Hybrid modeling of the interaction between the solar wind and planets

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Outline

- A general model for the interaction between planets and the solar wind
- Applications
  - Effects of Lunar surface absorption
  - Lunar wake currents

Model features

- A general hybrid solver for plasmas has been developed (hybrid = fluid electrons and ions as particles)
- It is part of the public FLASH software from University of Chicago. Parallel, adaptive grid. We use cluster with 15456 cores at the High Performance Computing Center North (HPC2N) in Umeå, allowing for giga-particle simulations and fast running times (hours)
- The model handles time dependent simulations, arbitrary internal resistivity profiles (conducting core and mantle),
- Surface relected ions
- Arbitrary permanent magnetic fields can be handled (dipole, or magnetic anomalies
- Chapman ionospheric production

Hybrid field equations

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

$$\mathbf{E} = \frac{1}{\rho_I} \left(-\mathbf{J}_I \times \mathbf{B} + \mu_0^{-1} (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p_e \right) + \frac{\eta}{\mu_0} \nabla \times \mathbf{B}$$

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

Vaccum in a Hybrid Model

- Solution proposed in the 70's by Harned, and by Hewit:
  High resistivity in vacuum regions
  => solve Laplace equation
- Not so easy to solve Laplace on an irregular, time varying domain.
  Instead, Faraday's Law gives a diffusion equation

For large resistivities, η, Faraday's law approaches

$$\frac{dB}{dt} = -\frac{\eta}{\mu_0}\nabla \times (\nabla \times B) = \frac{\eta}{\mu_0}\nabla^2 B$$

which is a diffusion equation, similar to the heat equation, and gives a time step limit of

$$\Delta t < \frac{\mu_0 \Delta x^2}{2\eta}.$$

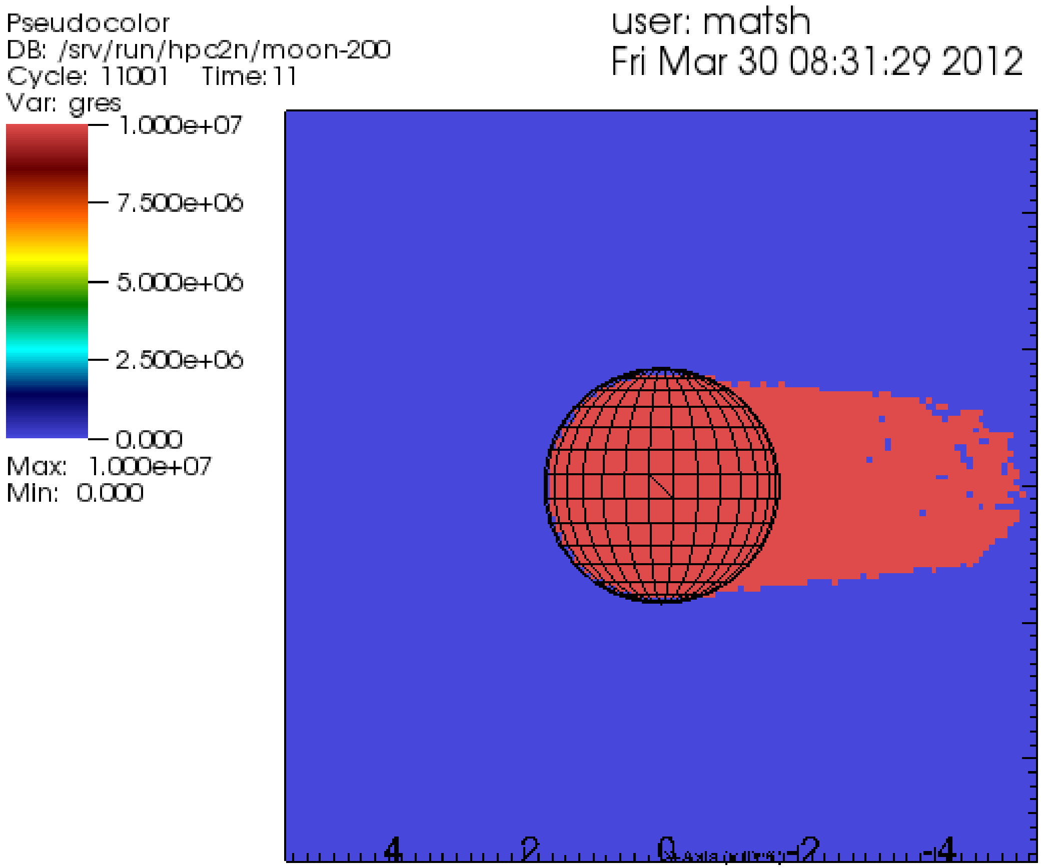
Thus, for large resistivities, if we increase η by 10, Δt needs to be decreased by 10 for stability.
We are really solving two different equations!

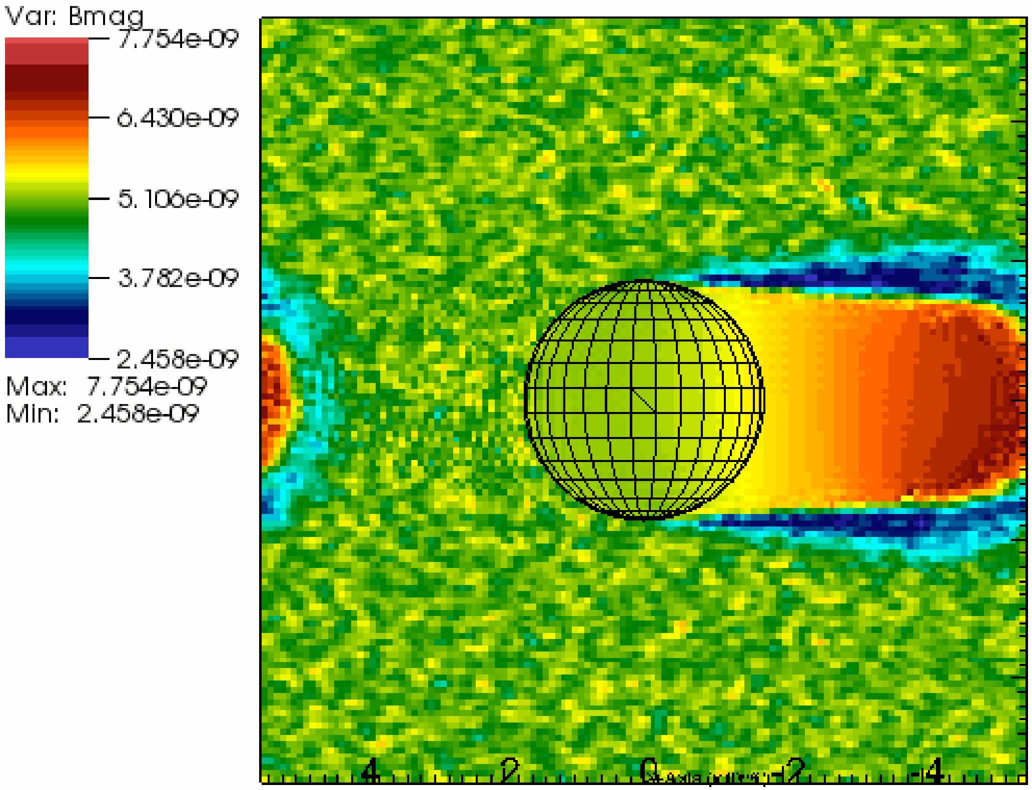
Resistivity implementation

- The logic is
  - if cden<cmin # in obstacle or vacuum
        cden_inv = 0
        if outside obstacle # vacuum
            res = res_vacuum

