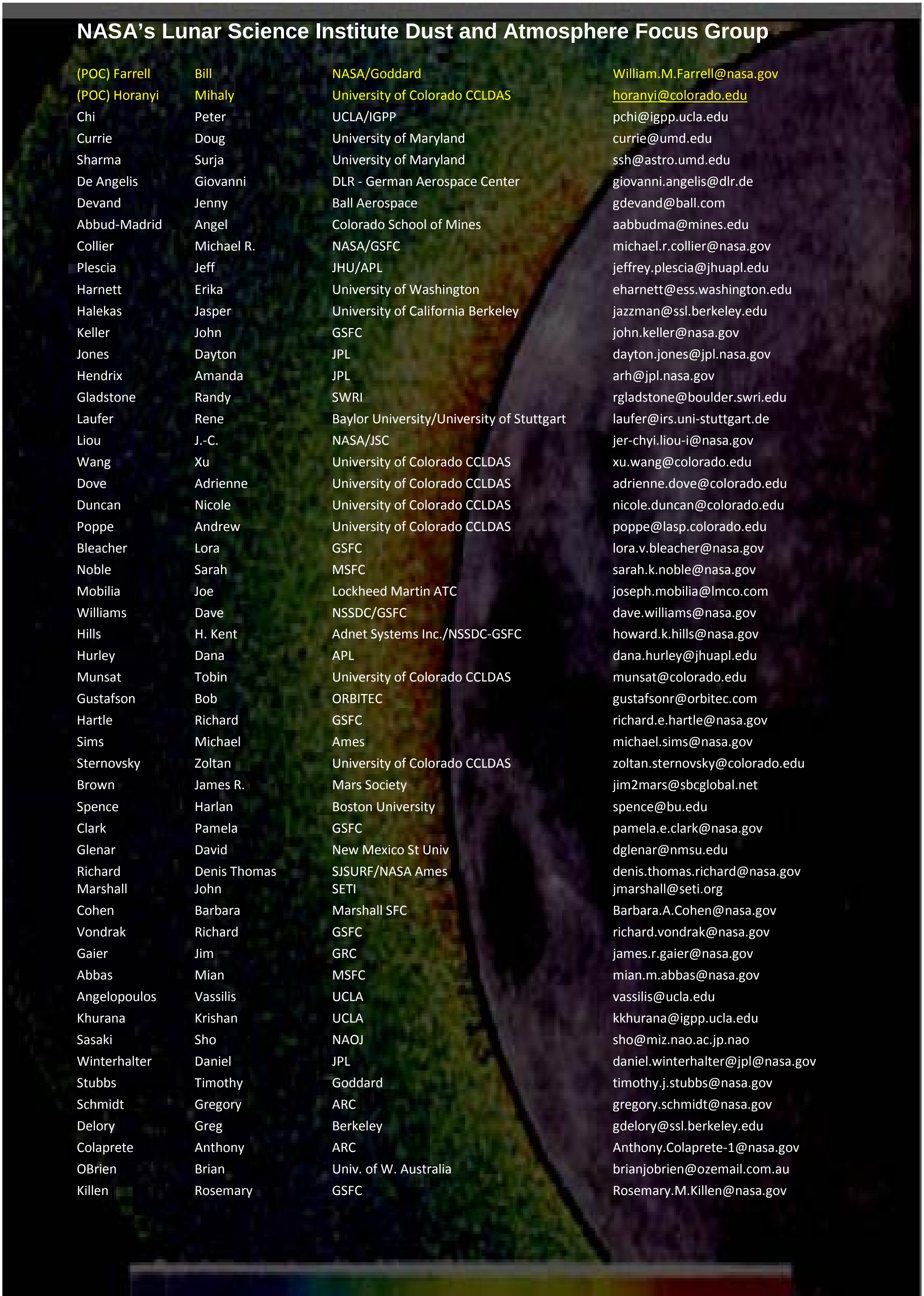
The Lunar Dusty Exosphere: The Extreme Case of an Inner Planetary Atmosphere



