Effect of Surface Topography on the Lunar Electrostatic Environment: 3D Plasma Particle Simulations

Yohei Miyake and Masaki N Nishino
Education Center on Computational Science and Engineering, Kobe University
Solar-Terrestrial Environment Laboratory, Nagoya University

Contact: y-miyake@eagle.kobe-u.ac.jp

The Japanese lunar orbiter KAGUYA has revealed the existence of vertical holes on the Moon, which have spatial scales of tens of meters and are possible lava tube skylights. The hole structure has recently received particular attention than other landscapes, because the structure is regarded as an evidence for past existence of underground lava flows and gives an important clue to the complex volcanic history of the Moon. Furthermore, the holes have high potential as locations for constructing future lunar bases, because of fewer extra-lunar rays/particles and micrometeorites reaching the hole bottoms. In this sense, these holes are not only of significance in selenology, but are also interesting from the viewpoint of plasma environments. The dayside electrostatic environment near the lunar surface is governed by interactions among the solar wind plasma, photoelectrons, and the charged lunar surface, providing topologically complex boundaries to the plasma. Thus we applied three-dimensional, massively-parallelized, particle-in-cell simulations to the near-hole environment on the Moon. The vertical wall of the hole introduces a new boundary for both photo and solar wind electrons. The current balance condition established at a hole bottom is altered by the limited solar wind electron penetration into the hole due to loss at the wall and complex photoelectron current paths inside the hole. The self-consistent modeling not only reproduces intense differential charging between sunlit and shadowed surfaces, but also reveals the potential difference between sunlit surfaces inside and outside the hole, demonstrating the uniqueness of the near-hole electrostatic plasma environment as well as providing useful knowledge for future landing missions on the Moon.
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Yohei Miyake*1, Masaki N Nishino*2
1. Education Center on Computational Science & Engineering, Kobe University
2. Institute for Space-Earth Environmental Research, Nagoya University
E-address of Y.M.: y-miyake@eagle.kobe-u.ac.jp


Airless body-plasma interactions
Electrodynamic interactions take place among solar wind, airless body (e.g., moon) surface, and photoelectrons.

Moon-plasma interactions
Asteroid-plasma interactions

Sun

[Credit: Halekas & Delory of U.C. Berkeley, and Farrell & Stubbs of the Goddard Space Flight Center]

[Zimmerman et al., Icarus, 2014]
“Charging” of lunar surface

Lunar surface is charging due to deposition of plasma particles (like “spacecraft charging”)

- Insulating surface
- Major current sources:
  - (Positive) solar wind proton, photoelectron
  - (Negative) solar wind electron
- Minor current sources:
  secondary electron, heavy ion, charged dust grains

Lunar-surface charging

For flat surface, the problem is 1-dimensional...

Plasma currents:

- \( J_{SWI} \sim J_{SW0} \)
- \( J_{SWE} = J_{THE0} \exp \left( \frac{\phi_{MIN}}{T_{THE}} \right) \)
- \( J_{PE} = J_{PE0} \exp \left( \frac{\phi_{LS} + \phi_{MIN}}{T_{PE}} \right) \)

Combined with Poisson’s eq.,
1D solution obtained
[Guernsey and Fu, 1970]

In reality, surface topography (3D) might be important...
Lunar vertical holes (e.g., Marius Hills Hole) with diameter & depth of \( \sim 10 \) m

[Haruyama et al., 2012]
[Robinson et al., 2012]

“Possible lava tube” to be explored in future

[Haruyama et al., 2009]

- Interesting topic in selenology
  → Future landing missions such as the “UZUME” project
- Possible candidate for constructing future lunar bases (Japan, USA, etc.)
3D plasma particle simulations

We applied EMSES (EM spacecraft environment simulator) to lunar environment.

Huge number (~$10^{10}$) of plasma macro-particles → Newton’s eq. of motion

Electrostatic field on grid points → Poisson’s eq.

1. Solar wind (SW) plasma downflow
2. Photoelectron (PE) emission
3. Plasma captured at lunar surface

...are taken into account

Configuration & setup

Nominal SW & PE conditions
- SW: 5 /cc, 8.6 eV, 450 km/s, 5nT
- PE: 4.5 μA/m², 2.2 eV

[Willis et al., 1973]

Grid width: 50 cm
Domain: $200 \times 200 \times 1000$ m³
# of particles: ~$10^{10}$

⇒ Use of supercomputer, $10^3$-parallelism
Lunar surface charging: $\theta = 30^\circ$

- Positive charging
- Potential overshoot
- Differential charging (>40 V)

Higher at hole bottom

E-field: 50 V/m

E-field: 20 V/m

Potential overshoot

SS boundary

Lunar surface charging: $\theta = 30^\circ$

- Positive
- Negative
- Potential overshoot

SS boundary

x-axis
SW plasma distribution & dynamics

$J_i > J_e \rightarrow$ Higher potential at hole bottom

Photoelectron distribution & dynamics

$PE$ current path from vertical wall to hole bottom
Current balance at hole bottom

Current balance condition is totally changed.

Dependence on hole depth

- **Surface potential**
  - Larger p. difference
  - Smaller p. difference

- **SW electron**
  - For shallow hole: Larger amount of electrons approaching the hole bottom
Summary

- Plasma environment near airless body surface strongly depends on its surface topography.
- Particularly, our plasma simulations near lunar holes reveal unique electrostatic features:
  1. Differential charging between sunlit & shadow regions
  2. Higher potential at hole bottom resulting from modified current balance condition
  3. Potential overshoot near sunlit-shadow boundary

Future works:
- Modeling of charged-dust environment around the holes

Next step

Numerical modeling of dust environment

- Output of plasma simulations:
  1. Potential distribution
  2. Lunar surface charge dist.
- Determine initial charge, position, and velocity
- Eq. of dust motion incl. gravitation force
- Modeling of time variation of dust charge

Test particle analysis

- Dust dynamics
- Dust distribution
Issues to be resolved

- Dust charging
  - Time variation of charging
  - Quantized charging state

- Dust dynamics
  - Electromagnetic, gravitation, drag, & solar pressure forces
  - Lift off condition of the dust grains

- Interactions among dust, plasma, & EM-field
  - Dusty-plasma wave modes
  - Binary collision between dust grains (in case of strongly-coupled) \(\rightarrow\) crystallization?

Large gap in spatial\&temporal scales is big problem.
Questions?

References: