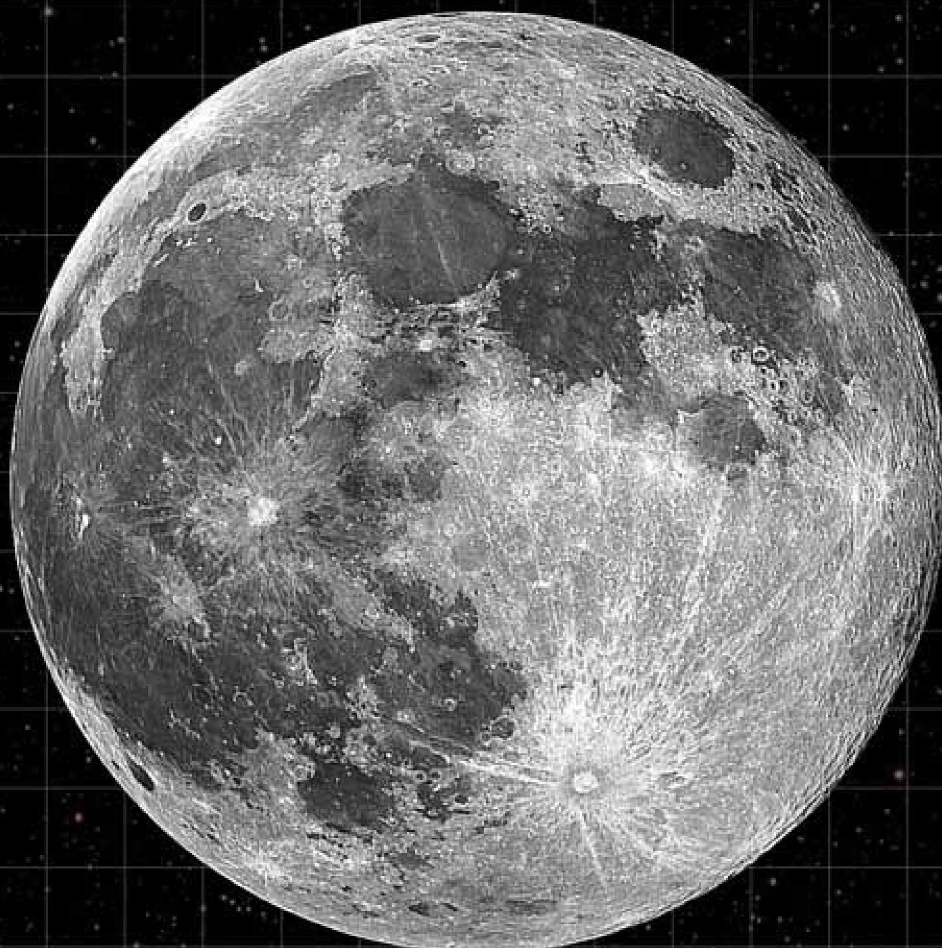
National Aeronautics and Space Administration

NASA Science Definition Team
for the



Lunar Atmosphere And Dust Environment Explorer
Study Report

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NASA
Science Definition Team (SDT)

for the

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Contents

1.0 PREAMBLE

The National Aeronautics and Space Administration (NASA) determined in 2008 that its Lunar Science Project will pursue the launch of an orbiter to the Moon in the 2011 timeframe. This planned orbiter, the Lunar Atmosphere and Dust Environment Explorer (LADEE), will seek new information about the tenuous lunar atmosphere and dust environment before that environment is altered by extended human activity on the Moon.

NASA formed a Science Definition Team (SDT) to devise goals and measurement objectives for LADEE and to consider candidate payloads. Like the LADEE mission, the SDT was small and focused. Dr. Laurie Leshin (GSFC) chaired the SDT and Dr. William Farrell (GSFC) was Vice-Chair. A complete list of SDT members and their affiliations is provided in Appendix 1.

The SDT met almost weekly by telecon between mid-February and mid-May 2008. The team held two face-to-face meetings. The first was March 14, 2008 in Houston, TX and the second was April 17-18, 2008 in Greenbelt, MD. At both meetings, the team considered science objectives and potential instrument performance for both the atmosphere and dust goals. The critical trade of payload mass vs. trajectory (see Section 4.3) was detailed by the Project Team, led by Project Manager Mr. Butler Hine (ARC) and Mission Design Lead Mr. Will Marshall (ARC).

This report summarizes the activities and recommendations of the SDT. Section 2 identifies the key science questions the SDT believes LADEE can address in the 2011 launch timeframe. Section 3 lists the SDT's specific recommendations to the NASA Science Mission Directorate (SMD) Planetary Science Division and Lunar Science Project. Section 4 includes highlights of the discussions that led to the SDT's recommendations. Section 5 summarizes broader programmatic issues. Supporting material is available in the Appendices. Appendix 2 traces the LADEE science goals and measurements to the National Academy of Sciences (NAS) Scientific Context for Exploration of the Moon (SCEM) Report, and flows LADEE goals through measurement approaches and into how these parameters will drive instrument and spacecraft requirements.

2.0 SCIENCE OBJECTIVES FOR LADEE

The science focus of LADEE was prescribed in the LADEE SDT Charter – the mission is intended to explore the tenuous lunar exospheric species and dust above the Moon's surface. These high level goals are consistent with one of the high priority "science concepts" described in the SCEM Report: **Concept 8: Processes involved with the atmosphere and dust environment of the Moon are accessible for scientific study while the environment remains in a pristine state.** As discussed in Section 4, the lunar atmosphere is interesting as the most accessible example of a surface boundary exosphere. The dust is of interest for scientific reasons (as additional particulate matter in the exosphere) as well as for exploration purposes (the dust above the surface and the processes that cause its lofting should be accounted for in the design and operation of lunar surface habitats).

Through evaluation of these concepts and consideration of the most promising science that LADEE could achieve within them, the SDT recommends the following Science Objectives for the LADEE mission:

LADEE Objective 1: Determine the composition of the lunar atmosphere and investigate the processes that control its distribution and variability, including sources, sinks, and surface interactions

LADEE Objective 2: Characterize the lunar exospheric dust environment and measure any spatial and temporal variability and impacts on the lunar atmosphere

The SDT recommends that LADEE address both of these objectives.

