Electromagnetic particle-in-cell simulations of the solar wind interaction with lunar magnetic anomalies

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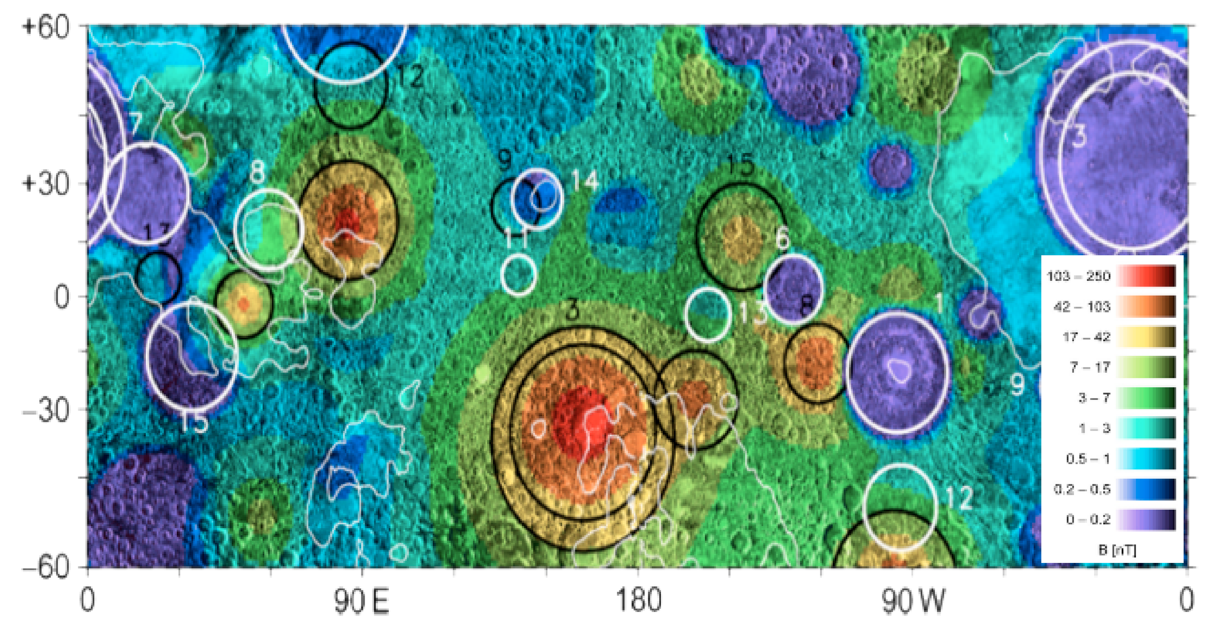
Abstract

We present the first three-dimensional fully kinetic and electromagnetic simulations of the solar wind interaction with lunar crustal magnetic anomalies (LMAs). Using the implicit particle-in-cell code **iPic3D** *[Markidis et al. 2010]* we confirm that LMAs may indeed be strong enough to stand off the solar wind from directly impacting the lunar surface, forming a mini-magnetosphere *[Deca et al. 2013, submitted to PRL]*. In contrast to MHD and hybrid simulations, the kinetic nature of **iPic3D** allows investigating the electron physics dominating the near-surface plasma environment.

Lunar magnetic anomalies

The Moon lacks an intrinsic magnetic field, but possesses regions of local magnetization.

- Non-dipolar, small-scale, $\mathbf{B}_{\text{surface}} \sim 0.1\text{nT} \rightarrow 1000\text{nT}$, mainly clustered on the far side.
- Origin unclear:
  - Presence of an early lunar dynamo. *[e.g. Hood et al. 2011]*
  - Shock magnetization from meteor impacts. *[e.g. Halekas et al. 2003]*



Global map of lunar crustal magnetic fields by the Lunar Prospector Electron Reflectometer. ▶
(Figure courtesy: *[Mitchell et al. 2008]*.)

