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.

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

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

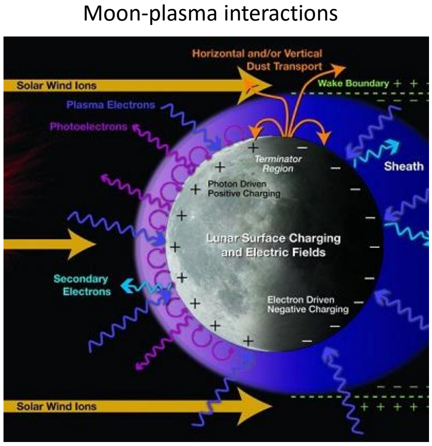
Symposium on Planetary Science 2016: Feb. 22, 2016

Airless body-plasma interactions

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

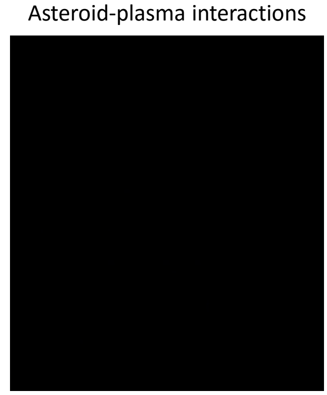
Moon-plasma interactions

Sun



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

Asteroid-plasma interactions



[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:

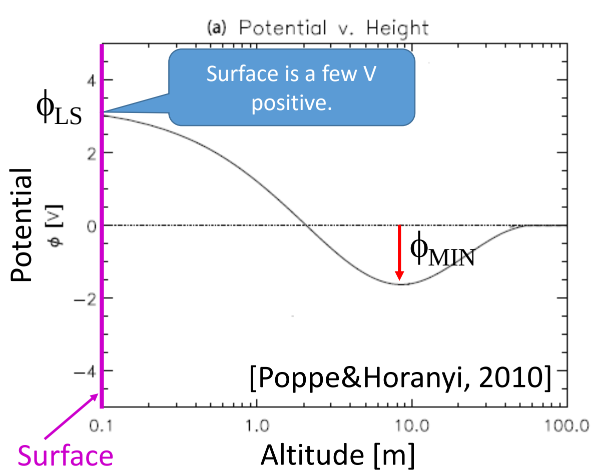
  (Positive) solar wind proton, photoelectron

  (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:

