ISSI International Research Team proposal on

Plasma – Surface Interactions with Airless Bodies in Space and the Laboratory

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Abstract:

The goal of our Team is to explore key challenges in plasma-surface interactions at airless planetary bodies by exploiting the synergies between in-situ observations, computer simulations, and laboratory experiments to identify and understand the fundamental physical processes determining the global and local near-surface plasma environment.

Our solar system contains a wide range of airless planetary bodies, including the Moon, Mercury, asteroids, dormant comets, and the moons of Mars: Phobos, and Deimos. In-situ observations near the Moon, and remote-sensing measurements of many of these objects, led to the recognition that their surface properties and exosphere are strongly influenced by complex interactions between the dusty regolith, the solar wind plasma and UV radiation, with vastly different upstream and downstream plasma conditions as a consequence. The charging of small dust particles present in the near-surface environment may lead to their mobilization and transport, often making it difficult to analyze and interpret remote-sensing observations. For example, these processes have been suggested to be responsible for the lunar horizon glow and the formation of dust ponds on asteroids. The role of magnetic anomalies and their possible connection to lunar swirls (unusual albedo markings) remains especially enigmatic.

To address these issues, we propose to bring together a team of international experts and young scientists to merge observational, experimental and numerical modeling knowledge and expertise. Guided by existing space-based observations, our team will first identify key physical challenges that can be reproduced in a laboratory setting. We will exercise our numerical models to recreate these initial laboratory experimental results and build confidence that the codes correctly capture and predict the details of the plasma – surface interaction physics. As our numerical frameworks mature and successfully reproduce laboratory experiments with an increasing level of complexity, we will operate them to guide our analysis and interpretation of space-based observations. This is envisioned as an iterative process that converges on the identification of the most important physical processes that shape the surface properties of all airless bodies exposed to the solar wind environment. In contrast to earlier efforts, the maturity of the laboratory experiments will provide the vital link. In the lab one can simplify a real-life space scenario while being sure not to neglect essential physical processes, as they are inherently present.

The proposing group of scientists is expert in in-situ plasma measurements, surface spectroscopic measurements, and imaging. The existing laboratory experimental setups are readily available to generate flowing plasmas, UV radiation, surfaces with/without magnetic fields, and have full diagnostic capabilities. The group will also include experts on numerical studies of plasma kinetic processes using hybrid and full-particle methods.

To conclude, the proposed project will greatly improve our understanding of fundamental surface-plasma interaction mechanisms with airless bodies. Although not driven by space exploration, our insights will be able to provide guidance for the development of better instrumentation for future robotic and human missions.

Scientific rationale of the project

Airless bodies are ubiquitous in our Solar System, including the Moon, most of the planetary moons, Mercury, asteroids and dormant comets. Their response to external plasma and magnetic fields is vastly different from bodies that do support a substantial atmosphere (e.g., Mars, Venus) or an intrinsic magnetic field (e.g. Earth, the gas giants). In the latter cases, the surface is shielded from the impinging solar wind plasma either by an induced conductive ionosphere/magnetosphere or the large-scale global magnetic field itself. In contrast, on airless, non-magnetized bodies charged particles and photoelectrons have free rein to directly interact with the dusty surface and trigger both short and long-term changes. Typically no upstream bow shock is formed, and the majority of the impinging plasma is either absorbed or neutralized, and a plasma void is created behind the body. The essentially insulating material allows the magnetic field to be dragged through the body almost undisturbed leading to a complex and fascinating interplay between the various processes. These include direct particle interactions with surface sources and sinks generated by the dusty regolith by photoemission, backscattering, secondary electron emission, sputtering and surface charging, to name a few. The plasma interactions with the surface of these airless bodies play a key role in space weathering, generating their tenuous exospheres, and the redistribution of dust on their surfaces.

The importance of comprehending plasma-surface interactions has been recognized since the beginning of the space age. Already during the cold war inspired 'Space Race' the physical understanding and exploration of the Moon proved to be much more complex than anticipated. Over time, as the observations accumulated and became increasingly sophisticated, the emerging picture only got more complicated (Fig. 1). We will concentrate here on the Moon, as it is the most thoroughly studied object and believed to be a benchmark for other airless bodies in the Solar System.