3.0 SDT RECOMMENDATIONS TO NASA

Consistent with the Science Objectives described in Section 2, the SDT outlined recommendations for the LADEE mission (Table 3.1). The source for each recommendation is included with a pointer to further discussion in Section

4. These recommendations are the source of the baseline science mission (Section 4.4) and are the starting point for the definition of the measurement requirements, mission requirements, and instrument requirements (Appendix 2, Mission Traceabilty).

In summary, the SDT recommendations are:

Atmosphere. The SDT derived four critical recommendations for atmospheric study, including the LADEE science approach (Recommendation 1.1), the preferred LADEE trajectory (Recommendation 3.1), LADEE mission duration (Recommendation 1.5), and the LADEE atmosphere instrument complement (Recommendation 1.4). For the scientific approach to the lunar atmosphere, the SDT recommends that the inventory of species should be as comprehensive as possible, with traceability back to the species' atmospheric sources (solar wind, regolith, radiogenic). The science value is increased if LADEE is designed to detect a number of candidate species in each source category to determine the impact the source drivers have on the response of the surface/exosphere interface. To fulfill LADEE's goals, the SDT recommends a mission duration of at least one lunation (Recommendation 1.5), so the Moon passes from the solar wind into the magnetosphere. This will modify the driving charge particle environment that affects the atmosphere (via sputtering), providing some predictable variability to the surface source function. To enhance the likelihood that LADEE will detect trace atmospheric species from the surface, the SDT recommends that the LADEE orbit should pass at low altitudes (< 50 km) over the lunar-sunrise terminator (Recommendation 3.1, 3.2), where both the exospheric gas and particulates are most concentrated. It was noted that no one instrument can detect the full lunar atmosphere, and therefore, a primary instrument (such as a neutral mass spectrometer (NMS)) should have a supporting instrument (UV spectrometer or ion mass spectrometer (IMS)) to enhance trace species detection (Recommendation 1.4.1-3).

Dust. The SDT derived four critical recommendations for dust detection, including the LADEE science approach (Recommendation 2.1), the preferred LADEE trajectory (Recommendation 3.1), LADEE mission duration (Recommendation 2.5), and LADEE dust instrument complement (Recommendation 2.4). Two anticipated dust sources are the focus of LADEE's science approach: dust from the surface and interplanetary dust in the lunar environment. Surface-derived dust is expected to be submicron in size and slow, and hence difficult to detect. Interplanetary dust is high velocity and thus easier to detect via in situ instrumentation. Electrostatically lofted dust is expected to have peak densities near the terminators, and its density is likely to remain highly variable in response to changing plasma conditions. The preferred trajectory (Recommendation 3.1) to maximize atmosphere detection – low altitudes over the terminator – is also ideally suited for maximizing lofted dust detection. Models suggest that the lofted dust concentrations maximize when the surface potential is large and negative, which drives the SDT recommendation for a mission duration of at least one lunation (Recommendation 2.5). This will enable LADEE to monitor dust activity as the Moon passes through the magnetotail hot plasma (which will make the surface potential large and negative; see also Recommendation 2.3). Because lofted dust is so difficult to detect, the SDT recommends a set of strong complementary sensing systems, such as using remote sensing UV/VIS to support an in situ sensor (Recommendation 2.4).

Trajectory/Spacecraft. The SDT's trajectory recommendations are driven by the atmosphere and dust recommendations, especially the requirement to target LADEE at low altitudes over the lunar-sunrise terminator (Recommendation 3.1, 3.2). In addition, the SDT also recommends that spacecraft cleanliness and environment be a special consideration (Recommendation 3.4) since the candidate instruments considered are sensitive to outgassing, thruster firing, etc. The SDT recommends serious consideration that LADEE not be co-manifest with the Gravity Recovery And Interior Laboratory (GRAIL) mission (Recommendation 3.3), which would significantly relieve

Table 3.1: LADEE SDT Recommendations Feed Forward to Mission Requirements

	Recommendations	Source of Recommendation	Refer to Section
Lunar Gas Exosphere			
1.1	LADEE Science Objective 1: "Determine the composition of the lunar exosphere and investigate the processes that control its distribution and variability, including sources, sinks, and surface interactions.	Consistent with SCEM Goal 8a. Goes beyond a "when and where" survey to examine "why" species are there.	2.0, App. 2
1.2	LADEE should provide a thorough species inventory traceable back to atmospheric sources.	Connect gas species to the processes that create them.	4.1.1, 4.1.2
1.2.1	If the species is one of the very few definitively known to exist (i.e., Ar, He, Na, K), define the species variability to as short a time-scale as possible	Use known species as temporal "markers" to understand interface variability.	4.1.2
1.2.2	For species that have only upper limits (no known detection), either reduce the known limit or make the discovery detection of the species.	Expand the list of known species to further define the lunar atmospheric composition.	4.1.2
1.3	While a complete and instantaneous composition of a sample environment may not be obtained, a sampling of species in each of the primary sources (solar wind, regolith, and radiogenic) is desired.	Consistent with Objective 1	4.1.2
1.4	Fly a set of instruments that reliably provides the largest possible coverage of species detection.	To obtain a set of species in each source category, LADEE will need a number of complementary instruments (a set).	4.1.1, 4.1.2
1.4.1	A NMS can readily detect primary constituents (Ar, He) but at least one other complementary instrument is required to obtain further composition.	Consistent with Objective 1	4.1.2, 4.4
1.4.2	The most likely complementary sensor is a UV spectrometer that can address remote measurements beyond LADEE orbit and can connect lunar exospheric gas and particulates.	Enhance composition via remote sensing.	4.1.2, 4.4
1.4.3	An IMS is also a candidate instrument that is capable of detecting trace species; any such instrument on LADEE should have temporal resolution and sensitivity improvement over the Kaguya IMA.	Enhance composition by increased sensitivity to trace ionized species.	4.1.2, 4.4
1.5	The set of instruments should fly for no less than one lunation to ensure LADEE passes through the magnetotail.	Varying plasma environment will impact sputtering. Over one lunation there is also the likelihood of passing through a meteor stream and some likelihood of being present during a solar storm.	4.1.1, 4.3, 4.4
Lunar Dust Exosphere			
2.1	LADEE Science Objective 2: "Characterize the lunar exospheric dust environment and measure any spatial and temporal variability and impacts on the lunar atmosphere."	Consistent with SCEM Goal 8a.	2.0, App. 2.0
2.2	Any in situ dust detector should have the capability to detect submicron particles to increase the likelihood of sensing small lofted grains.	The dust of lunar origin is expected to be small and slow moving.	4.2.1, App. 2.0
2.3	LADEE should take full advantage of the extreme variations of the driving external environment to increase the likelihood of dust detection, including sensing incoming micro-meteoroids and associated ejecta during predicted meteor showers and detecting lofted dust during plasma sheet crossings and solar storms (when the surface potential is large and negative).	Recognize that dust lofting is a function of the lunar environment and use the extremes in conditions to aid in detecting the difficult-to-sense lofted dust.	4.2.1
2.4	Use of both in situ and UV remote sensing techniques to obtain a complementary and consistent dust detection data set.	It will be a challenge for in situ dust detection to sense small lofted dust. UV provides a reasonable supporting capability.	4.2.2
2.5	Dust measurements should occur over at least one lunation.	Driven by the need to have a passage through the magnetotail/plasmasheet where surface potentials are large and negative (drive lofted dust to higher altitudes).	4.2.1
Spacecraft/Trajectory Recommendations			
3.1	The SDT recommends that the orbit be retrograde, and as close to circular, with as low an altitude and as low an inclination as possible (but no higher than 50 km and inclination 180deg +/- 20), consistent with delivering a payload mass of at least 20 kg.	Retrograde orbit for instrument protection (ram out of sunlight during lunar-sunrise terminator passes), equatorial orbit passes through greatest gas concentration, and 20 kg allows NMS, dust, and supporting instrument measurements.	4.1.1, 4.2.1, 4.3,
3.2	The orbit target is a box of +/- 5 km centered at 45 km altitude or lower over the lunar-sunrise terminator.	Lunar atmosphere has largest concentration at this terminator.	4.1.1, 4.2.1,4.3
3.3	Consider a separate launch at a schedule more compatible with the spacecraft and payload development, and independent of constraint with GRAIL.	The GRAIL ride-share limits the LADEE launch mass and increases science risk.	4.3
3.4	Project provides a systemic approach to spacecraft environmental cleanliness, including early development of plans to optimize outgassing, thruster firings, and EMI.	Spacecraft is "dirty" and emissions could set the background thresholds for gas and dust detection.	