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Introduction

The lunar surface, as many other objects in the solar system, is directly exposed to the harsh space environment including a continual bombardment by interplanetary impactors large and small, high energy radiation, UV/xrays, and solar wind plasma. In addition, the Moon spends about 1/4 of its orbit within the terrestrial magnetosphere, exposed to similar warm/hot plasma conditions to moons orbiting within other planetary magnetospheres. As indicated in Figure 1, in direct response to these intense and variable environmental drivers, the Moon releases a low density neutral gas forming a collisionless atmosphere. This ~100 tons of gas about the Moon is commonly called the lunar **surface-bounded exosphere** (or SBE, see Stern [1999] and references therein). Ions are also created directly either by surface sputtering or subsequent neutral photoionization, forming a tenuous exo-ionosphere about the Moon. Due to the incident solar radiation and solar wind plasma, the lunar surface becomes charged much like the wall of a plasma chamber [Manka, 1973], and electrostatic forces appear to be capable of lifting dust from the surface [Stubbs et al., 2006]. The efficiency of this process, as well as the height these small charged particles might reach, remains an intensely debated issue since the Apollo era. By analogy, the Moon is essentially a **nearby laboratory** to study the evolution of exposed surfaces to the harsh space environment with direct applications to other near-airless bodies (e.g., Mercury, asteroids, KBO) throughout the solar system. The neutral, plasma and dust environment of the Moon is largely shaped by the Sun. This **solar-lunar connection** will be explored by NASA's Lunar Atmosphere and Dust Detection Explorer (LADEE) to be launched early 2012, when solar activity is the greatest and storms are expected to force the dusty exosphere to expand and contract in cadence with the extreme events [LADEE SDT report, 2008]. Some of the most critical questions of the Moon's dusty exosphere are listed in Table1.

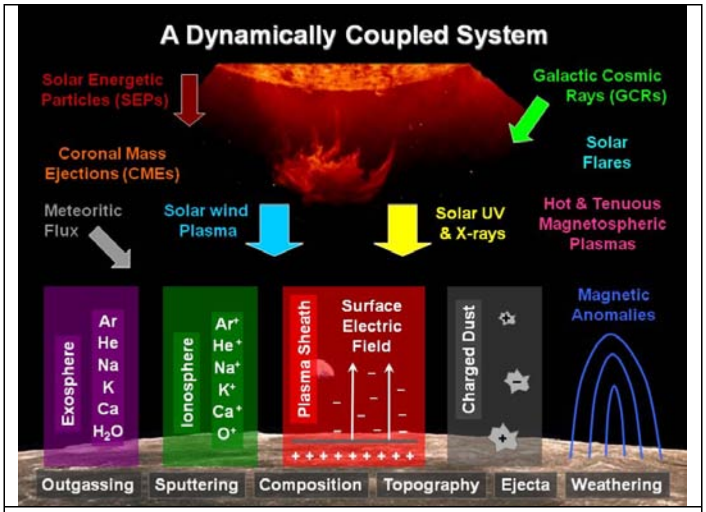

Figure 1- The response of the Moon to the outflowing solar energy and matter – the creation of a dusty exosphere (From Stubbs et al., 2008)

Table 1- Critical Questions of the Lunar Dusty Exosphere
What is the relative importance of the various processes that sustain the lunar exosphere?
How do volatiles originate, migrate and collect at the lunar poles? What is the efficiency of their preservation?
What is the composition of the exosphere and where are the missing 'expected' species like H and O?
What drives dust transport, especially to great heights from the surface?
How does the lunar surface respond to solar storms, meteor showers, big impacts, human activity, and other extreme events?
How does the space weathering processes affect the properties of the surface and interfere with our interpretation of the geological record?

Comparative Planetology and Basic Processes

The response of the dust, plasma and atmospheric environment to the variable solar conditions at the Moon is of great interest and can serve as the 'Rosetta stone' of understanding the vast differences in the evolutionary path of the near surface environments of other solar system objects.