Plasma parameters

- Plasma density: $n_0 = 3\,\text{cm}^{-3}$ ($d_i = 130\,\text{km}$)
- Temperature: $T_i = T_e = 35\,\text{eV}$
- Solar wind: $v_{sw} = 350\,\text{km}\,\text{s}^{-1}$
- $B_{IMF} = 6\,\text{nT}$, // to the dipole axis. ($r_{g,i} = 200\,\text{km}$)
- Dipole moment: $11.2 \times 10^{12}\,\text{Am}^2$
- Source: $11.2\,\text{km}$ below surface.
- Mass ratio: $m_i/m_e = 256$

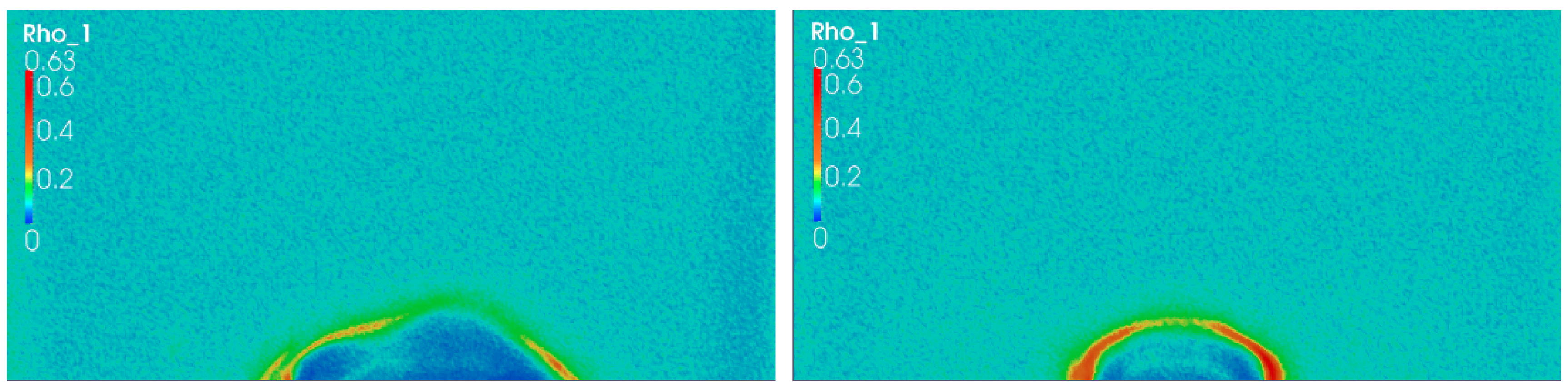
Simulation parameters

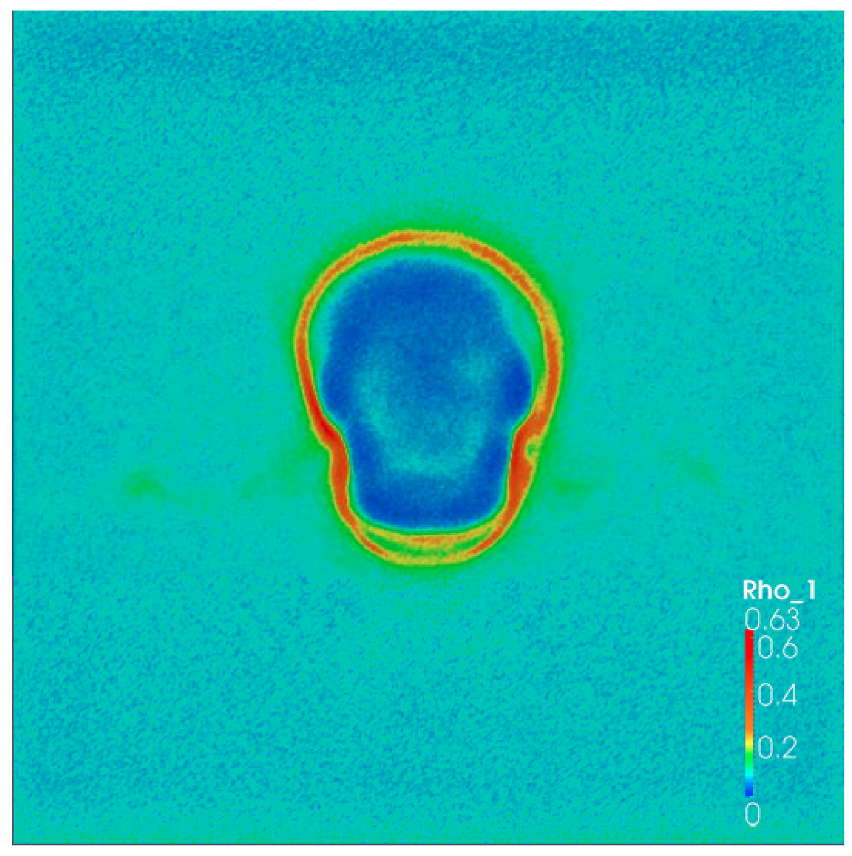
- $\Delta t = 0.0375\,\omega_{g,i}^{-1}$
- $(L_x, L_y, L_z) = (0.5, 1, 1)\,d_i$
- $(N_x, N_y, N_z) = (128, 256, 256)$, with **64** particles/cell/specie.
- $d_e = 0.0625\,d_i = 16\,\Delta x$, with Δx the grid spacing.

Formation of a mini-magnetosphere

We model the strongest dipole component of the Reiner Gamma anomaly *[see Kurata et al. 2005]* under average solar wind conditions and show the **formation of a mini-magnetosphere** above the lunar surface.

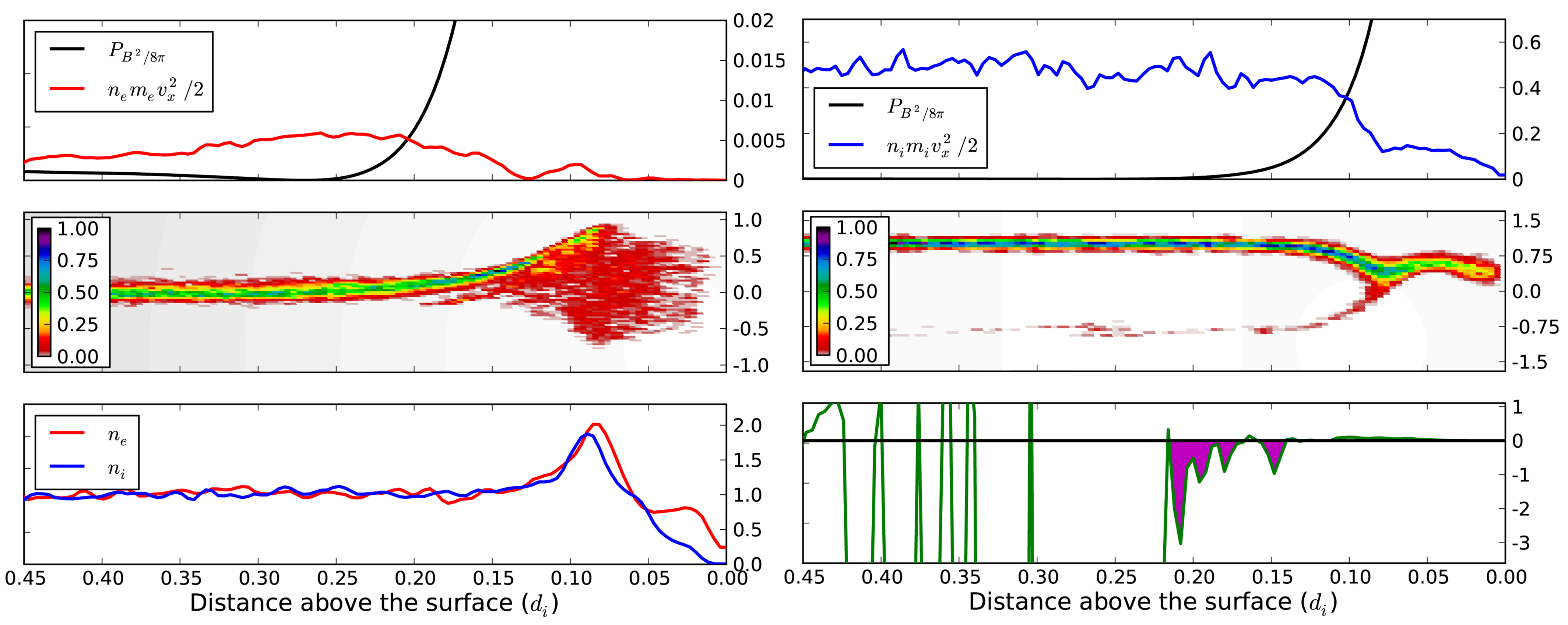
Ion charge density (code units) cuts perpendicular (left ◀) and along the dipole axis (middle▼) and just above the lunar surface (right ▶). The solar wind flows perpendicular to the surface.