	Recommendations	Source of Recommendation	Refer to Section
Programmatic Recommendations			
4.1	The SDT recommends creation of a strong science team, both in instrument selection and in an active participating science community.	LADEE should not just buy instruments; needs science expertise to achieve the objectives.	5.2
4.1.1	The science teams should be integrated into LADEE as soon as possible (in FY08 or early 09) since mission PDR is currently scheduled for 9/08.	The quick response requires a an early science presence to assist in PDR preparations.	5.2
4.2	A lunar observation ground campaign to occur concurrent with the LADEE mission should be supported by the mission.	To support and complement the LADEE observation set.	4.1.1
4.3	Integrate atmosphere and dust modeling science into the LADEE Science Team.	To interpret and extend the observations.	4.1.1, 4.2.1
4.4	Access to space weather monitor data sets (most likely from other satellites upstream from the Moon) for correlation with LADEE atmosphere and dust observations will greatly enhance the science return.	Determine the controlling effect of the charged particle environment.	4.1.1, 4.2.1

spacecraft and instrument schedule pressures and enhance LADEE mission capability.

Programmatics. The SDT strongly recommends including both instrument science and participating science teams as early as practical in the LADEE mission, which will optimize operations and data products use (Recommendation 4.1). The SDT also recommends developing an active atmospheric gases (Na, K) remote sensing ground campaign in support of LADEE (Recommendation 4.2). This ground campaign may provide relatively affordable options to enhance LADEE science.

4.0 DISCUSSION OF SDT FINDINGS

Section 4.1 and 4.2 present a discussion of SDT's atmospheric and dust science findings that support the recommendations outlined in Section 3. Formal SDT findings are highlighted in red.

4.1 Atmosphere Science

The tenuous lunar exosphere is largely unexplored. After the Apollo program and ground-based observing campaigns, only four constituents of the lunar atmosphere have been positively identified: Ar, He, Na, and K. Argon and helium are thought to be the main constituents of the exosphere. Sodium and potassium have been observed in spite of their low abundance due to their strong spectral signatures. There are many more species that are expected to exist in the lunar atmosphere that have not yet been confirmed. Furthermore, the spatial and temporal variability of the lunar exosphere is not understood. The sources, release mechanisms, loss processes, and atmosphere/surface interactions all contribute to the distribution and variability. Models exist to probe these relationships [e.g., Hodges, 1980], but there are insufficient data on lunar exospheric variability for validating said models. So much remains unknown about the lunar exosphere that even a modest science payload onboard an orbiting spacecraft like LADEE can provide data that will yield a significant increase in understanding of the inventory of the lunar exosphere, its variability, and the governing physics.

Given that there are only four confirmed atmospheric species, it is expected that LADEE will discover numerous others and/or will place greatly improved lower limits for the relevant trace species suspected to be released into the lunar exosphere. In this regard, LADEE is truly a discovery-oriented mission.

4.1.1 Current State of Knowledge on Surface-bounded Exospheres

The lunar atmosphere is a surface-bounded exosphere, meaning that particles in the atmosphere can be considered collisionless until they encounter the lunar surface. As such, the particles follow ballistic trajectories upon release. Even so, the lunar exosphere is hardly simple. Not only have we detected very few of the species in the exosphere, we do not understand the mechanisms of the lunar exospheric system. Table 4.1 lists the known and suspected lunar exospheric species (modified from Stern [1999]). The densities listed in bold were measured previously via the Apollo 17 Lunar Atmospheric Composition Experiment (LACE) mass spectrometry or ground-based spectrometry.