First, the outgassing and sputtering of lunar neutrals represents **the most primitive atmosphere in the inner solar system**. While Venus represents one ‘high density’ extreme, the Moon is our ‘low density’ extreme in the spectrum of atmospheric systems. The lunar surface gas concentration consisting primarily of Ar-40 and He is less than 10^6 cm^{-3} - compared to 10^{19} cm^{-3} at Earth and 10^{17} cm^{-3} at Mars. In many ways the lunar exosphere looks more like the atmosphere of an asteroid or KBO, and thus its understanding represents a gateway to understanding other low density SBE’s at icy/rocky bodies and especially that at Mercury. In fact, some of the newly discovered hot neutral gases at Mercury ejected at temperatures in excess of 30000K are reminiscent of the hot sodium ejected from the lunar surface. How these escaping gases leave the surface at such high temperatures is simply not understood at this time.

Second, the polar regions of near-airless bodies represent special regions where **volatiles can collect within cold traps**. Of interest is the collection of water and other volatiles that is either delivered to the surface via cometary impacts or created via regolith/micro-meteoroid interactions [Vondrak and Crider, 2003]. From a comparative planetology perspective, there is a tendency for cool inner solar system rocky bodies to collect water/volatiles at the poles. The exact processes for the collection may differ depending upon whether the atmosphere is collisional (convection driven circulation) or collisionless (surface-atom migration), but there appears to be a certain universality to polar water and volatile collection. The processes at the Moon would clearly represent the collisionless collection extreme. An engaging white paper featuring an extended discussion of **lunar volatiles by Hurley et al.** has been submitted to the Inner Planets Decadal Survey team - providing further information on the current state of knowledge of volatile processes and path forward.

Third, another common set of processes acting on rocky bodies are the **mobilization, lofting, and transport of particulate matter (aerosol, dust)** from their surfaces –creating dust-laden atmospheres. In the case of Earth, dust is lifted via gas dynamic forces created in a collisional atmosphere. However, particles are also lofted from the surfaces of objects having collisionless atmospheres like the Moon and asteroids like Eros. For collisionless exospheres exposed to the space environment, electrostatic forces are suspected to be a primary driver to create dust transport. In essence, the near-surface intense E-fields in these dusty plasma systems now play the role of the gas-dynamic forces in collisional atmospheres in creating the surface stress. In the case of Mars, it has been suggested that electrostatic forces work in tandem with gas-dynamic forces to enhance dust lifting – making Mars a hybrid case where electrical forces at times become comparable to gas-dynamic forces [Kok and Renno, 2008]. As such, surface-originating aeolian particles (aerosols, dust) are a component of any atmosphere/exosphere system - the Moon and other airless bodies are no exception. A comprehensive white paper has also been submitted on the **basic issues of lunar dust by O’Brien, Dyer, et al.** that addresses

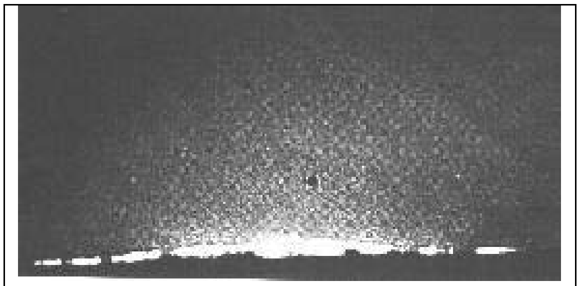

Figure 2- Surveyor 6 observations of lunar horizon glow from electrostatically-levitated dust at twilight [Criswell, 1973].

more detailed science, engineering, and operational aspects of lunar dust – which has direct applications to any future exploration to dusty environments like near-Earth asteroids and Mars.

Fourth, the inner planets are all connected to the Sun –via radiation and conductive coupling. However, the nature of the **solar connection for inner solar system bodies** differs depending upon both the thickness of the body's atmosphere and strength of its magnetic field. Inner solar system bodies provide a unique range of magnetic shielding from fully unprotected enabling the direct deposition of solar wind plasma, to a 'magnetosphere-like' setup where sufficiently intense magnetic anomalies can divert the solar wind flow. The near-airless, weak-field Moon again represents one extreme case where variable solar energy and matter has direct contact and influence on the surface – responsible for driving surface activity. The Earth and Venus represent the other extremes. It is for this reason that the LADEE mission will occur in 2012, during the peak in the solar cycle when the probability of a solar storm is high. LADEE will be joined by the **ARTEMIS 2-spacecraft fleet (see Khurana et al. White Paper**) that will make simultaneous space plasma observations. LADEE and ARTEMIS enable an unprecedented opportunity to explore the solar-lunar connection, and the study of this strongly driven exosphere that is expected to expand and contract in cadence with variable solar conditions. **It is one of the highest priorities of the lunar community to simultaneously operate LADEE and the ARTEMIS fleet in 2012 during solar maximum conditions.**

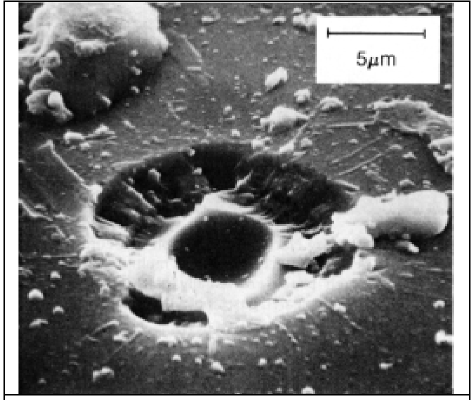

Figure 3 –Evidence of surface erosion from micro-meteoroid impact site [Hortz et al., 1991]

Finally, due to sputtered gases and lofted dust, there is a **space weathering/surface erosion** effect continually ongoing on the lunar surface (Figure 3). This environmental weathering is not as great as within the terrestrial atmosphere, but has an estimated erosion rate on rocks of about 1-m loss for every billion years [Horz et al., 1991; Stern et al., 1999]. It is often suggested that the Moon contains pristine, unaltered samples from the cataclysmic bombardment period ~3.8 Gyr ago. In fact, any samples from that period have been exposed to long-term space weathering: Today's few kilogram rock sample has most likely lost a substantial fraction of its original mass since the late heavy bombardment period. As such, the study of the lunar dusty atmosphere (as a by-product of surface erosion) has a direct connection to the nature of surface samples used as the **chronological record of the cataclysmic bombardment** from lunar basins. Understanding the erosion rates (as ejected flux of material into the atmosphere) is vital to placing any return sample in proper historical context.

Habitability Path: A Possible History for the Lunar Atmosphere and Geologic Connection

The Earth and the Moon share a common orbit and thus have been exposed to the same solar and impact conditions since the proposed large Moon-forming impact over 4.5 Gya. Despite the shared space environments, the Earth and Moon took extraordinarily different habitability paths. The juxtaposition of the two bodies in such close proximity is an illustrative example of a possible underlying fragility which may be common throughout the solar system. With the detection of extrasolar planets and the possibility of organics on primitive bodies, astrobiology is in a period of ‘new optimism’. However, the Earth-Moon system is an ever-constant reminder of how easily paths may diverge toward the harsh extremes. As such, **the Moon represents a critical data point in comparative habitability studies of inner solar system bodies** that may have been underappreciated in the past.

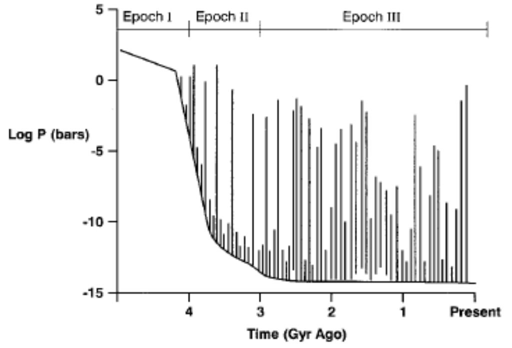

Figure 4 – A possible pressure chronology of the lunar atmosphere [Stern, 1999]

A key factor in habitability is the creation and maintenance of an atmosphere at any given body. Stern [1999] describes a possible evolution of the lunar atmosphere (see Figure 4): In its first 1.5 Gyrs, the primordial Moon’s magma oceans created hot gases and thus the formation of a high-pressure atmosphere. As the surface cooled over time, the atmosphere escaped the body via a number of mechanisms (e.g., Jean’s escape, sputtering) to form a low density surface bounded exosphere. However, larger impacts or volcanic eruptions releasing > 10^7 kg of gas could have created a series of short-lived collisional atmospheres – indicated by ‘spikes’ in Figure 4. How long this high-pressure atmosphere stays bounded to the Moon is unknown but is a question being considered by a number of NASA Lunar Science Institute (NLSI) teams.