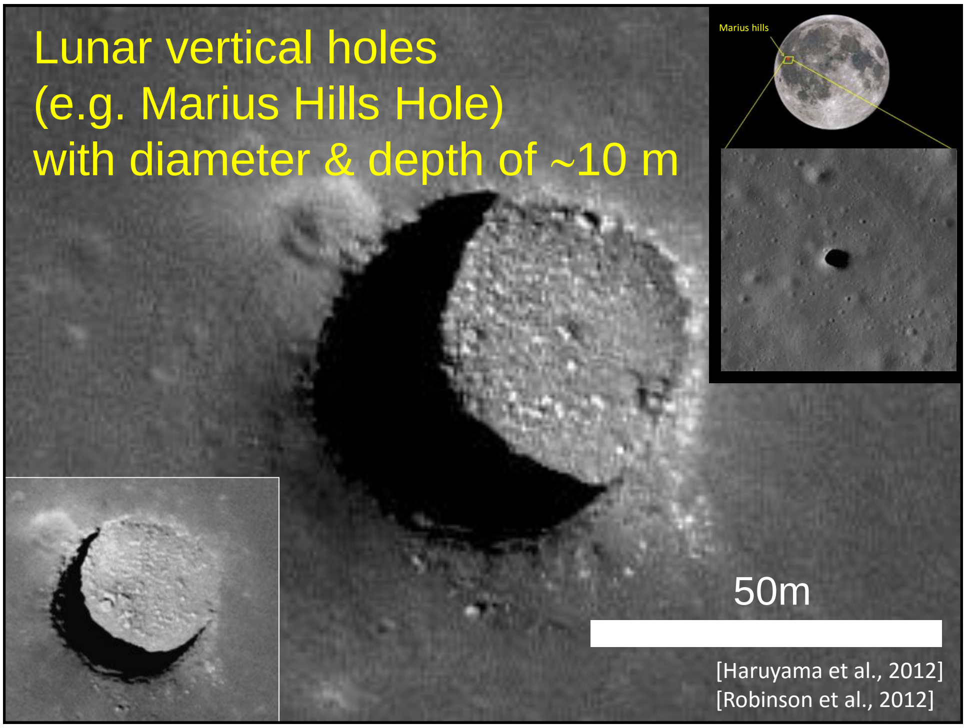
$$J_{SWI} \sim J_{SW0}$$

$$J_{SWE} = J_{THE0} \exp\left(\frac{\phi_{MIN}}{T_{THE}}\right)$$

$$J_{PE} = J_{PE0} \exp\left(\frac{\phi_{LS} + \phi_{MIN}}{T_{PE}}\right)$$

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

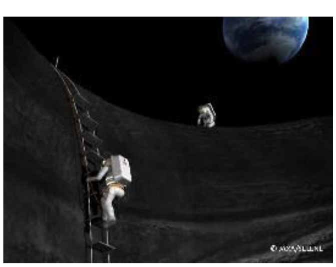
In reality, surface topography (3D) might be important…

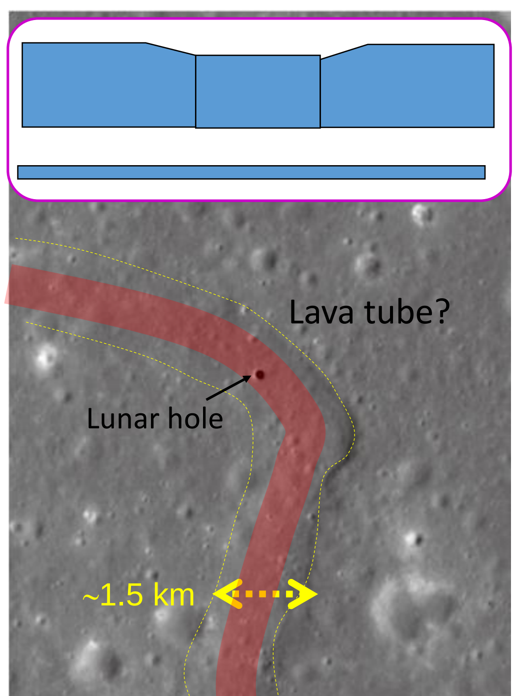


"Possible lava tube" to be explored in future

[Haruyama et al., 2009]

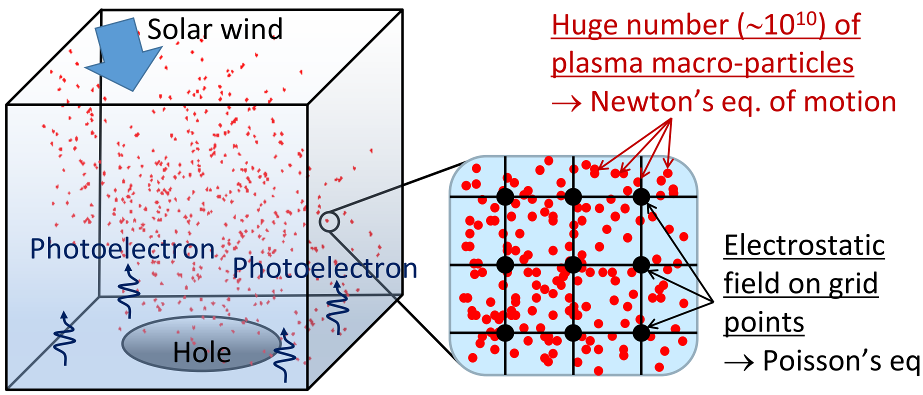
- Interesting topic in selenology
  →Future landing missions such as the "UZUME" project
- Possible candidate for constructing future lunar bases (Japan, USA, etc.)





3D plasma particle simulations

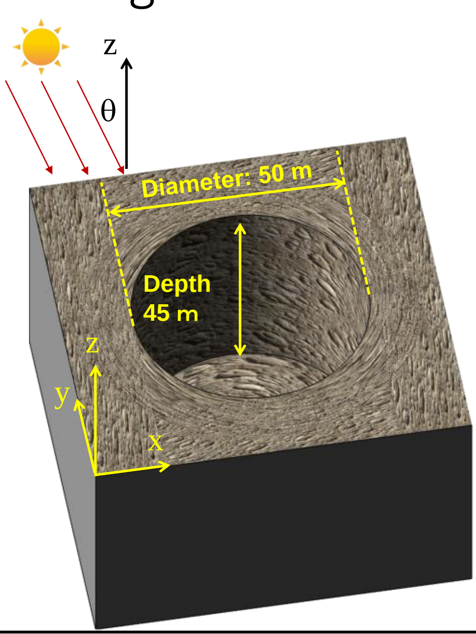
We applied EMSES (EM spacecraft environment simulator) to lunar environment.