Table 4.1: Known and Expected Lunar Atmosphere Constituents

Species	Science Relevance	Sources	Sinks	Expected 50 km Density (#/cm3)
Ar	Asthenospheric/seismic; good atmosphere tracer	Radiogenic	Ionization	**5000**
Si	Below Stoichiometry	Regolith	Ionization	<48
Al	Below Stoichiometry	Regolith	Ionization	<55
Ca	Below Stoichiometry/Sputtering	Regolith	Sticking	<1
Fe	Tracer of regolith	Regolith	Ionization	<380
Ti	Below Stoichiometry	Regolith	Ionization	<1
Mg	Below Stoichiometry	Regolith	Ionization	<6000
Na	Observable extended coma; 3 competing release mechanisms	Regoltih; Soil erosion	Ionization/escape	**~70**
K	Observable coma; short lifetime	Regoltih; Soil erosion	Ionization/escape	**~17**
He	Solar wind surface interaction	Solar wind	To Earth's corona	**<20000**
CH_4	Interstitial chemistry; surface processes	Solar wind	Dissociation/escape	<1500
CO	Interstitial chemistry; surface processes	Solar wind	Ionization	<15000
CO_2	Interstitial chemistry	Solar wind	Ionization	<1000
H	Interstitial chemistry; Quantify backscatter rate	Solar wind	Escape	<10
N	SW interaction w/ surface	Solar wind	Ionization	<600
C	Source and regoltih processes	Solar wind	Ionization	<40
H_2	Interstitial chemistry; primary form of escaping solar wind H	Solar wind	To Earth's Corona	<13000
OH	Distribution related to water vapor	Sputtering or dissociation of H_2O	Dissociation	<1000000
N_2	Solar wind/surface interaction	Solar wind	Dissociation/escape	<800
O	Regolith Marker species	Regolith	Ionization	<90
S	Tracer of regolith	Regolith	Ionization	<150

Key: Bolded densities measured via LACE mass spectrometry or ground-based spectrometry. Others are approximate near-surface upper limits based on optical/UV remote sensing [see Stern, 1999].

The other densities are approximate near-surface upper limits based on optical/UV remote sensing [see Stern, 1999].

There are multiple sources to the lunar exosphere, including the solar wind, the regolith/levitated dust, meteoric input, and outgassing from the lunar interior. These sources are the reservoirs that supply the constituents. However, exospheric abundance, spatial distribution, and temporal variations are also determined by the release mechanisms, surface interactions, and loss processes. Sputtering, photon-stimulated desorption, impact vaporization, and outgassing are four processes that can release particles into the lunar exosphere with different energy distributions at release. The height distribution of species in the lunar exosphere varies from species to species, depending on mass and the distribution of release energy. For all elements, density decreases with increasing altitude. However, the constituents typically have ballistic hop heights in the hundreds of km range [e.g., Crider and Vondrak, 2000]. Species that make up the lunar exosphere are thus prevalent at 50 km, and will have increasing concentration with decreasing altitude. The percolation of the atoms to high altitude will allow detection by a near-surface orbiter like LADEE.

In an ideal exosphere, the concentration goes with the temperature to the –5/2 power [Hodges and Johnson, 1968]. Thus atmospheric density should peak on the cold nightside of the Moon. However, many of the exospheric species adsorb to the cold nightside of the Moon [Hodges et al., 1973]. This reduces concentrations at night for condensable gases. Those gases would have atmospheric concentrations that would peak at the terminator, where the temperature is low, but sunlight still acts to stimulate desorption. However, since any particle that condenses on the nightside remains adsorbed until dawn, there is an additional source region at the dawn terminator compared to the evening terminator, which is only a sink. This source outweighs the other sources of the atmosphere because it is reinforced constantly. That is, a particle that is released as it rotates into sunlight at dawn has a 50% chance of being driven back to the nightside immediately, where it recondenses until it rotates back into sunlight a few hours later.

As suggested by Figure 4.1, peak exospheric densities are thus typically expected between 5 hour and 9 hour local time, just after sunrise (just dayside of the sunrise terminator). Generally, gas densities will peak at equatorial latitudes. Polar regions will see a reduced concentration (by about 50%) with maximum values along the sunrise terminator. Other sinks to the system include photoionization or dissociation (and other ionization mechanisms to a lesser extent), escape, and adsorbing to a permanent cold trap at the lunar poles.

Some of these processes have been observed at work and have been modeled. However, because of the dearth of data, many assumptions are required for the models. More direct measurements will make true advancements toward understanding the physics of the lunar surface-bounded exosphere system, including the advancement, improvement, and validation of existing models of the gas-surface interface.

4.1.2 Constituent Reservoirs

While a complete compositional inventory may not be obtained due to the low concentrations of gases involved, the SDT recommends obtaining a sampling of species from the primary sources: solar wind, regolith, and radiogenic (outgassing). These three reservoirs are represented by the four known constituents of the lunar exosphere: Ar (radiogenic), He (solar wind), Na (regolith), and K (regolith). The SDT finds that there is high likelihood of LADEE being able to address these different sources with the combination of a remote sensing spectrometer and an in situ NMS.

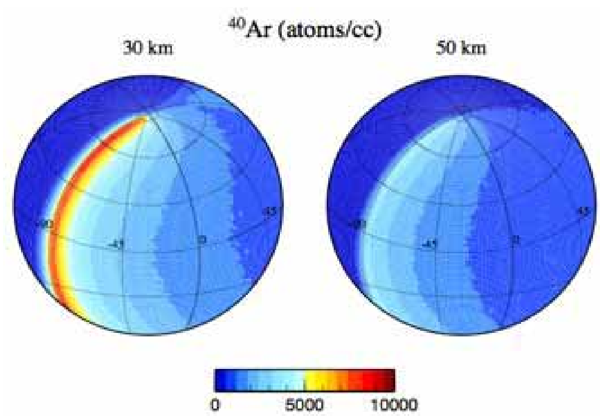
Additional insight can be gained through the detection of other species. Regolith-derived species may or may not exist in stoichiometric proportions. These "regolith" species may be released from either the surface or lofted dust in the lunar exosphere, providing a connection between the atmosphere and dust. Also, although there is a constant rain of hydrogen onto the Moon from the solar wind, there is not much hydrogen implanted in the regolith. Thus most solar wind hydrogen must be leaving the Moon nearly at the supply flux. LADEE would illuminate the path of the solar wind hydrogen by looking for H, H_2, and OH in the lunar atmosphere. This hydrogen path is of particular interest because of the enhancement of hydrogen observed near the lunar poles, which might be water ice sequestered in permanently shadowed regions. Likewise the path of carbon on the Moon is not known. The paucity of carbon in the regolith indicates that the carbon delivered there is not retained. It must pass through the exosphere in its journey away from the Moon.

Meteoritic material may also be present in the lunar exosphere. It would be highly beneficial if LADEE mission duration were long enough to include a lunar encounter with one or more meteor streams. This opportunity would greatly expand LADEE's capability to outline the constituent reservoirs to the lunar exosphere.