In comparing Earth, Mars, and the Moon, it becomes evident that the sustainability of an atmosphere is strongly tied to the body’s **geologic activity**. Volcanoes provide a ready source of outgassing (one of many possible sources) while even deeper planetary dynamos act to create a **large-scale magnetic field** which deflects the atmosphere-eroding solar wind plasma and energetic particles. In essence, active geology provides both an internal gas source and a natural protection against external losses. In this perspective, the Earth represents the geologically active extreme with a substantial and contained atmosphere. In contrast, the Moon represents the geologically dormant extreme with a small outgassing source and substantial losses.

Mars is thus an intermediate case: it is now geologically dormant and no longer possesses a large-scale global magnetic field. Hence, the solar wind is constantly eroding the upper atmosphere – leading to substantial gas escape. The atmospheric escape rates are estimated to be ~ 0.02-2 kg/s [Chassefiere and Leblanc, 2004] and will be more-firmly quantified by the upcoming MAVEN mission. Mars may eventually end up as an SBE – but apparently the time scales to get to that point may be extraordinarily long - especially given sequestered volatile sources such as the current polar reservoirs and suspected hidden aquifers. This raises a number of interesting questions: Is the current Mars atmosphere similar to the Moon’s atmosphere about 4 Gya (at the start of Epoch 2 in Figure 4)? Why is the Moon’s past collisional atmospheric dissipation rate then considered relatively fast (~1 Gyr as seen Figure 4, and even much faster for transient sources) while Mars’ current escape rates suggests atmospheric dissipation times that are substantially longer (> 10 Gyrs to deplete the ~10^{18} kg polar reservoir)? Why is Mars not a fast-dissipater like the Moon? Given this perspective, **the Moon becomes an important comparative planetology data point, representing the geologically-dormant example for juxtaposition to the Martian atmosphere.** LADEE and MAVEN thus may be providing key atmospheric data sets for two dormant bodies in differing stages of dissipation – that make a nice addition to MESSENGER (CONTOUR would have completed the exospheric set).

Relevance

We know the top 5 atmospheric constituents at Venus, Mars, and (obviously) the Earth, but not at our nearest neighbor, the Moon. This fact is unfortunate since the Moon as a primitive body has unique processes for creating and maintaining its own atmosphere that differs from the more gaseous rocky planets. From a comparative planetology argument, it thus warrants is own unique investigation. The fact that the Moon also happens to be very close to Earth makes it a very desirable and approachable target. The urgent need to study the basic processes at the Moon is supported by numerous strategic science studies listed in Table 2. The common thread in all of these reports is 1) the recognition of our lack of fundamental understanding of the basic processes of all near-airless bodies on both short and geological time scales, and 2) the unique opportunity to use the Moon as an accessible laboratory to study such processes.