- We can have an arbitrary resistivity profile inside the obstacle

Vaccum resistivity





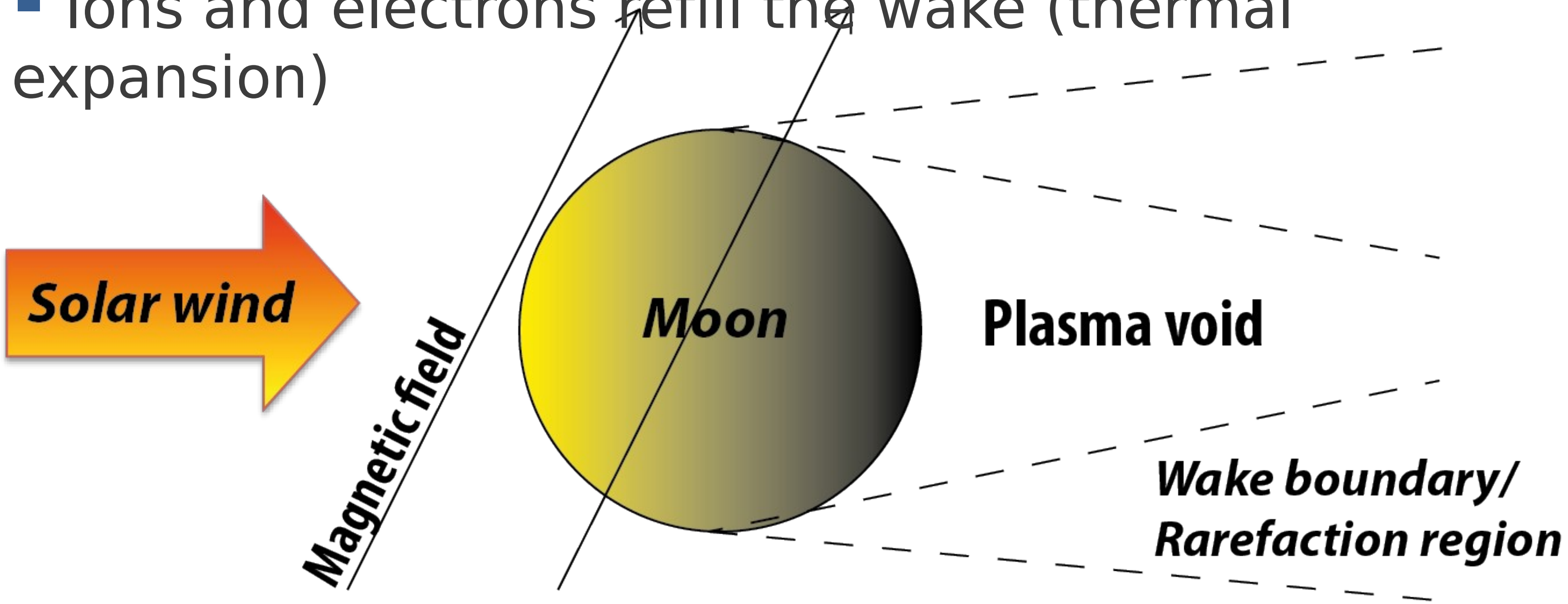
Moon-Solar Wind Interaction

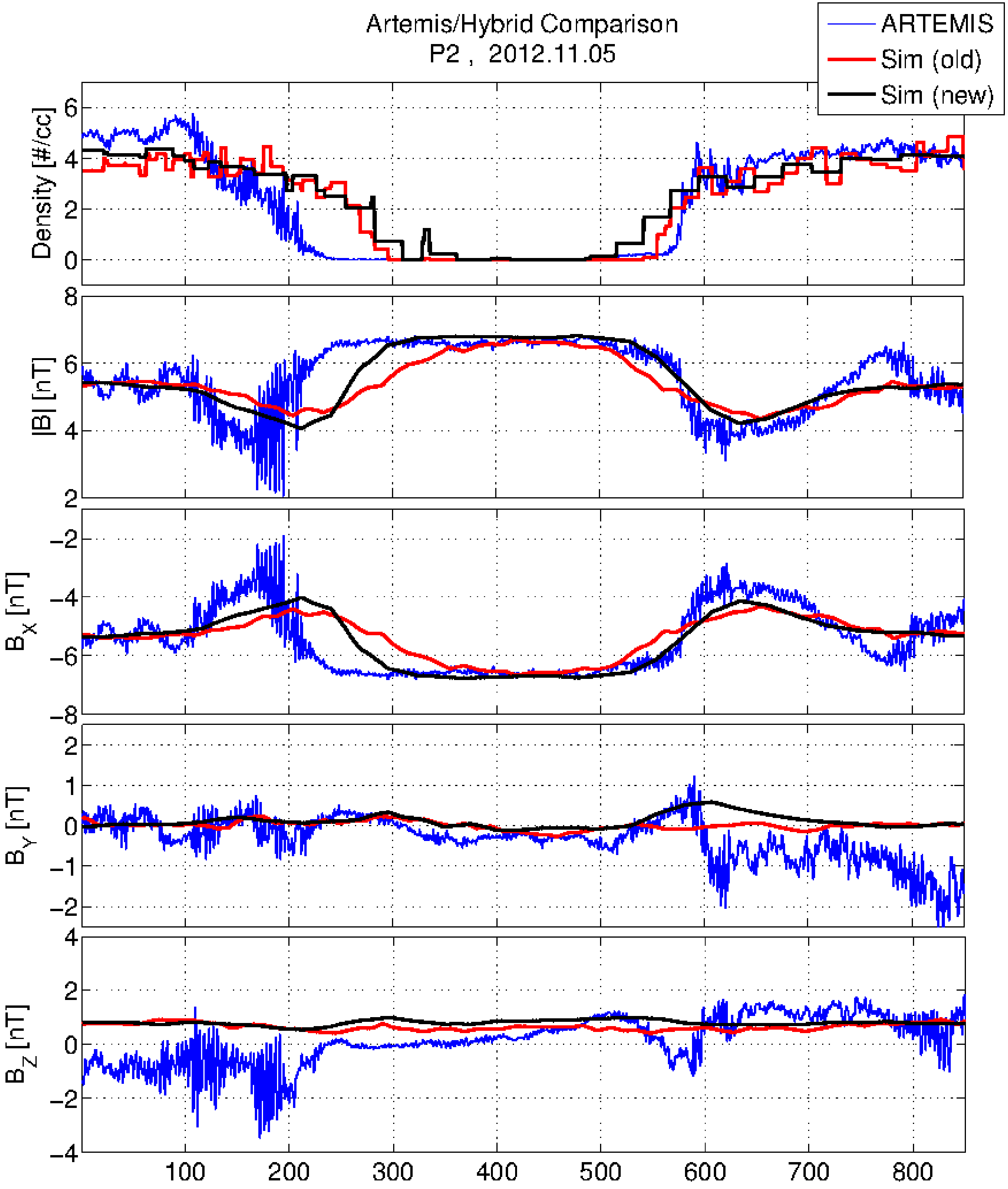
- The Earth’s Moon:

    no global magnetic field, no atmosphere, without conductivity.

    => ideal case for modeling.

- Solar wind impacts the Moon and is absorbed => plasma void
- Ions and electrons refill the wake (thermal expansion)





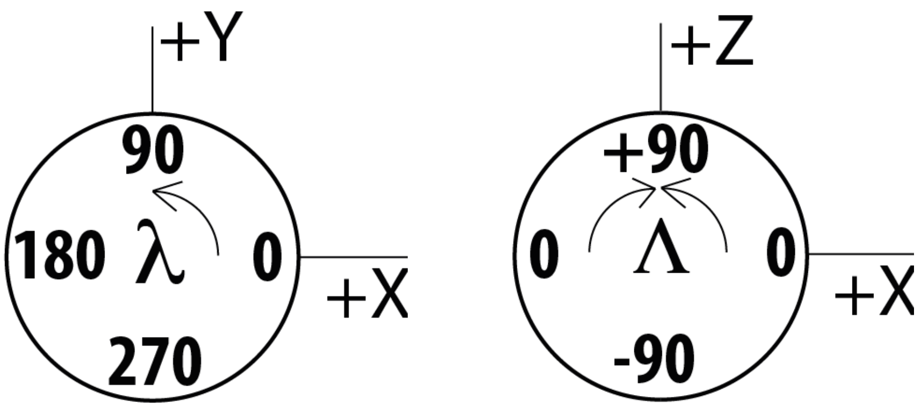
Artemis/Hybrid Comparison
P2 , 2012.11.05
ARTEMIS
Sim (old)
Sim (new)
Density [#/cc]
|B| [nT]
B_X [nT]
B_Y [nT]
B_Z [nT]
0
2
4
6
8
−2
−4
−6
−8
1
−1
100
200
300
400
500
600
700
800

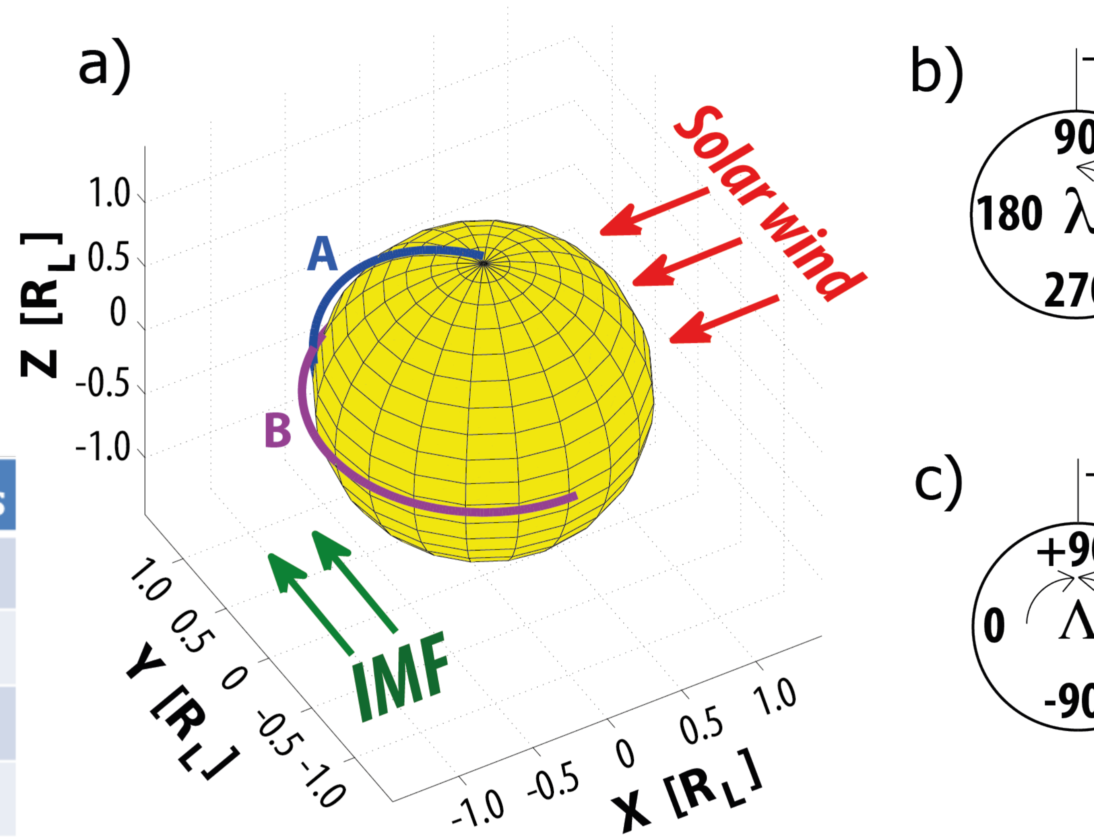
Motivation

How much does the lunar surface plasma absorption affect the proton velocity distributions in the lunar wake?

Methodology

- Hybrid model [Holmström, 2010]
- Backward Liouville method [Fatemi et al., 2012]

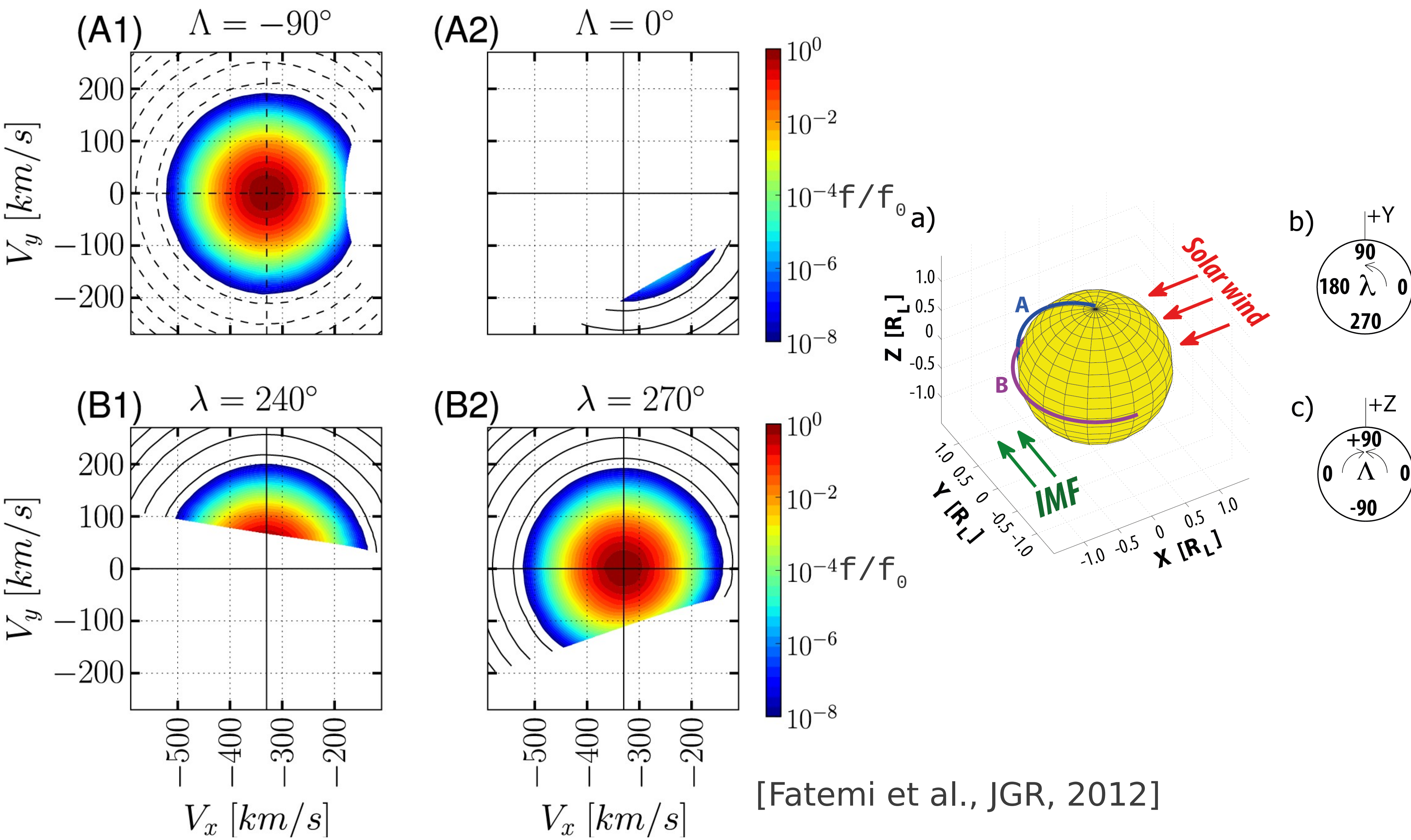




Parameters	Simulation Values
Solar wind velocity	(-330, 0, 0) km/s
Magnetic field	(0, +3, 0) nT
Proton density	1.70 cm^{-3}
Proton temperature	8.37 eV
Electron temperature	15.50 eV