4.1.3 Release Processes

Exosphere constituents can be released into the atmosphere by different processes, including thermal desorption, photon-stimulated desorption, backscattering, physical sputtering, and chemical sputtering. These mechanisms each have a characteristic velocity distribution. LADEE can address the relative contributions of the release processes by studying the temporal and spatial distributions of known atmospheric constituents and correlating the variability to known drivers.

Radiogenic species gain a thermal distribution as they percolate up through the regolith. The



Global distributions of argon-40 at 30 and 50 km.

Figure 4.1: Model of the expected global distribution of Ar-40 at 30 km and 50 km [provided by D. Hodges]. Note that gas densities peak at the sunrise terminator, where desorption is greatest. The gas densities are sizeable and detectable (> 4000/cc at 50 km).

source rate of argon is known to be variable and could be constrained by LADEE measurements.

For solar wind derived species, backscattering (for H and maybe He) and chemical sputtering (for CH_4, CO, CO_2, N_2, H_2, or H_2O) eject the constituents into the exosphere. Variations in He abundance as a function of upstream parameters (provided by existing solar wind monitors) will address the solar wind interaction with the lunar dayside surface. Changes in properties of the solar wind exist on timescales of minutes and hours, but the lunation is possibly the most significant time scale, since the Moon will pass from the solar wind to the magnetotail (and possibly into plasma sheet). Also, occasional solar storms occur with a great intensification in the solar wind.

Physical sputtering plays a role in release of the regolith-derived component of the exosphere (Si, Al, Fe, Mg, Ca, O, Ti). Abundances of regolith species differing from stoichiometry may be indicative of the ion sputtering process that ejects the species or subsequent interactions.

Sodium and potassium have already been observed in the lunar exosphere through ground-based observing campaigns. Both elements have low abundances in the exosphere, but are detectable due to their strong spectral signatures. Both elements are volatiles. They are ejected from the lunar regolith into the atmosphere easily because of their low binding energies. However, there are several possible processes capable of releasing these regolith constituents into the exosphere, and the relationship between these mechanisms is controversial [Sarantos et al., 2008]. Photon-stimulated desorption has been shown to better explain the distribution in the lunar exosphere. However, a correlation is observed with incident ion flux and the abundance of sodium. The history of observations and the synergy of contemporaneous orbital and Earth-based observations of Na and K will enable a better understanding of the release mechanisms. Thus, the SDT notes that there is special emphasis on detection of Na/K as a marker for complementary groundbased studies.

Impact vaporization also occurs on the Moon, adding meteoric material and regolith material to the lunar exosphere. Because the Moon travels through meteor streams at distinct times in the year, taking data during one of these encounters is highly desirable for the LADEE mission. This infalling meteoric material is connected to the dust investigation. Likewise, the SDT notes that all of the processes that release material from the regolith also act on levitated dust grains, and such dust can be considered a point-source gas emitter. Thus, there is great synergy between the atmosphere and dust investigations defined by LADEE, with both exospheric gases and particulates in mutual interaction.

While a mission lifetime of a year is desirable, an operational lifetime of 3-4 months is enough to include detection of any atmospheric variations from lunation (magnetotail crossings), meteor showers/cometary debris streams, and possibly may even include a solar storm (because the mission is set to fly near solar max).

4.1.4 Surface Interactions

LADEE can contribute nicely to understanding the surface/atmosphere interface by probing the sunrise region, where the effects of adsorption/desorption are most pronounced. The dawn enhancement observed in argon and reproduced by lunar exosphere models occurs because of the large inventory of gas that condenses/adsorps on the cold lunar nightside. Adsorption occurs whenever an atom (or molecule) encounters a soil grain. The atom moves laterally over the grain surface along the potential gradient to find an adsorption site, and it desorbs when a sufficient number of phonons add in phase to overcome the activation energy. Because of the loose packing of soil grains, a desorbing atom is more likely to encounter another grain than to enter the exosphere. The path of an atom in the regolith is like a 1-dimensional random walk, with the attendant problem that return to the surface is not guaranteed.

The time that an atom spends in the soil, which is determined by the sum of the temperature-dependent intervals between adsorption and desorption along its migration path, is obviously much greater at night than in daytime. Just before sunrise, where equatorial temperatures are similar to permanently shadowed polar cold traps, condensible gases are removed from the exosphere. After sunrise, the condensed gases essentially evaporate from the surface and flow back across the terminator to be re-assimilated into the cold nighttime soil.

Detailed information about surface interactions and the energy distribution of desorbing atoms are contained in the morphology of the pocket of desorbing gases at the dawn terminator. The LADEE mission focuses on collecting data at the dawn terminator by setting periapsis to that local time and repeating many crossings with similar trajectories for intercomparison of in situ data. Simultaneous limb-viewing toward the pole for remote sensing will provide an extended view of this region of enhanced abundances. Only through repeated crossings can LADEE characterize the spatial variations in the exospheric density at the dawn terminator necessary to quantify the binding and release mechanisms for adsorbing particles.

By studying the component nightward of the terminator, LADEE investigators will learn about reaccommodation to the nightside for those species driven across the dawn terminator to the night. By probing the gradient from dawn to noon, LADEE investigators will learn about the migration process.

Helium has also been detected in the lunar exosphere by the Apollo 17 LACE instrument. In contrast to Ar, He does not adsorb to the lunar nightside. The highest concentrations of helium in the lunar exosphere were observed on the nightside of the Moon. Thus, the spatial distribution of He in the lunar exosphere is quite different than Ar. If LADEE can quantify the spatial distributions of both He and Ar, it will cover both condensable and non-condensable gases, incorporating a wide range of surface interactions.

4.1.5 Sinks

Particles that enter the lunar exosphere are subject to a set of diverse loss mechanisms. Ionization and dissociation, either by photons or by charged particles, occurs on timescales of hours to days at the Moon [e.g. Huebner et al., 1992]. For light elements, escape from lunar gravity into the Earth-Moon system is expected on short timescales. For constituents with mass greater than helium, escape from lunar gravity is generally unlikely. However, atoms and radicals that acquire added energy from photo-dissociation, such as OH, can escape. Regolith constituents that are vaporized and dissociated by micro-meteor impact processes escape at a rate of about 1-m per Gyr [Fireman, E.L, 1974]. Solar radiation acceleration will affect the transport dynamics of Na and K, creating non-ballistic trajectories [Smyth and Marconi, 1995]. In addition, permanently shadowed regions near the lunar poles may trap volatiles for durations of Gyrs. Over the course of a year, LADEE could possibly detect the pole-to-pole migration of volatiles that condense in seasonally shadowed regions.