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/m^2, 2.2 eV [Willis et al., 1973]

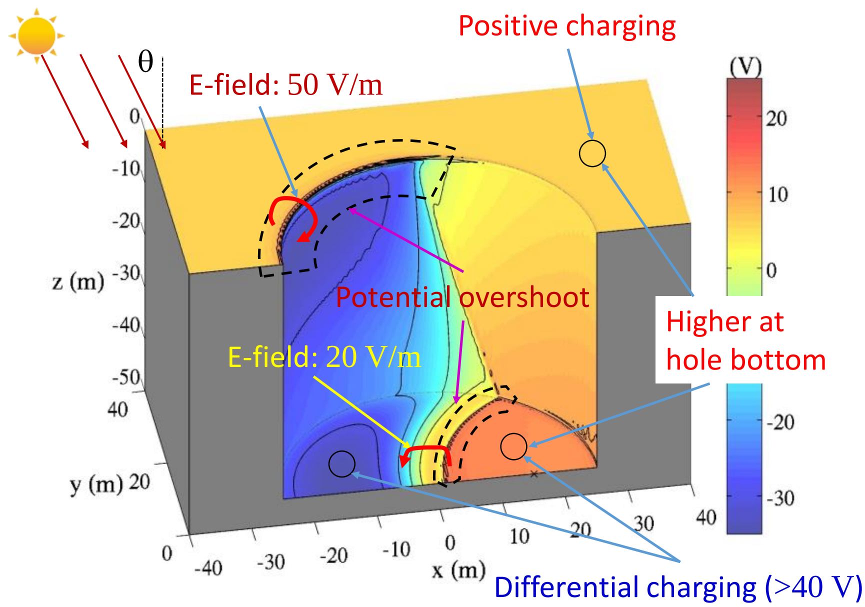
Grid width: 50 cm

Domain: 200 × 200 × 1000 m^3

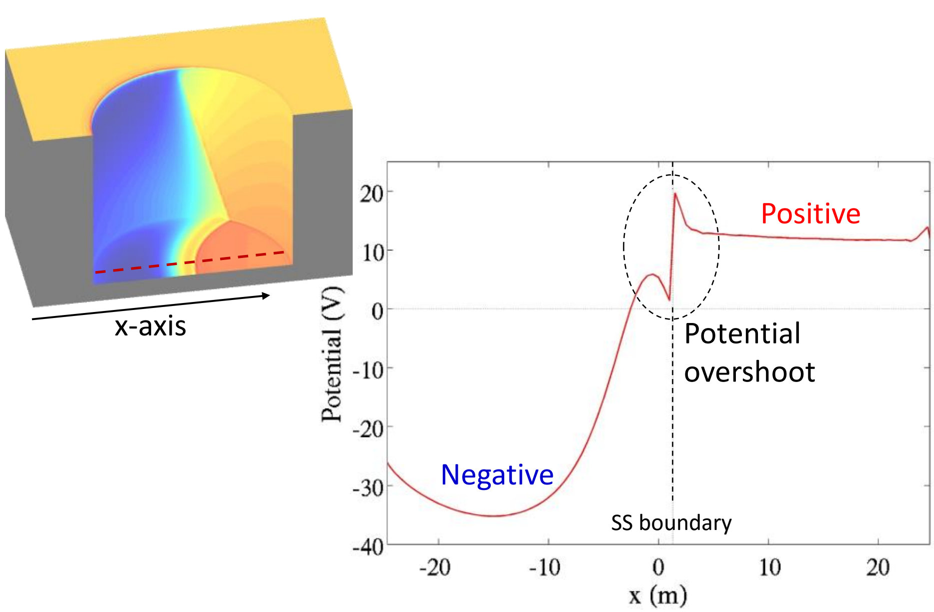
# of particles: ~10^{10}

⇒ Use of supercomputer, 10^3-parallelism

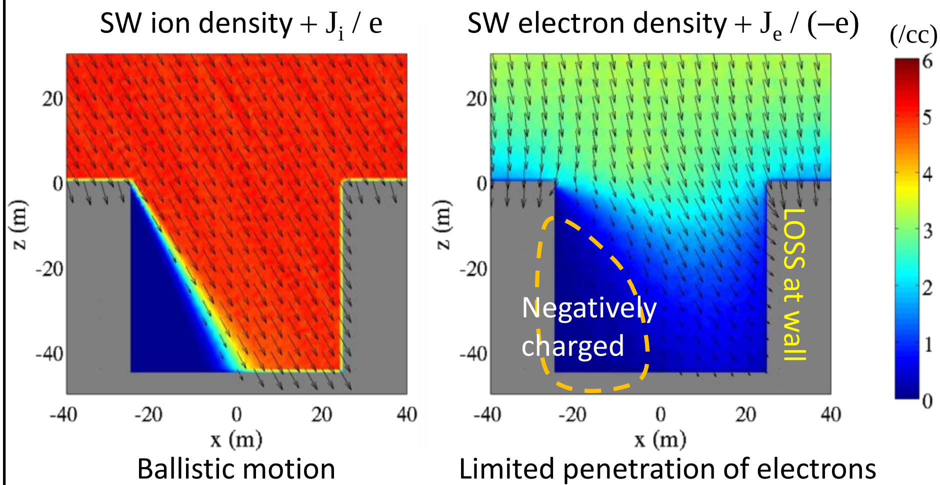
Lunar surface charging : θ = 30°



Lunar surface charging : θ = 30°

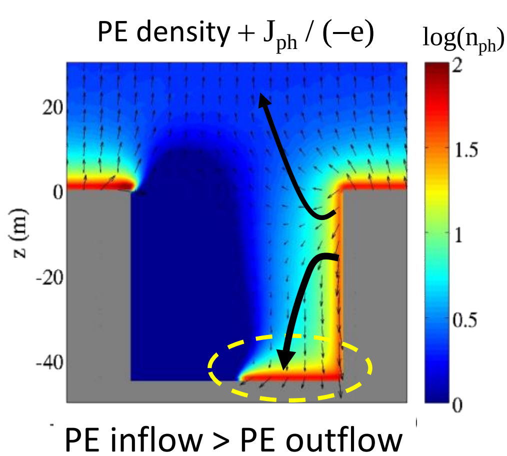


SW plasma distribution & dynamics



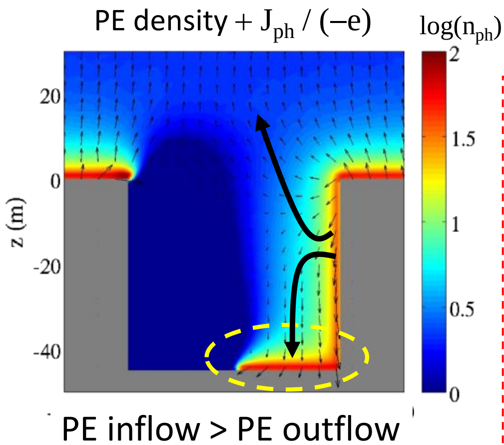
$J_i > J_e$ → Higher potential at hole bottom