Table 2. Strategic plans are in support of Lunar dusty exospheric studies

Study Title	Lunar Dust and Atmosphere Applies to:
NAS/New Frontiers Decadal Study 2003	Cross-cutting Theme #2 Volatiles and Organics: The stuff of Life Q6. What global mechanisms affect the evolution of volatiles on planetary bodies? [The Moon's volatile migration and evolution is analogous to that at other primitive bodies including asteroids and KBO. As we ID the mechanisms at Moon, we thus gain insight of these other more distant objects.] Cross-cutting Theme #3 Origin and Evolution of Habitable Worlds Q7: What processes are responsible for generating/sustaining a habitable world? [Comparative planetology of rocky body atmospheres including the Moon will provide insights – including the cross-comparison of geologic activity, magnetic fields and atmosphere thickness.] Q9. Why have the terrestrial planets differed so dramatically in their evolution? [Moon provides insight into the formation of Mercury's and possibly Mars' atmospheric state and habitability pathway.] Cross-cutting Theme #4 Processes: How do Planetary Systems work? Q11. How do the processes that shape the contemporary character of planetary bodies operate and interact? [Surface bounded exosphere is in fact the most prevalent atmosphere in the solar system and thus warrants investigation – the Moon being a close target available to obtain that key understanding.]
NAS/Scientific Context for the Exploration of the Moon (SCEM) 2007	Concept 4. Lunar poles as special environments for water flux Concept 6. The Moon as a laboratory to study impact processes Concept 7. The Moon as a laboratory to study regolith loss and space weathering Concept 8. Study of processes involved in the lunar atmosphere and dust environments
Lunar Roadmap 2009	Objective Sci-A-1: Understand the environmental impacts of lunar exploration Objective Sci-A-3: Characterize the environment and processes in lunar polar regions and in the lunar exosphere Objective Sci-A-4: Understand the dynamical evolution and space weathering of the regolith Objective Sci-A-7: Understand the impact process
Heliophysics at the Moon 2007	Science Objectives: • Characterize the Near-Lunar Electromagnetic and Plasma Environment • Map and Determine the Origins of the Moon's Remnant Crustal Magnetic Fields • Interaction of Plasmas with the Moon • Characterize and Understand the Interaction of Dust and Plasma on the Surface of the Moon and in the Lunar Exosphere

Strategy to Obtain Science Closure

An ideal measurement strategy is to have both landed and orbital assets making simultaneous measurements of the lunar dusty atmosphere. **The strategy is similar to Earth's meteorological studies spearheaded by NOAA: a network of landed, orbital, and modeling assets are all intimately tied together to provide both contextual and predictive information**

on the lunar dusty atmosphere. Network-landed assets distributed at equator , poles, in permanently shadowed regions, and in magnetic anomalies, can provide surface level neutral gas, dust and plasma densities as a function of solar zenith angle and local topo/field conditions. Especially emphasized on such packages is the study of processes that creates local surface ejection of material – including gases and dust. The orbital assets overhead can provide scale height information based on surface-to-orbit gas and dust density differences which will vary both with solar zenith angle and prevailing solar wind conditions. Orbital studies also provide a global view of the lunar weather. These observations will be continuously assimilated into up-to-date models that extrapolate forward into new temporal regimes. Also, assets from upstream solar radiation/solar wind monitors shared with the terrestrial space weather community can be used in correlative studies. Specific opportunities/packages possible for dust and atmosphere studies are included in Table 3. While the list below is in approximate priority, we should emphasize that **every landed mission should contain a miniature 'lunar space weather station'** and we provide landed mission examples below. The argument is parallel to the Mars atmosphere researchers request for a meteorological station onboard every landed mission to provide sets of surface atmospheric measurements to validate and calibrate larger system-level models.

Table 3. Landed and Orbital Packages are used to obtain Dust and Atmosphere Science Closure.

Description	Type	Proposed Measurements	Lunar Dust and Atmosphere Science Closure
Lunar Atmosphere and Dust Environment Explorer (LADEE)	Orbit ~50 km altitude	-Neutral Gas density -Dust density and size -UV limb spectra (ID gas and lofted dust)	First orbital exploration of the lunar exosphere and dust environment scheduled for 2012 launch. Obtain temporal variation of known constituents and discover/place lower limits on currently undetected species.
Landed dust-gas instrument packages (e.g., ILN)	Landed	-Neutral gas density and energy -Ion and electron density and energy -Dust size, velocity, and charge -E-field/surface potential	Detail the connection between suspected drivers and ejected gas/dust concentration and energy. Examine sputtered gas and ions, their correlation with driving solar wind and energetic particle, and dust lofting via electrostatic fields. ILN to launch in 2018 and their SDT has identified a geophysical package as that to fly.
Suitcase Science Package (like ALSEP)	Landed	-Neutral gas density and energy -Ion and electron density and energy -Dust size, velocity, and charge -E-field/surface potential	ALSEPs included many of these, but spread over different packages and missions. We propose to merge all of these with a common IDPU to examine detailed correlations.
Polar Crater Explorer	Landed	-Neutral gas density and energy -Ion and electron density and energy -Dust size, velocity, and charge -E-field/surface potential	Any proposed Discovery or NF mission into PSRs should include a gas-dusty plasma package. The gas detector will examine volatile content just above the surface while the dusty-plasma package will examine sputtered losses and H+ collection processes.
Lunar Polar Dust Sample Return Mission	Orbit 10's km altitude over poles	-Dust sample collector (e.g., Aerogel system) -In situ dust mass, velocity, charge, & composition/spectrometer	If LADEE demonstrates that dust is lofted to 10's of km at terminator regions, then an orbiter can collect samples of lofted dust from regions of strongly negative surface potentials within permanently shadowed crater. In essence, use the 'lift' provided by natural E-field to collect polar dust surface samples for return to Earth
Lunar Mini-Magnetosphere Explorer	Orbit 10's km altitude over high B	-Neutral gas density and energy -Ion and electron density and energy -Dust density, mass, & charge -E-field/surface potential -B-field -Surface Imaging/spectrometry	Detailed examination of high-B regions. Correlate plasma, neutrals and surface features (like at Reiner-Gamma Formation) to understand space weathering and gas escape in high B-field regions.