4.1.6 Measurements and Instruments

The SDT indicates that a thorough inventory of species traceable back to atmospheric sources is a strong LADEE driver. LADEE atmospheric science advancements are thus defined in two forms: 1) If the species is known to exist (e.g., Ar, He), LADEE will confirm its continued presence and define the species variability to as short a timescale as possible. 2) For species that have only upper limits (no known detection), LADEE will either reduce the upper limit or make the discovery detection of the species. Given the number of species with only upper limits, the SDT anticipates many new discoveries with LADEE.

4.1.7 Confirmation of Known Species

During Apollo, both Ar and He were detected by a neutral mass spectrometer deployed on the lunar surface [Hoffman et al., 1973]. The presence of these species persisted, although at differing levels, for several lunations. Because a high abundance of these species is predicted even at several tens of kilometers above the surface and because of their low reactivity, both He and Ar are expected to be detectable by a neutral mass spectrometer (NMS) in lunar orbit. The SDT suggests confirming the continued existence of these species given the inherent short lifetimes of lunar exospheric particles.

Sodium and potassium have also been observed in the lunar exosphere through ground-based observing campaigns [e.g., Potter and Morgan, 1988; Stern and Flynn, 1995]. Both elements have low abundances in the exosphere, but are detectable due to their strong spectral signatures. Both elements are volatiles. They are ejected from the lunar regolith into the atmosphere easily because of their low binding energies. There are several possible processes capable of releasing these regolith constituents into the exosphere, and the relationship between these mechanisms is controversial. However, the history of observations and the synergy of contemporaneous orbital and Earth-based observations of Na and K enable a better understanding of the release mechanisms. Thus, the SDT notes that there is special emphasis on detection of Na/K as a marker for complementary groundbased studies. Thus, sodium and potassium are complementary to helium and argon in what they exemplify about the lunar exosphere.

Both Na and K can be observed with a remote sensing limb spectrometer onboard the LADEE spacecraft, provided the instrument is sensitive in the visible. Neither species would be detected by an orbiting NMS. Ar and He emit in the Far UV and may not be detectable within the wavelength range of a UV-VIS spectrometer onboard LADEE. In fact, the SDT found that no single method of detection will obtain a comprehensive/complete detection of all species in a given volume. Thus, the SDT suggests flying a set of instruments that reliably provides the largest coverage of species possible. A NMS can easily detect primary constituents, but at least one other complementary instrument is required to obtain further composition.

4.1.8 Discovery of Unknown Species

Through non-detections by the Apollo Lunar Surface Experiments Package (ALSEP) program, orbiting UV spectroscopy, and ground-based searches, upper limits have been established for several plausible constituents of the lunar exosphere. Some of the upper limits are very close to the expected abundances, thus further refinement of these limits can instruct us about the sources, sinks, and processes that are important to the lunar exosphere. Some species of interest include H, H_2, OH, N_2, CO, CH_4, C, N, O, S, Si, Al, Fe, Ca, Ti. Typically, Far-Medium UV detection (like Lyman-Alpha Mapping Project (LAMP) on Lunar Reconnaissance Orbiter (LRO)) tends to sense species of solar wind origin, while NearUV-Vis detection (like VisSpec on Lunar CRater Observation and Sensing Satellite (LCROSS)) tend to sense species tied to the regolith.

A NMS can detect the most abundant species (Ar, He), but will have some difficulty in direct detection of reactive species (OH and other radicals). Na will not be directly detectable by an NMS. The most likely complementary sensor is a UV spectrometer that can address remote measurements beyond LADEE orbit and that can be an instrument connecting lunar exospheric gas and particulates. UV should detect or place improved limits on many (most) of the primary constituents, with the number of detectable species increasing as the sensing wavelength band increases. An IMS is another candidate instrument capable of detecting trace species, but any such instrument should have temporal resolution and sensitivity improvement over the Kaguya IMA. IMS will provide the in situ detection of ions of nearly all atmospheric constituents and allows a sensing of surface emission, but requires a photo-ionization probability conversion and instrument efficiency to derive the underlying

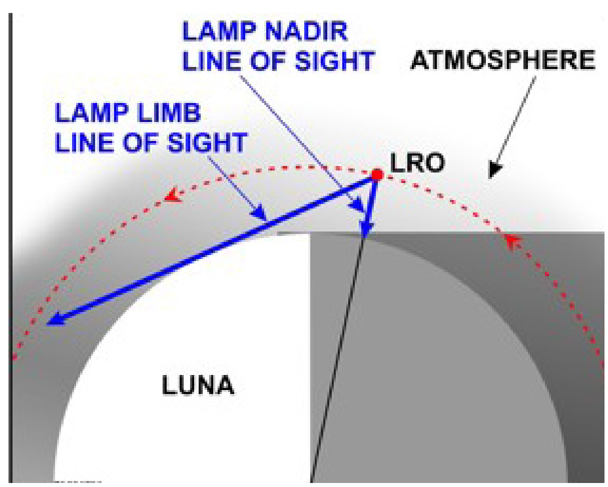


Figure 4.2: UV instrument remote sensing along the limb line-of-sight should provide an opportunity to detect numerous gas species via their accumulated emission along the columnar path [Figure adapted from Retherford et al. (2006); provided by LAMP team member P. Feldman].

neutral densities. Long integration times may also impact the ability of IMS to address variability.

4.2 Dust Science

SCEM Goal #8 considers the quantification of the gas and dust environment of the lunar exosphere together. While it may not seem completely obvious why exospheric gases and dust are considered connected, it is noted that atmospheres of the rocky planets always contain some level of small solid particulate matter originating from the surface interface. Vertical forces lift the small particles, and a lifting force appears to be present in every case.