Photoelectron distribution & dynamics



PE current path from vertical wall to hole bottom

Current balance at hole bottom



Positive current | Negative current

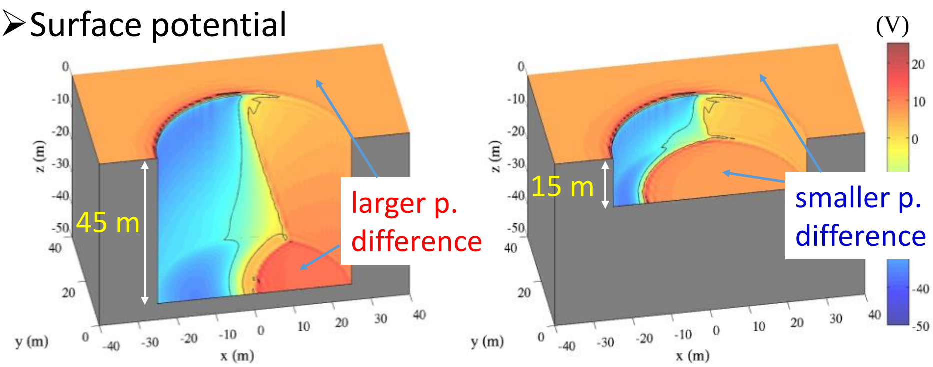
Lunar surface: $J_{ph} + J_i = J_e$

Hole bottom: $J_i = J_{ph} + J_e$

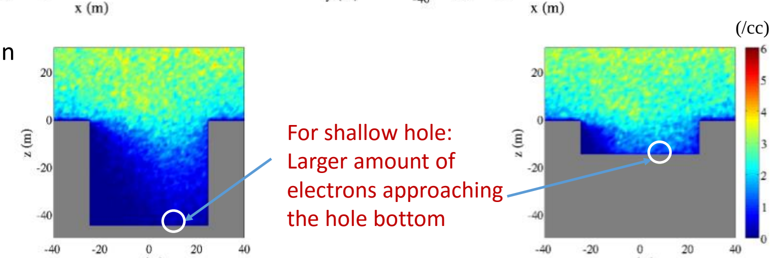
<u>Current balance condition is totally changed.</u>

Dependence on hole depth

- Surface potential



- SW electron



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
①Potential distribution
②Lunar surface charge dist.