Technology Drivers. The planetary and space science communities already have mature designs for neutral, plasma, E and B fields, and dust detection instrumentation. Example of these are currently being flown as part of Kaguya, LADEE and ARTEMIS missions and have flown in the past onboard spacecraft to study the icy moons of Jupiter and Saturn.

The primary driver will be to optimize these instruments for the anticipated orbital and surface environments. At orbital altitudes dust sizes may be small and difficult to detect. Neutral gas densities may also be relatively small and thus an in situ neutral mass spectrometer (NMS) should be optimized for this case. The LADEE SDT considered this optimization and suggested the inclusion of a UV/VIS spectrometer for remote sensing of lofted dust and gas via collective optical scattering from the large limb-directed gas column. Ion mass spectrometry is also a sensitive technique for detection photo-ionized and sputtered species. On the surface, atmospheric concentration may be higher and thus easier to detect but instrumentation should be placed away from contaminating landed systems. Dust may also be larger and thus easier to detect. Every effort should be made to create a **low-power integrated suite of dust-atmosphere-plasma instruments that could then fly as a standard package on every landed mission**.

Laboratory studies are also recommended to be vigorous, to provide further validation of the expected basic processes occurring in the dusty atmosphere. Such studies will allow: (i) interpretation of orbital and landed measurements, (ii) characterization of lunar dust analogs and Apollo samples, (iii) modeling of the scattering and polarimetric behavior of these particles, especially large grains expected near the surface (iii) guide the design of new optical and dusty plasma instruments and refine that of existing ones.

Conclusions

NASA is noted for many cultural achievements and arguably two of its most important are derived directly from comparison studies of the inner planet atmospheres: Nuclear winter scenarios based on a Mars analog and greenhouse gas/global-warming scenarios based on a Venus analog. These studies emphasize the fundamental axiom that as we gain contextual understanding of other systems around us, we in turn gain far-reaching and new insights into our own system that can impact culture, politics, and finance. Hence, there is tremendous value in inner planet comparative planetology studies, and the Moon should be actively included in any such comparison.

The Moon is an extreme type of atmosphere – a surface bounded exosphere – and may represent the final 'ground state' of any geologically dormant body. Mercury seems very close to this dormant state, Mars may ultimately be heading that way, while the Earth and Venus remain geologically active enough to be different from the Moon for an apparent long time. The Moon is thus a key book rightly positioned at the end of an important volume set – a set that has stimulated critical insights into basic processes of our own world. However, these books are not complete. For the lunar atmosphere, we suggest a combinations of dust, plasma, and gas packages on orbiters and on the surface can greatly advance our understanding of the basic processes associated with " selenio-meteorology". Their results have immediate applicability to other primitive bodies, like asteroids, KBO, and Mercury. Clearly, LADEE and the two ARTEMIS probes in lunar orbit during solar maximum represent an exciting new chapter on the solar-lunar environmental connection to be written very shortly.

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