On Earth, the gas pressure is high enough to create a truly collisional atmosphere to hundreds of kilometers. In Earth's high pressure atmosphere, dust is lifted from dry regions (Sahara, Gobi deserts) and creates aerosol layers that can become global in nature. There is now a renewed appreciation for the terrestrial atmospheric dust and aerosol content since it may contribute to global dimming (to offset global warming) and has been pointed to as a possible controlling element in seasonal Atlantic hurricane activity (Sahara dust and the effect on the African easterly waves). In the lower pressure Martian atmosphere (1/100th the pressure of Earth), lofted dust from the surface interface is a key part of the atmospheric composition and results in the creation of a global seasonal atmospheric instability on the planet. In this context, the Moon (along with Mercury, Saturn's rings, asteroids, etc.) may represent a very low pressure "airless" limit - an extreme example - to a dusty atmosphere, where gas densities are so low as to be collisionless but lofted dust densities remain high. A similar system may be Saturn's dense rings, which are continuously bombarded by interplanetary dust, UV, and magnetospheric ions, and hence a source and sink of their own plasma and neutral atmosphere. Spokes – the intermittently appearing radial markings in the B-ring – are likely analogues of electrostatically lofted dust particles on the lunar surface. The dust-to-gas mass ratio may in fact be larger in these surface-boundary exospheres than in high -pressure atmospheres. LADEE measurements would enable the first estimate of particle-to-gas mass ratios for the lunar exosphere, which can then be compared to other planetary bodies.

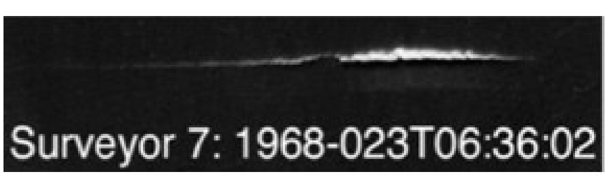


Figure 4.3: An unprocessed image of the lunar horizon glow from Surveyor 7.

The dust environment of the Moon has remained a controversial issue since the Apollo era. Visual observations and photographic images from the Apollo command modules, and images from the Clementine mission have been used to indicate the presence of dust at high altitudes above the lunar surface. There are also *in situ* and remote sensing observations on the lunar surface, indicating that dusty plasma processes are responsible for the mobilization and transport of lunar soil. However, there is a lack of both observations and theoretical understanding to directly relate the existing surface and high altitude phenomena, and the existence of a significant 'dust exosphere' remains a question.

There are two fundamental processes that could be responsible maintaining a lunar dust exosphere: 1) The lunar surface is continuously bombarded by interplanetary dust particles that produce secondary ejecta grains with sufficient speeds to reach tens of kilometers in altitude, expected to form a 'permanently' present, approximately spherically symmetric dust exosphere. 2) In addition, the lunar surface is exposed to solar wind plasma, UV radiation, and/or the plasma environment of Earth's magnetosphere. which charges the lunar surface and electrostatically lifts dust many 10's of kilometers, probably forming a temporarily and spatially variable component of the lunar dust exosphere.

LADEE will provide definitive observations about the spatial and temporal variability of dust in the lunar environment and gauge the dust content of the lunar atmosphere. These observations will also identify the relative strength of the processes responsible for supplying dust from the surface to the atmosphere.

4.2.1 Current State of Knowledge of the Lunar Dust Environment

Images taken by the television cameras on Surveyors 5, 6, and 7 gave the first indication of dust transport on the airless surface of the Moon [Criswell, 1973; Rennilson and Criswell, 1974]. These TV cameras had 25 and 100 mm focal length lenses, shutters, and color filters surmounted by a mirror that could be adjusted by stepping motors to move in both azimuth and elevations. Images taken of the western horizon shortly after sunset showed a distinct glow just above the lunar horizon that was dubbed horizon glow (HG). This light was interpreted to be forward-scattered sunlight from a cloud of dust particles < 1 m above the surface near the terminator. The HG had a horizontal extent of about 3 degrees on each side of the direction to the Sun (Figure 4.3).

Assuming that the observed signal is dominated by diffraction of sunlight, this horizontal extent corresponds to spheres of radius ~5 μm. Micrometeoroid ejecta, scattering off surface grains, and reflections involving glints off the spacecraft can all be ruled out as an explanation for these images due to the intensity of the signal, its duration (up to 2.5 hours), and its vertical and horizontal extent [Rennilson and Criswell, 1974]. However, it is difficult to analyze these images. To determine the physical dimensions of the bright cloud, the determination of the distance to the cloud is needed. By analyzing the shape of the lower boundary of the Surveyor 7 HG cloud, and matching it to the local topography from orbital photographs of the Surveyor 7 landing site, Rennilson and Criswell [1974] placed the cloud at the visible horizon, or approximately 150 m from the camera. The vertical extent of the cloud is 1.9 mrad or about 30 cm at that distance. Its horizontal extent of ~100 mrad makes the observed cloud 14 m wide, though this dimension may be a result of the light scattering properties of the cloud: it could be much larger with the parts of the cloud further from the Sun line not scattering sufficient light into the cameras. The astrophotometer on the Lunokhod-2 rover also reported excess brightness, most likely due to HG [Severney et al., 1975].

An independent set of observations related to dust levitation/transport phenomena is the description of the visual observations of the Apollo 17 crew during sunrise as it was seen from lunar orbit (Figure 4.4). They reported the appearance of bright streamers with fast temporal brightness changes (seconds to minutes) extending in excess of 100 km above the lunar surface. McCoy and Criswell [1974] argued for the existence of a significant population of lunar particles scattering the solar light. The rough photometric estimates indicated ~0.1 μm sized grains. These drawings were analyzed again [Zook and McCoy, 1991] and most of the earlier conclusions were verified. This study also estimated the scale height of this 'dusty-exosphere' H ~10 km, and suggested that dust levitation could be observed using ground based telescopes. A recent simple theoretical model suggests that these could be particles lofted from the lunar surface by electrostatic forces [Stubbs et al., 2006].

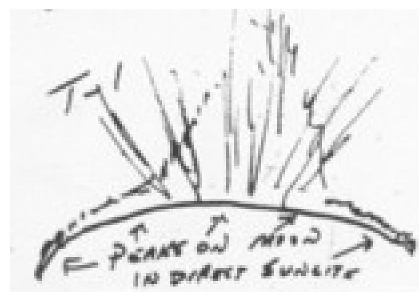


Figure 4.4: A sketch drawn by E. A. Cernan (Commander, Apollo 17) one minute before sunrise as viewed from lunar orbit flying over the sunset terminator on the surface.

Figure 4.5: A reoriented Clementine image (1994) showing a similar geometry to Figure 4.4. The 'Gaussian' brightness distribution is due to light scattering from Zodiacal dust grains in interplanetary space. The bright 'wings' along the lunar surface have been suggested to be due to lofted dust and/or sodium atoms.