Due to the absence of an intrinsic magnetic field and significant atmosphere, the global Moon-plasma interaction is driven strongly by the Sun, directly affecting the lunar surface and exosphere. To first approximation, the upstream solar wind plasma should impact the dayside lunar surface almost undisturbed. Recent observations by Kaguya and Chandrayaan-1, however, have shown that 20-50% of the solar wind ions are scattered/reflected away from the surface, especially in regions with strong crustal magnetization. Some of the reflected particles are protons that capture an electron and become energetic neutral atoms (ENAs). Indications of reflected particles have been found up to a few hundreds of kilometers above the surface. ENAs interact only weakly with the plasma environment, but the reflected ions, on the other hand, have a more complex life. Interacting with the convective electric field and the interplanetary magnetic field (IMF), they may re-impact the lunar surface or follow cycloidal trajectories propagating downstream, complicating the wake interaction. Also sputtering from the lunar surface and ionization of neutral particles in the Moon's exosphere contributes to the amount of pick-up ions. Hence, the Moon is both a sink and a source of plasma in the solar wind.

In contrast to the upstream lunar surface, the downstream region of the Moon holds a vastly different plasma environment. A plasma void is created when the supersonic solar wind plasma particles flow past and interact with the dayside Moon. The Wind spacecraft observed Lunar wake signatures as far as 25 R_L (~43,000 km) behind the Moon. When the surrounding plasma refills the wake, the lighter and faster electrons move inwards ahead of the ions, producing an ambipolar

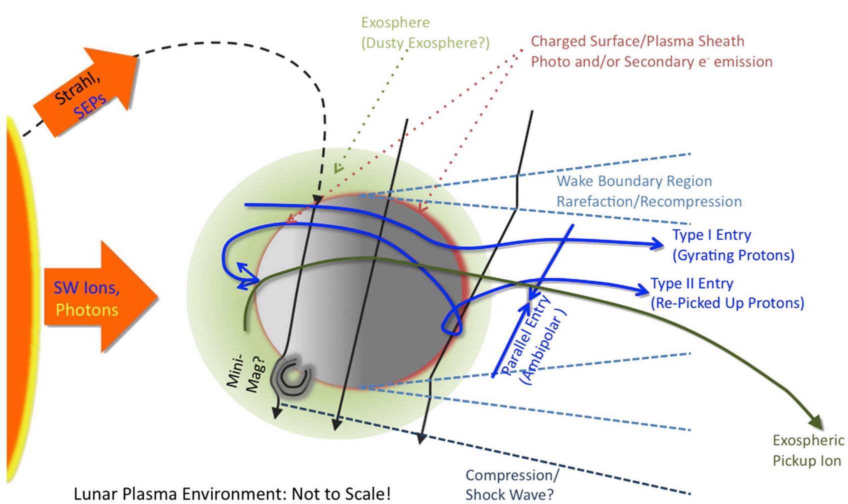

Fig. 1: Overview of the lunar plasma environment, including the solar drivers and fundamental physical processes. Image courtesy: Halekas et al. [2011].

electric field (because of charge separation) that accelerates ions and decelerates electrons into the wake. The IMF controls the refilling process. The resulting diamagnetic current system causes slightly elevated fields inside the wake cavity, whereas in the expansion region immediately surrounding the wake the opposite holds. This leads to the formation of rarefaction waves.

The lunar regolith, like any object immersed in plasma, will collect electrical charge. In contrast to most spacecraft, however, the Moon has very low surface conductivity. As a consequence, the lunar dayside charges positive (up to a few eV) due to photoemission when not eclipsed by the Earth. The nightside surface, on the other hand, may obtain very large negative potentials, depending on the plasma regime the Moon travels through. Measurements of electrons reflected from the night side surface by Lunar Prospector suggest a surface potential of at least −35eV with a typical value near −100eV, and up to -1000eV, with respect to the ambient plasma potential. Although the non-neutral plasma sheath above the charged lunar night surface has a scale-height of only on the order of the Debye length (roughly a few km), the associated potential differences are large enough to accelerate charged particles, connecting the surface potential of the body to that of the solar wind plasma, which on its turn may affect the global lunar plasma environment. Additionally, the role of magnetic anomalies and their possible connection to lunar swirls remains especially enigmatic. In-situ observations show the deflection, reflection and shielding of the solar wind flow, leading to the formation of mini-magnetospheres. Strong electric fields emerge from differential charging of the surface, as the electrons and ions interact with the magnetic field differently. The topology effects (e.g., and modulating the access of the solar wind flow, hence generating localized plasma dynamics (e.g., mini-wakes). In summary, the modes of interaction, the charging of the surface the dynamics of emitted photoelectrons, the distribution of electric fields, and the possibility of dust mobilization and transport are all open and outstanding questions.