↓

Determine initial charge, position, and velocity

↓

Eq. of dust motion incl. gravitation force

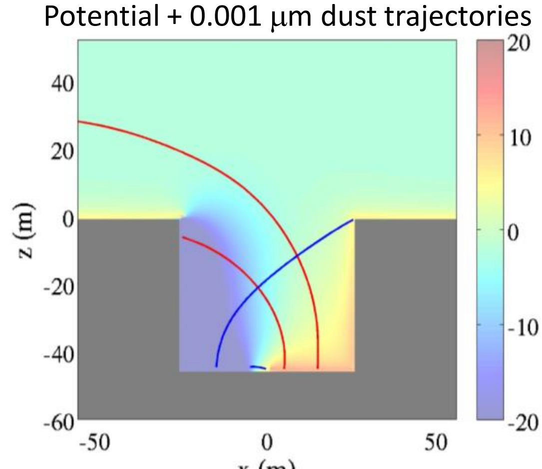
↓

Modeling of time variation of dust charge

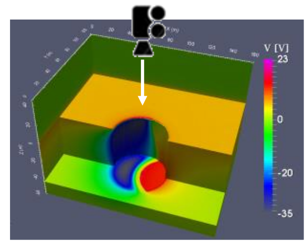
Test particle analysis →

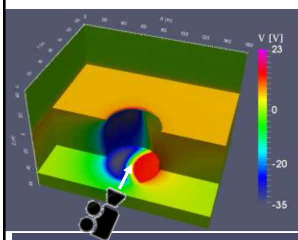
- Dust dynamics
- Dust distribution

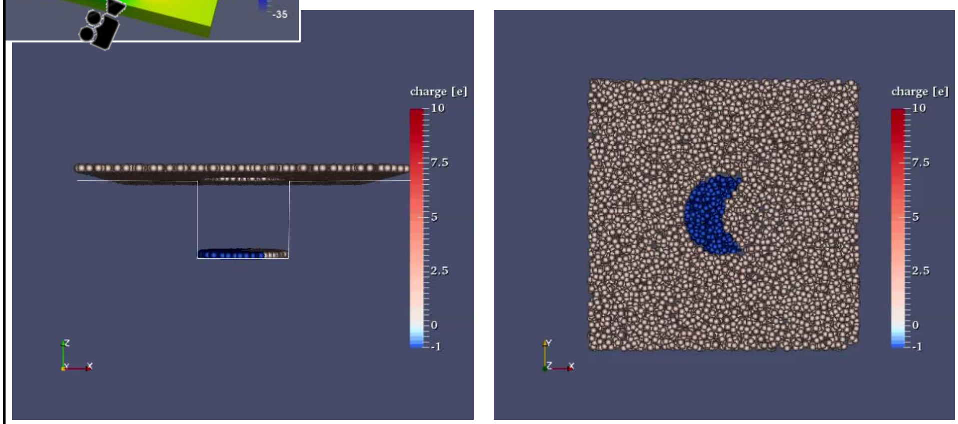
Potential + 0.001 μm dust trajectories



Test simulation







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) → crystallization?

Large gap in spatial&temporal scales is big problem.

Questions?

References:

1. Usui et al., PIC Simulation on Plasma Flow Response to a Meso-scale Magnetic Dipole in Space, AIAA Science and Technology Forum, 2015.
2. Deca et al., Electromagnetic Particle-in-Cell Simulations of the Solar Wind Interaction with Lunar Magnetic Anomalies, Phys. Rev. Lett., 2014.
3. Farrell et al., Complex electric fields near the lunar terminator: The near-surface wake and accelerated dust, Geophys. Res. Lett., 2007.
4. Poppe&Horanyi, Simulations of the photoelectron sheath and dust levitation on the lunar surface, J. Geophys. Res., 2010.
5. Guernsey and Fu, Potential distribution surrounding a photo-emitting, plate in a dilute plasma, J. Geophys. Res., 1970.
6. Haruyama et al., Lunar holes and lava tubes as resources for Lunar science and exploration, Moon, 2012.
7. Robinson et al., Confirmation of sublunarean voids and thin layering in mare deposits, Planet. Space Sci., 2012.
8. Miyake&Nishino, Electrostatic environment near lunar vertical hole: 3D plasma particle simulations, submitted.