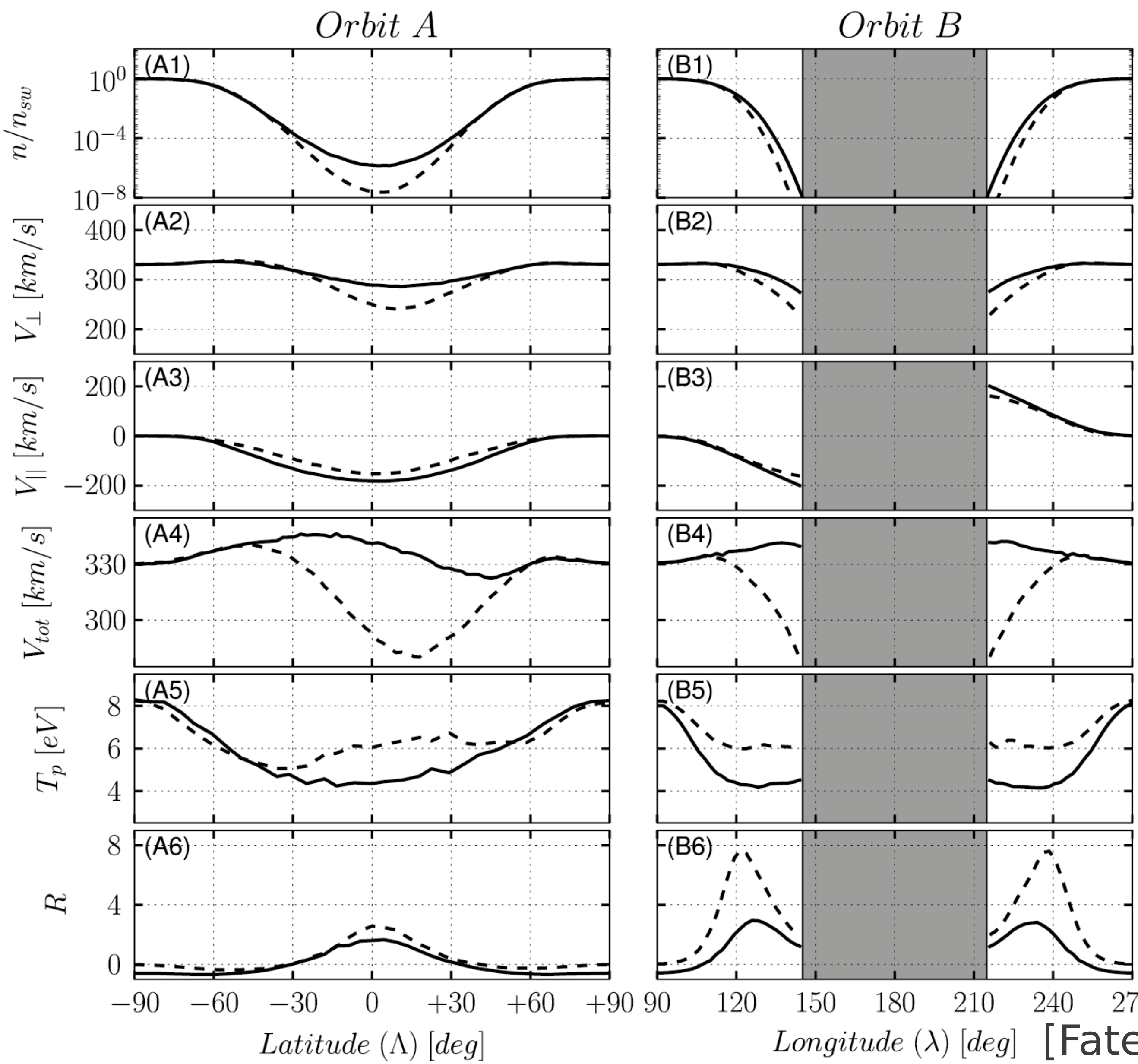
[Futaana et. al., 2010]

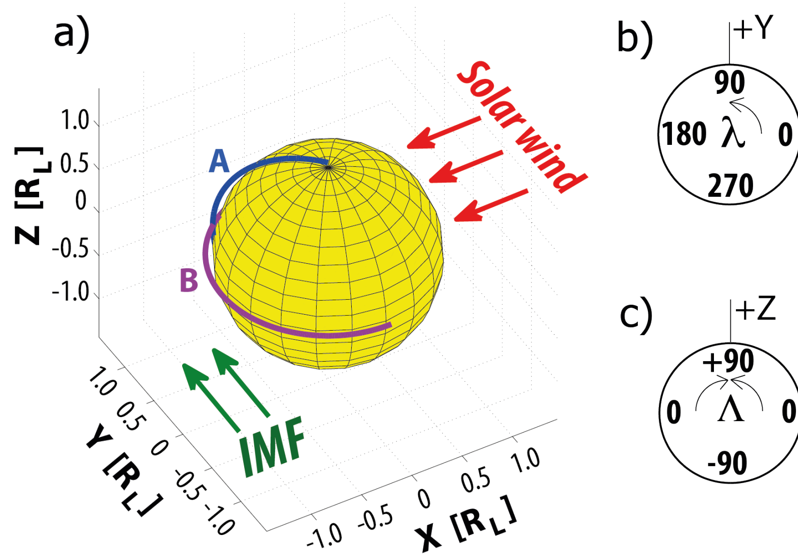
Phase space density



[Fatemi et al., JGR, 2012]

Moments of the distributions





$$R = T_\perp / T_\parallel - 1$$

[Fatemi et al., JGR, 2012]

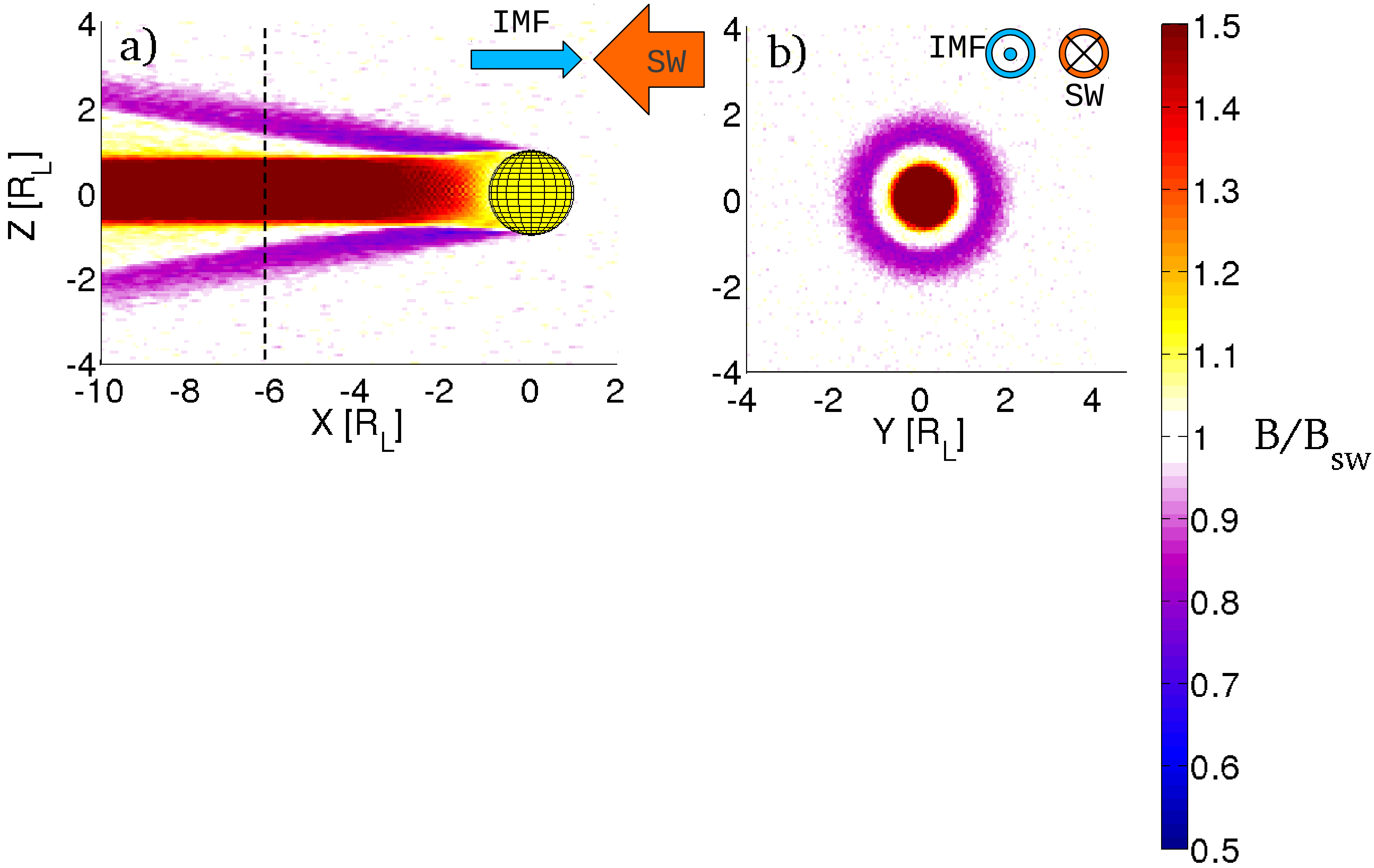
Summary: Surface Absorption

- This first application of the **Backward Liouville** method for PIC provides high velocity space resolution.