Identifying the correct theoretical description for the latest observations is not straightforward, because of the many unknowns in estimating the photoemission and secondary emission rates from the lunar surface and the description of dust in the models. Therefore, as a third, often forgotten pillar next to in-situ observations and modeling efforts, are the laboratory experiments that can provide an excellent and independent tool to recreate near-surface plasma environments and challenge the analysis and interpretation of space-based data and the appropriate use of numerical models. They have the particular advantage to be able to provide a complete set of diagnostics while being sure to not neglect essential physical processes, as they are inherently present, in contrast to numerical frameworks, which possess only the implemented physical model. The great strength of simulations of course is their capability to absolutely define the physical processes included in the model. One of the main goals of our proposed activities is to exploit this synergy between the (possibly incomplete) fundamental physics implemented in the simulation models on one side and in-situ observations on the other side by providing the vital link via state-of-the-art laboratory experiments (Fig. 2). The ultimate goal of the laboratory experiments is not to reproduce the full complexity of the space environment, rather than to focus on a few fully controlled processes and provide a challenge to the simulation/theory community to reproduce the results. The codes than can be exercised with a much higher level of confidence to aid in the analysis and interpretation of in situ observations, and to identify and describe the processes that are responsible for shaping plasma - surface interactions in space.

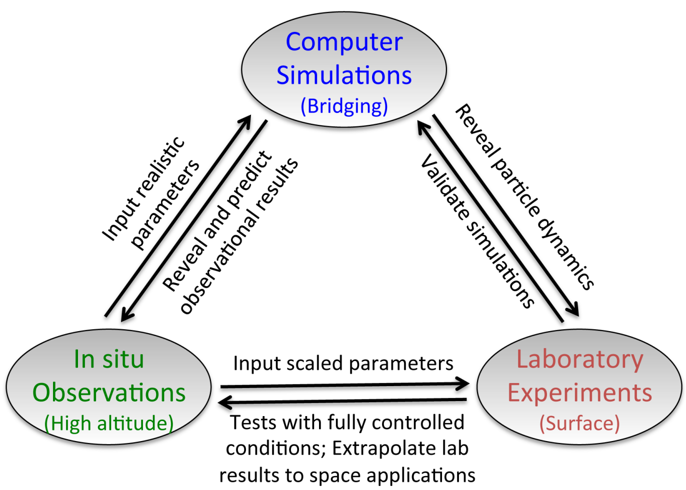

Fig. 2: Interrelationships between in-situ observations, computer simulations and lab experiments.

The Moon provides a unique environment to study the fundamentals of ion and electron decoupling, UV radiation and dust dynamics. Many of the fundamental lunar plasma processes will also operate at other airless bodies throughout the solar system. It is expected, however, that the coupling between the fundamental processes might not be so similar. The lunar plasma environment is very tenuous and most plasma processes will couple only weakly compared to other planetary environments. For example, most of the airless satellites in the Jovian and Saturnian system rotate within a very energetic magnetosphere with plasma flow driven by the planetary rotation. While traveling through the different regimes of the magnetosphere, the magnetospheric flow might change relatively rapidly from a subsonic to supersonic regime causing a dynamic reconfiguration of the wake. As proven by recent observations from the Cassini spacecraft visiting the Saturnian moons, often the solar photon flux to the surface will be at a very oblique angle to the predominant local plasma flow, leading to very complex interactions, unknown to our Earth's moon.

The other end of the spectrum is small moons and asteroids, where many plasma-surface interactions are similar to at the Moon, untroubled by large energetic/magnetic neighbors. However, we do expect a different plasma regime. Having typical sizes below the solar wind ion-gyro and inertial scales, simulations and early indications from the Rosetta mission have shown a very different wake structure and the principal kinetic processes at work might be different compared to the lunar case.

Various lunar and asteroid missions are on the way or in an advanced planning stage. It is imperative to map out the fundamental physical processes dominating the various plasma-surface interactions omnipresent in our Solar system in order to aid in the interpretation of future plasma measurements.

Scientific goals and objectives

The main goal of our team is to investigate and explore key challenges in the plasma-surface interactions with airless bodies by exploiting the synergies between in-situ observations, simulations models and laboratory experiments to better identify and understand the fundamental physical processes determining the global and local near-surface plasma environments. We envision the development of experiments and numerical models as an iterative process converging on the identification of the most important physical processes that shape the surface properties of all airless bodies exposed to the solar wind environment. Our key open questions include:

1) How is the upstream environment enriched by backscattered electrons/ions, ENAs, waves and heating processes?
2) What are the physical processes of the lunar wake refilling? What is expected for smaller bodies (i.e., the diameter smaller than the ion gyroradii and inertial lengths)?
3) What is the dust charging process and mechanism for dust mobilization?
4) What are the effects of topology on localized plasma environments and surface charging?
5) How does the solar wind interact with magnetic anomalies and subsequent effects on surface properties?
6) How do the co-rotation plasmas of the planets interact with their moons?