- Because the LMA scale size is small with respect to the solar wind ion-gyroradius ($r_{g,i} \approx 1.5\,d_i$), the configuration is driven by ELECTRON MOTION.
- Making the analogy with the Earth's magnetosphere one could therefore refer to the higher density barrier as an ELECTROSHEATH rather than the magnetosheath.
- We do not observe a clear shock associated with the mini-magnetosphere structure.

Kinetic effects



▲ **Profiles parallel to v_{sw} and through the dipole centre. Magnetic and kinetic pressure for the electron (upper left) and ion (upper right) populations. Z component of the electron velocity distribution (middle left) and X component of ion velocity distribution (middle right). Density profiles (lower left) and mirror instability criterium (lower right).**

- Electrons are heated and deflected inside the electrosheath, while most of the ions reach the surface almost unaffected. About 10% of the incident solar wind ions are reflected by the density halo.
- A zero point in the total magnetic field configuration is created at 0.27 d_i above the surface, but no particle flows associated with magnetic reconnection are observed.
- The mini-magnetosphere is unstable over time. Occasionally blobs of plasma are able to enter the density cavity and reach the surface. It is found that the configuration is slightly unstable to the mirror instability:

$$\beta_\parallel - \frac{\beta_\perp^2}{1+\beta_\perp} < 0.$$

Open boundary conditions

Particles:

- Model the lunar surface as a particle absorber.
- Inflow boundaries: Particles are sampled from a drifting Maxwellian.
- Other boundaries: Particle replenishing.

Magnetic field:

- $\mathbf{B}_{\text{IMF}}$ explicitly set on the boundary cells.

Electric field:

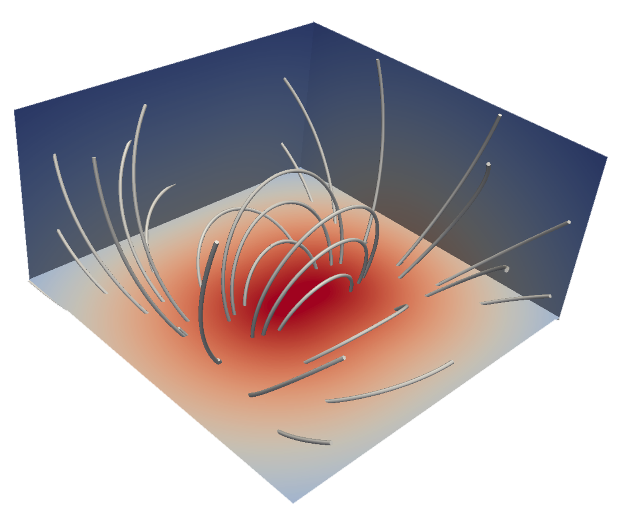
- $\mathbf{E} = -\mathbf{v}_{\text{sw}} \times \mathbf{B}$ explicitly set on the boundary cells.

Anomaly model

Generate a dipole field just below the lunar surface.

$$B_x = \frac{3\mu_0\,m}{4\pi}\frac{xz}{r^5}, \quad B_y = \frac{3\mu_0\,m}{4\pi}\frac{yz}{r^5}, \quad B_z = \frac{3\mu_0\,m}{4\pi}\frac{(3z^2 - r^2)}{r^5}$$

with $\mathbf{m}$ the dipole moment in Am^2, assuming the dipole axis in the Z-direction and centered at the origin.
Add as an external field to the particle mover and Maxwell solver



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