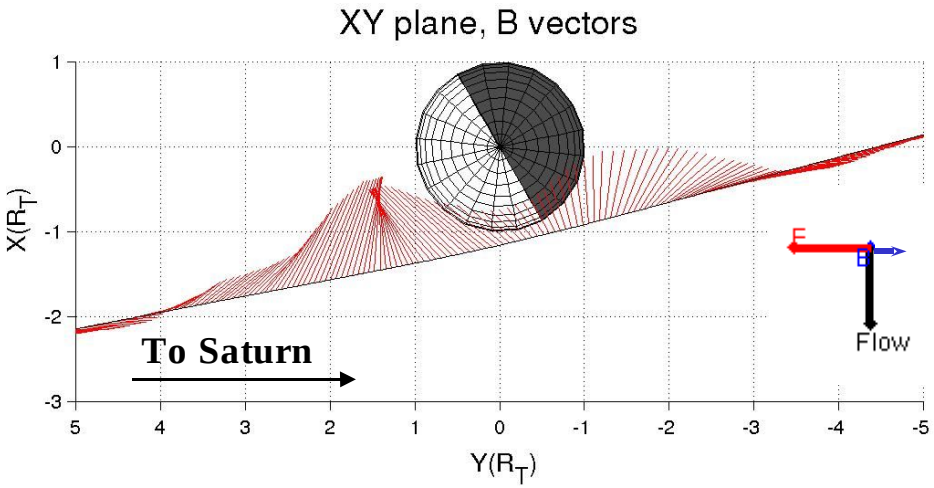
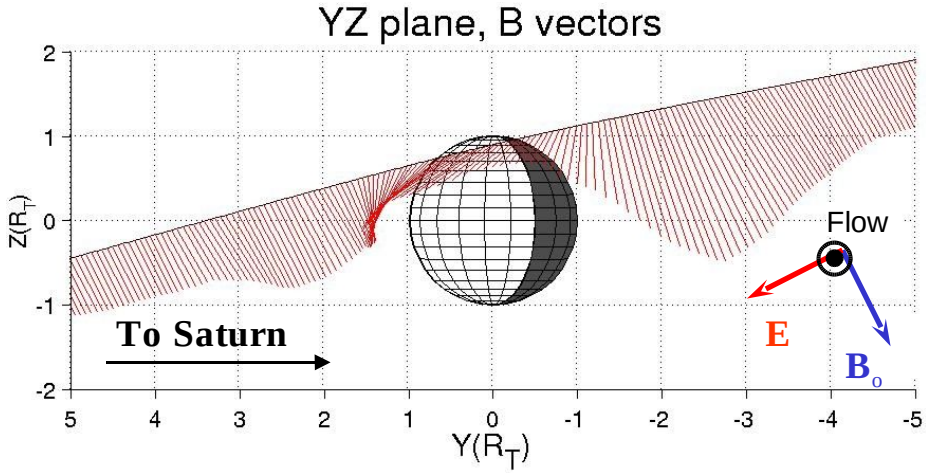
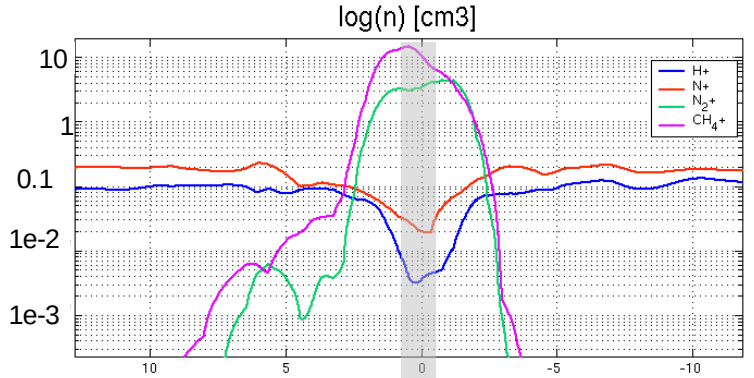
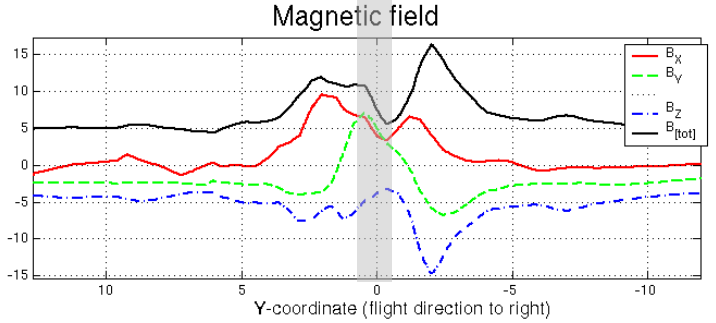

Titan





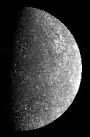
Cassini's flyby of Tita





Concluding remarks

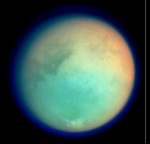
The Moon



Mercury

Venus

Mars



Titan

- **Solar System: various flowing plasma-object interactions:**
  - The Moon (*the "Moon-like" interaction*)
  - Mercury (*the "Earth-like" interaction"?*)
  - Venus, Mars, Titan (*the "Venus-like" interaction*)
  - *comets (the "comet-like" interaction)*
- **Global numerical simulations provide possibility to:**

  (I) Study the role of
  - the undisturbed plasma flow (SW/ magnetosphere)
  - the strength/ type of the intrinsic magnetic field
  - the exosphere/ atmosphere/ ionosphere
  - the electric properties of the object (conductivity)

  (II) Interpret new measurements in 3-D
  - MarsExpress, CassiniVenusExpress, BepiColombo,...