- The lunar plasma **surface absorption** effect is very strong for the near lunar wake.

- The Moon as a solar wind plasma absorber can change the proton moments and produce proton **temperature anisotropies** in the near lunar wake.

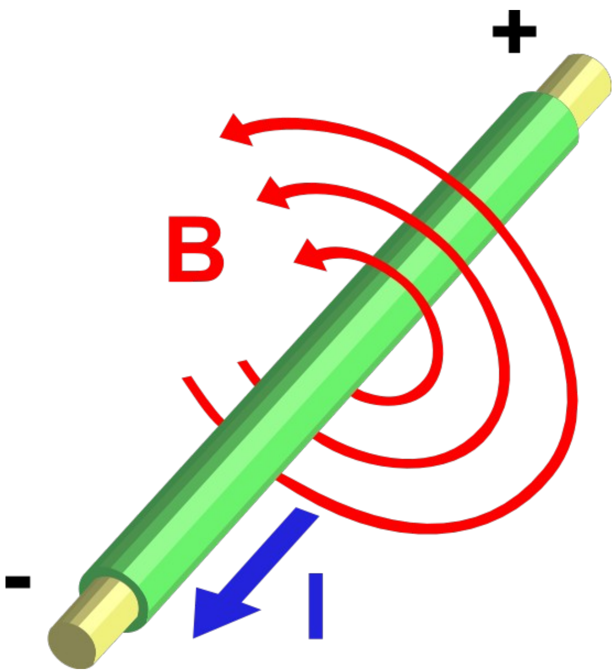
Magnetic fields from hybrid simulations



Lunar wake current

- Ampere's law

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



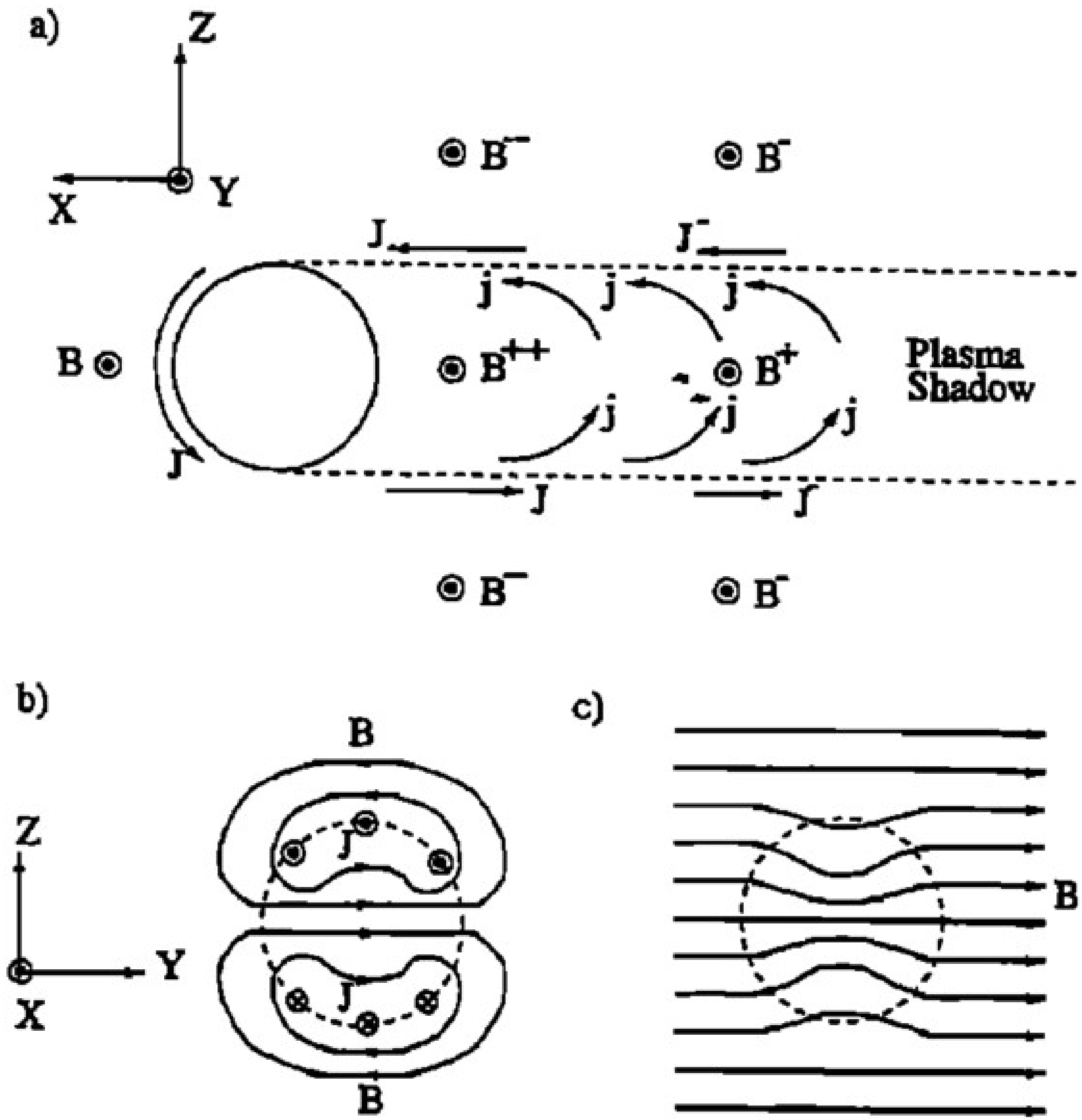
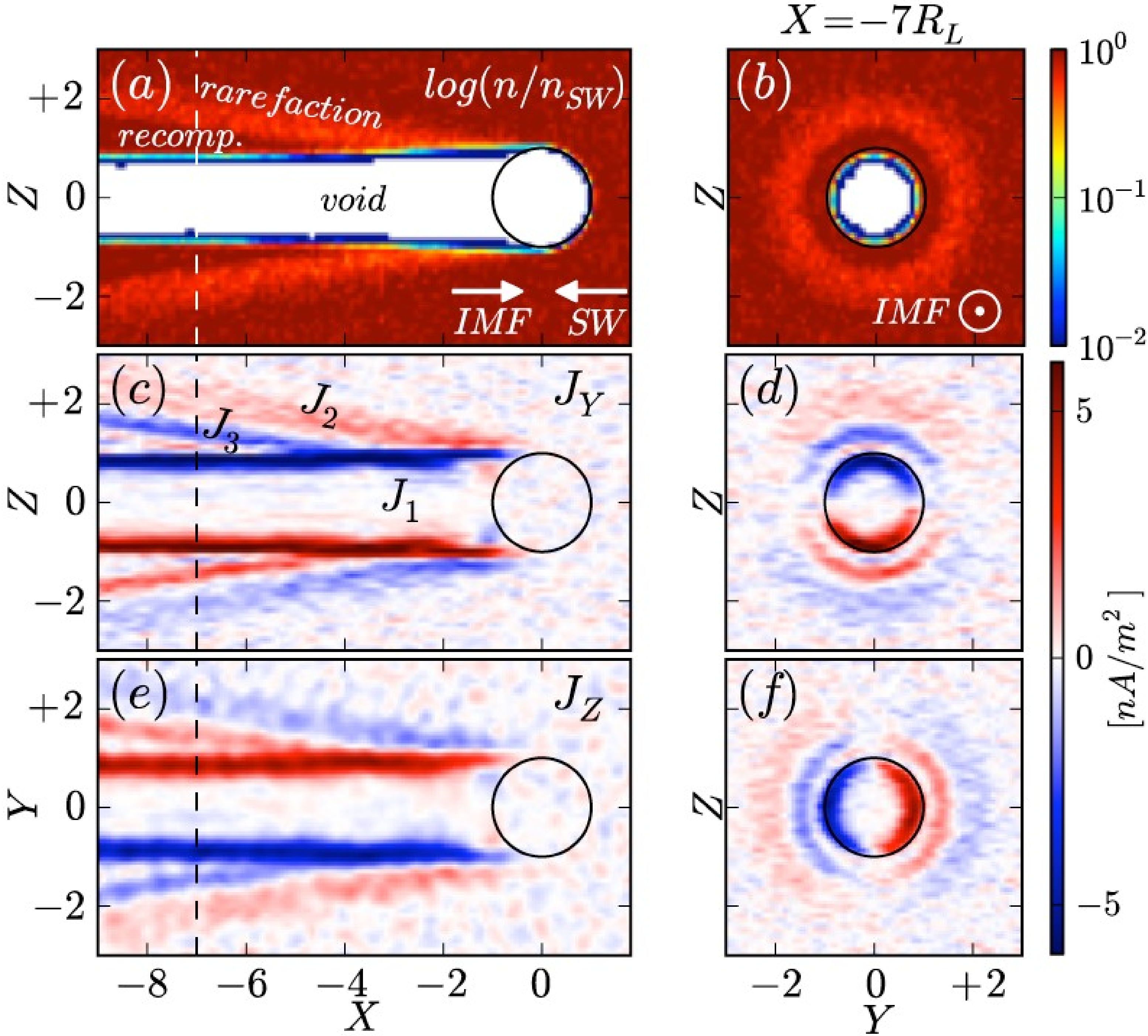