Note, these questions will not only improve our fundamental understanding of surface-plasma interactions, but are also directly related to the possible hazards of human and robotic exploration.

Timeliness of the project

In recent years a large number of space-based observations have become available for detailed studies of the Moon (e.g. Kaguya (SELENE), Chang'e 1, Chandrayaan-1, ARTEMIS, LADEE) as well as for other airless bodies such as Phobos (Mars Express), the Saturnian moons (Cassini) and the 67P/Churyumov-Gerasimenko comet (Rosetta). Additionally, driven by recent successes of full-kinetic simulations, also laboratory experiments are now fully developed and highly capable to study various kinetic processes believed to be important for the near-surface plasma interaction at airless bodies.

Up to now, the community has made efforts to combine observational results with numerical models and was successful at recreating the large-scale evolution of the system. To make accurate predictions, and access the next dimension to more completely understand the near-surface microphysics, laboratory experiments can provide the missing link.

Expected outcomes

This work is intended to bring our fundamental understanding of the plasma-surface interactions with airless bodies in our Solar System to an unprecedented level by making significant progress in identifying and characterizing the interplay of particles processes in the near-surface environment. We will publish our results in international, peer-reviewed journals and will also disseminate our progress and Team activities at international conferences. ISSI support will be acknowledged in all of the above publications. The Team Leaders will also setup a website for the project that will describe the following: the aims of the project, the members of the Team, the project schedule and the latest scientific results.

Reason for choosing ISSI Bern as implementation site

ISSI Bern provides the ideal opportunity to bring together a team of international experts. Establishing a collaboration among scientists with different expertise and approaches will strengthen the multidisciplinary aspects of the proposed research and result in a deeper understanding of the issues. Secondly, the city of Bern and the excellent facilities and reputation of ISSI provides the ideal location to bring to the same table theorists, experimentalists and observational scientists to discuss a shared problem. This is a highly appreciated given among the members of our team whom have visited ISSI before. Finally, the impact of financial support for the team cannot be underestimated for the success of this endeavor.

List of confirmed participants (alphabetical order)

Our Team has 12 members and 2 external experts (in alphabetical order):

	Participant	*Primary expertise*	
1.	**Bamford**, Ruth (RAL Space, UK)	- Lab experiments	
2.	**Deca**, Jan (University of Colorado Boulder, USA)	- Simulation (PIC/LMA)	- *Team leader*
3.	**Delzanno**, Gian Luca (Los Alamos National Labs, USA)	- Theory/simulation (PIC/dust)	
4.	**Futaana**, Yoshifumi (Swed. Inst. Space Physics, SWE)	- Observations (Chandrayaan-1)	
5.	**Halekas**, Jasper (University of Iowa, USA)	- Observations (Artemis)	
6.	**Henri**, Pierre (CNRS, FRA)	- Rosetta/Bepi-Colombo	
7.	**Horányi**, Mihály (University of Colorado Boulder, USA)	- Theory	*- External expert*
8.	**Jarvinen**, Riku (Finnish Meteorological Institute, FIN)	- Simulations (hybrid)	
9.	**Lue**, Charles (University of Iowa, USA)	- Observations	- Young Scientist
10.	**Nishino**, Masaki N. (Nagoya University, JAP)	- Observations (Kaguya)	
11.	**Poppe**, Andrew (University California Berkeley, USA)	- Observations (Artemis)	
12.	**Ratynskaia**, Svetlana (Royal Inst. of Technology, SWE)	- Theory	
13.	**Roussos**, Elias (Max Planck Institute, GER)	- Observations (Cassini, Galileo)	
14.	**Vignitchouk**, Ladislas (Roy. Inst. of Technology, SWE)	- Simulations	- Young Scientist
15.	**Wang**, Xu (University of Colorado Boulder, USA)	- Lab experiments	*- Co-team leader*

Schedule of the project

We request support for two team meetings at ISSI-Bern of one-week duration each. 1st meeting: fall 2015, 2nd meeting: late spring 2016. Completion of the project: end of 2016 (18 months after start).

Facilities required

The standard ISSI workshop facilities are required, i.e. a meeting room for 16 people (12 team members + 3 students/young scientists + 1 external experts), equipped with data projection facilities, wireless internet access and some limited printing facilities. We expect that most team members will use their own laptop computers. In addition, we would ask a room to arrange one-day splinter meetings.

Financial support requested to ISSI

We request that ISSI provide living expenses (per diem and accommodation) for 12 team members, twice for 5 days. Travel coverage for the Team leader, and if possible also for the Co-team leader (Boulder<->Bern) is requested, while all other Team members will be responsible for their own travel to ISSI.