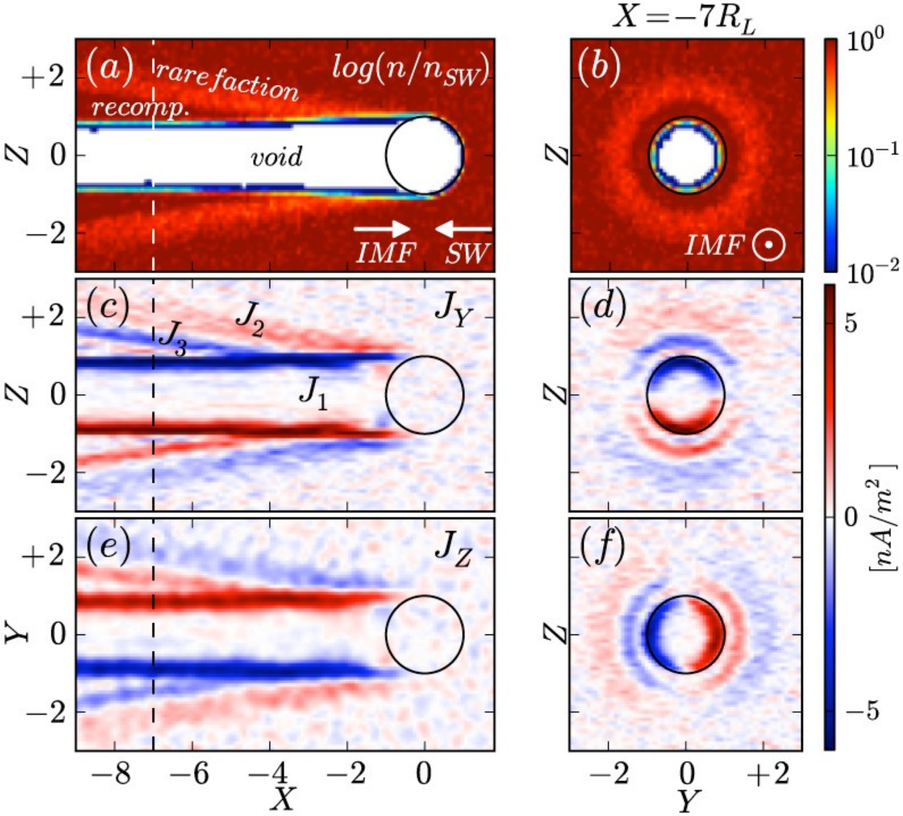
Figure 3. Sketch of the currents flowing around the lunar plasma cavity (upper panel) and the resulting changes in the magnetic field structure around the cavity (lower panel).

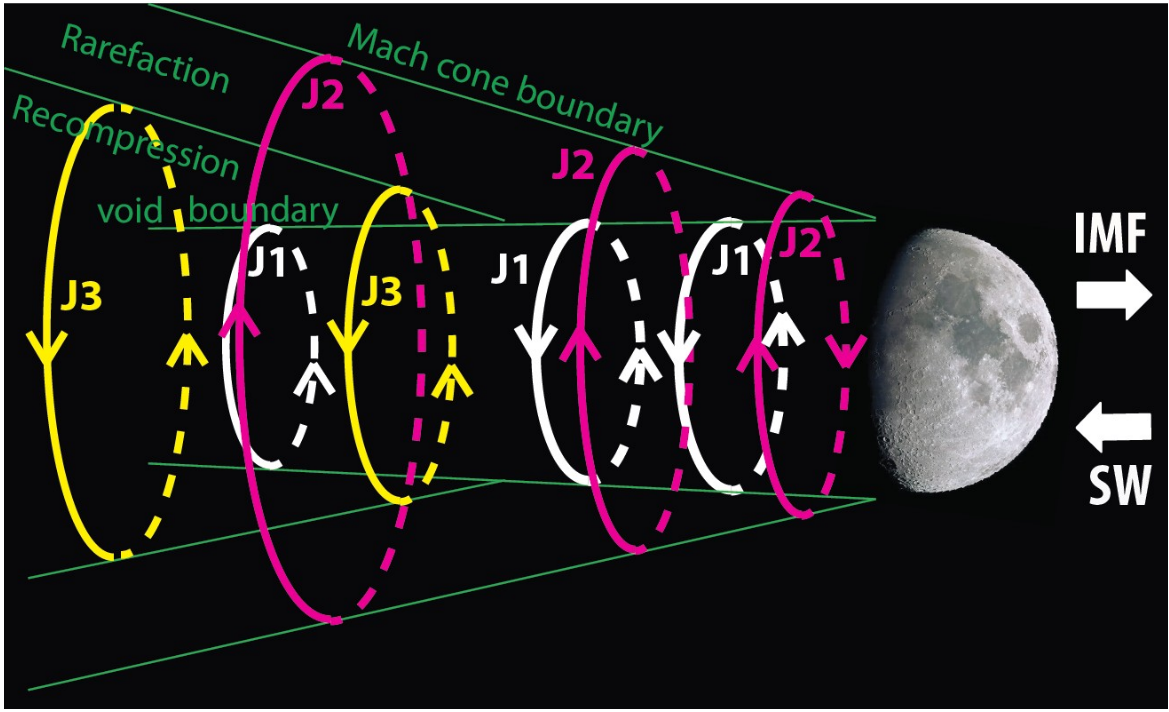
[Owen et al., GRL 1996]

IMF anti-parallel to the solar wind

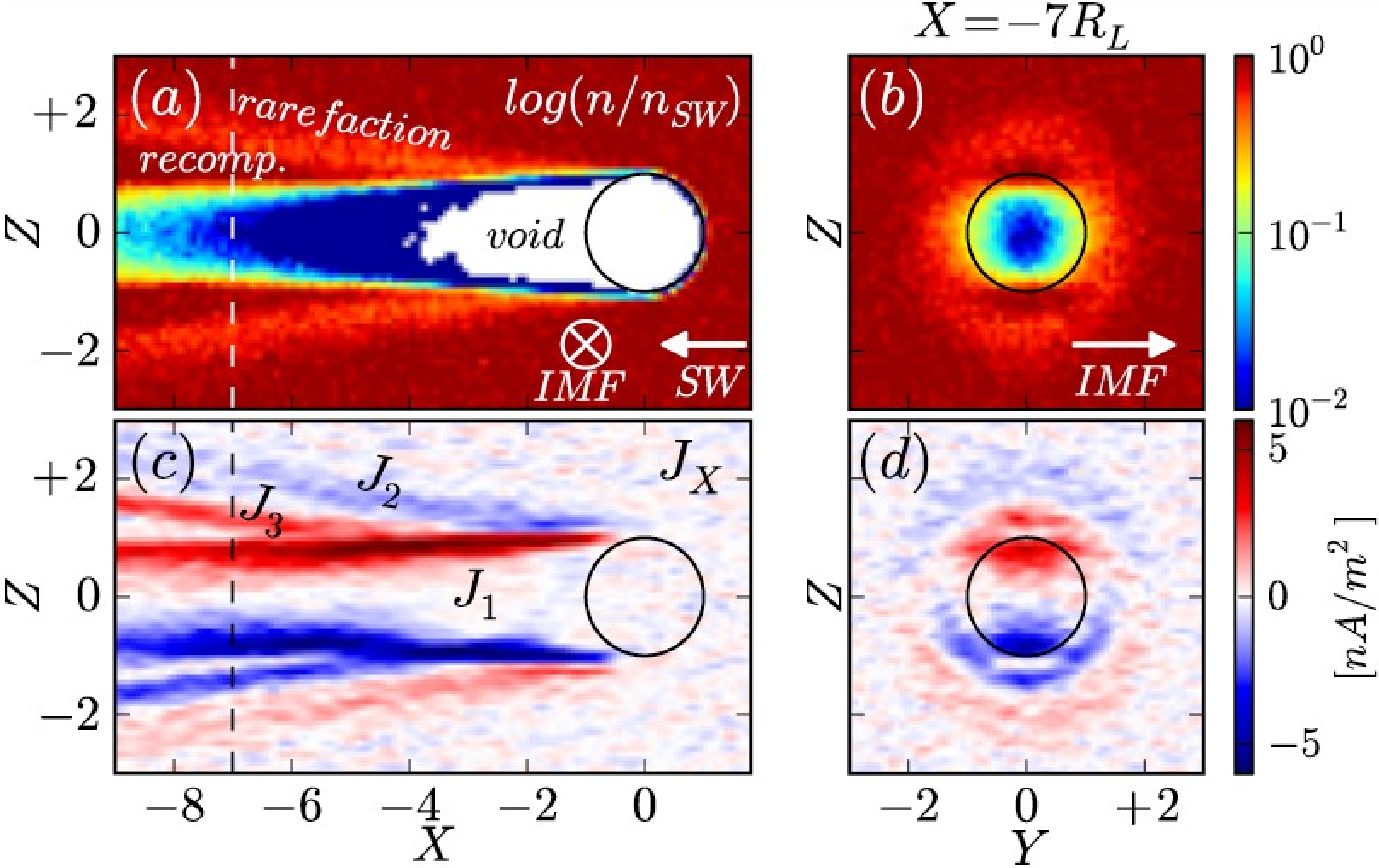


IMF anti-parallel to the solar wind

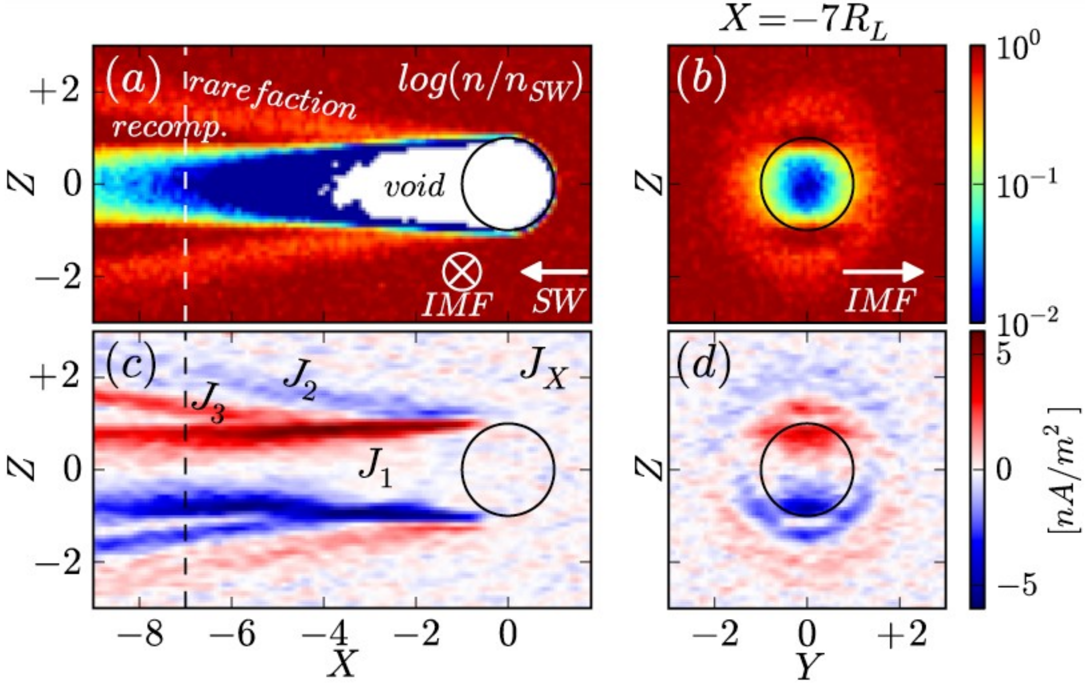


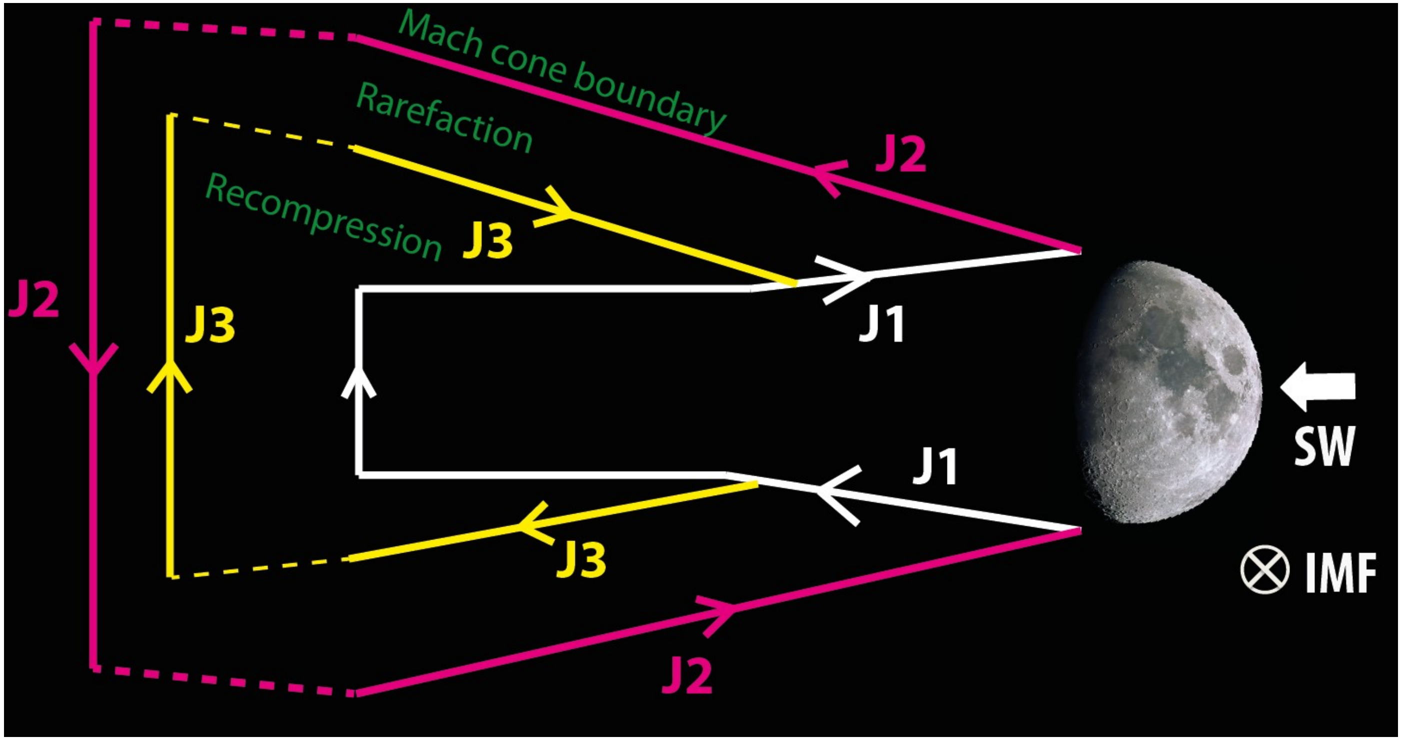


IMF perpendicular to the solar wind

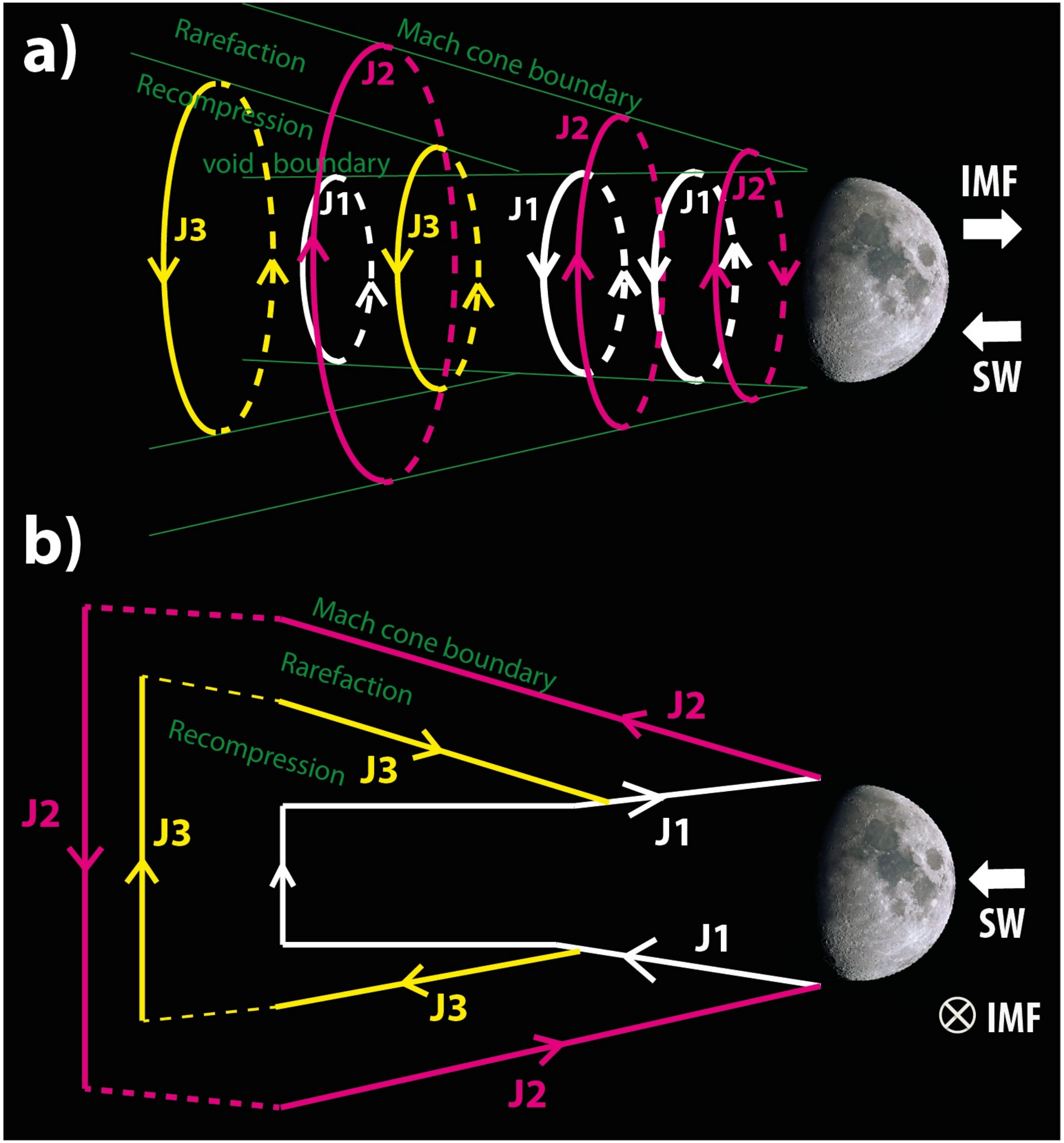


IMF perpendicular to the solar wind





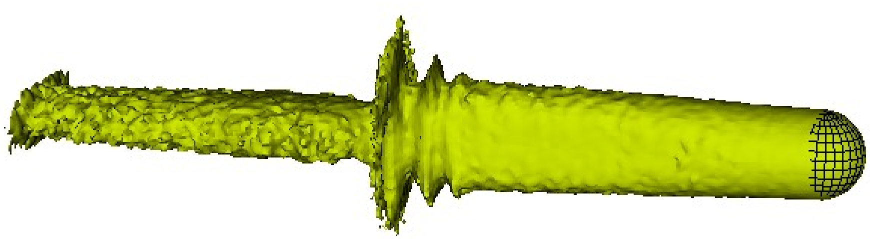
Currents: Summary

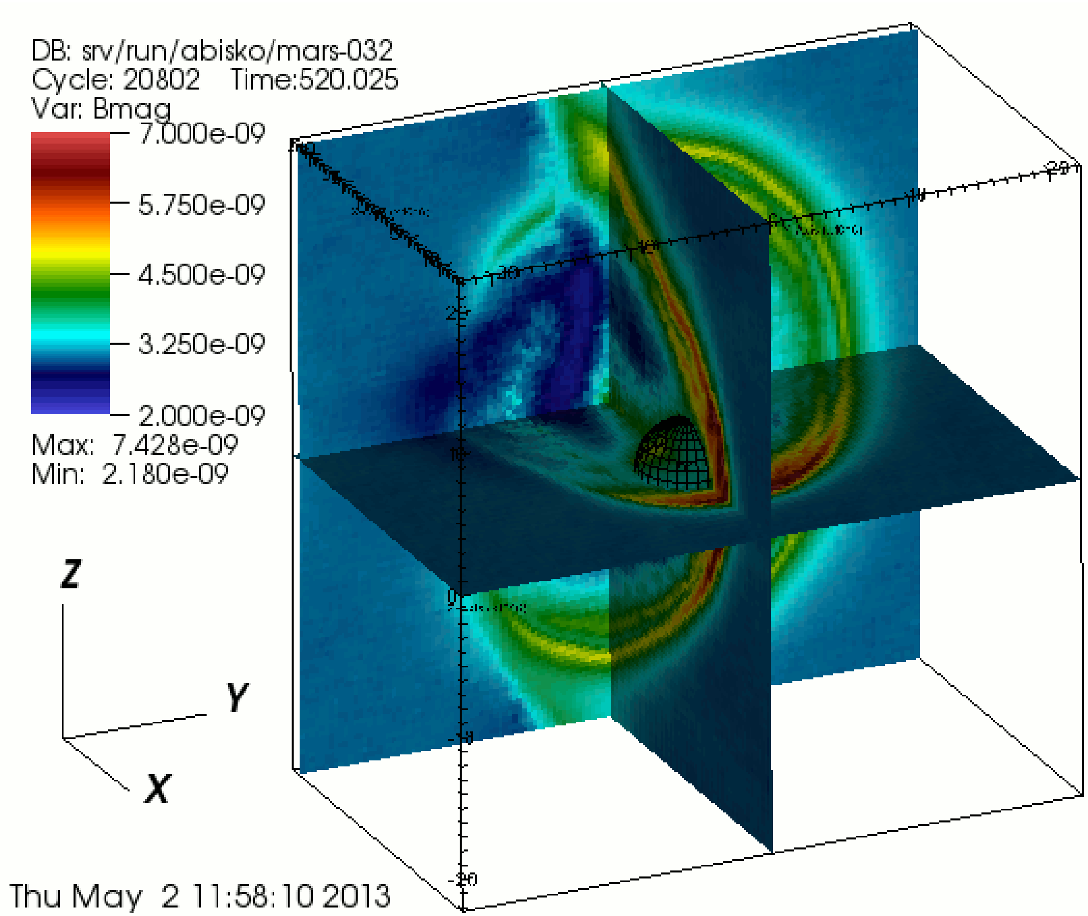


[Fatemi et al., GRL 2013]

Ongoing work

- Rhea and Callisto plasma interactions
- Time dependent effects of internal Lunar conductivity
- Mars and Venus
- Mercury





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