Images of the lunar limb taken by the star-tracker camera of the Clementine spacecraft also showed a faint glow along the lunar surface, stunningly similar to the sketches of the Apollo 17 astronauts (Figure 4.5). The interpretation of these images was complicated by the presence of the scattered light from zodiacal dust particles as well as Earthshine, and it was never completed due to the untimely death of H. Zook in 2001.

Finally, the Lunar Ejecta and Meteorites (LEAM) Experiment provided the only in situ dust measurement of the lunar surface to date. LEAM was deployed by the Apollo 17 astronauts and started measurements after the return of the landing module; it continued to make observations for about 3 years. The science objectives of LEAM were: (1) to investigate the interplanetary dust flux (primary particles) bombarding the lunar surface; (2) to investigate the properties of the lunar ejecta (secondary) particles; (3) to follow the temporal variability of these dust fluxes along the lunar orbit; and (4) to observe interstellar particles. The design and the expected performance of the LEAM experiment were similar to dust instruments onboard the Pioneer 8 and 9 spacecraft that were launched into heliocentric orbits in 1967 and 1968, respectively [Berg et al., 1973]. These original science goals were not achieved. Instead, LEAM was registering only an unexpected population of slow-moving, highly charged lunar dust particles. A subsequent experimental study using the LEAM spare showed that the observations were consistent with the detection of sunrise/sunset-triggered levitation and transport of slow moving (v < 100 m/s), highly charged ($Q > 10^{-12}$ C) dust grains. LEAM measurements indicate hundreds of microns-scale grain radii. Though these observations remained unexplained, they are thought to indicate that the undetected smaller grains could be lofted to high altitudes. This would also indicate that the dust exosphere is perhaps largely driven from the sunset/sunrise terminator regions.

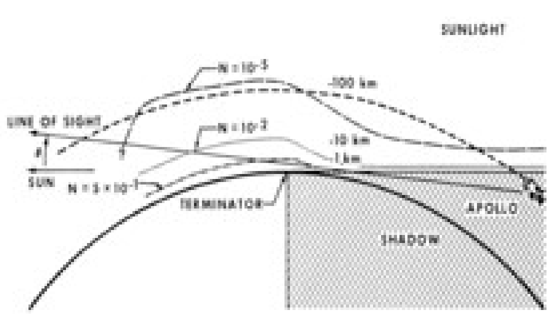


Figure 4.6: Line of sight to the solar corona through the suggested dust exosphere [McCoy, 1976].

Table 4.2: The expected density of the characteristic 0.1 μm dust grains from McCoy '0' model.

Height [km]	Density [cm^{-3}]
1	0.5
10	10^{-2}
100	10^{-5}

4.2.2 The Expected Dusty Environment at High Altitudes

While there is ample evidence from the Surveyor images and LEAM for significant dust transport near the surface, the inference of high altitude lofted dust is more controversial, relying on Apollo astronaut sketches and limited analysis of Apollo photographs. An alternate interpretation for the high altitude streamers and glow is a source from atomic gas emission of the exosphere rather than forward-scattered light from dust. In completing Objective 1 and Objective 2, LADEE will attempt to differentiate between these two possible sources (dust vs. gas) for the terminator glow emission.

Given the possibility that the glow emission originates from dust, McCoy [1976] indicates that the dust is of low density and should consist of small grains. He assumed the grains were on the order of 0.1 microns to derive the McCoy '0' model of the dusty exosphere. However, recently, Stubbs et al. [2006] suggested the dust electrical lofting through the sheath could also transport grains to high altitudes, but these grains are estimated to be at sizes less than 0.1 microns. The sheath E-fields are expected to be largest at the terminators (~ 10 V/m), thereby creating the greatest electrostatic grain lofting at these locations [Farrell et al., 2007]. The SDT finds that the lunar surface-lofted dust component thus consists of sub-micron grains at relatively slow speeds. The densities at 50 km are expected to be on the order of 10^{-4}/cc (see Figure 4.6) and are expected to have peak concentrations near the terminator.

While recent emphasis has been on electrostatic lofting of dust to high altitudes, some fraction of this dust will also result as secondary ejecta from micro-meteoroid impacts. The exact fraction of electrostatic vs. ejecta dust at 50 km is currently unknown. However, analysis of the near-surface Surveyor images indicate that the amount of dust electrically-levitated at the terminator is about 10^7 times that expected from dusty secondary micro-meteoroid ejecta [Criswell, 1973]. Both electrostatically-lofted dust and secondary impact ejecta originate from the surface. However, the lunar dust environment includes an external dust source – the primary micro-meteroids themselves – that are incident on the surface and are the direct source of the secondary ejecta emission. Consequently, the SDT finds that there are two dust components of interest to LADEE at 50 km: 1) The dust originating from the lunar surface (electrostatically-lofted and secondary ejecta) that is suspected to be slow and small (sub-micron), and 2) interplanetary dust (IDP) that is fast (2- 60 km/sec) and has a wider size distribution reaching up hundreds of microns. The latter is considered micro-meteoroids.

4.2.3 Environmental Control of the Lunar Dusty Exosphere

Given that the high altitude dust has both a micro-meteoroid and a surface electrostatic source, the SDT suggests using known targets-of-opportunities to enhance the likelihood of detecting small, slow lunar lofted grains. For example, in a 4-month baseline mission, LADEE will most likely pass through a known meteor stream/cometary debris streams, and the correlation of micro-meteoroid incidences and lofted dust with stream proximity can determine the degree to which micro-meteoroids drive the lofted dust component. Also in a 4-month baseline mission, the Moon will pass through the geomagnetic tail four times and possibly into the warm plasma sheet. In doing so, the lunar surface potentials will become large and negative, and will be capable of lofting larger grains to higher altitudes. This will enhance the likelihood of detection in an impact ionization sensor. Also, given that LADEE is expected to fly during solar maximum, there is a reasonable chance that the Moon will be in the solar wind during a solar storm, when again the nightside surface can charge to large negative values (below – 4kV, Halekas et al., [2007]), enhancing the upward flow of lofted dust. As such, the SDT suggests the baseline mission to be 4-months (and recommends a minimum of at least 1 month) to make use of the natural environmental variability in micro-meteoroid flux and surface solar wind/magnetotail plasma flux to improve the likelihood of lunar lofted dust detection. These targets of opportunity can be woven into spacecraft operations (increase data rate for dust detector, etc.) to maximize the likelihood of *in situ* dust detection.

4.2.4 Measurements and Instrumentation

4.2.4.1 In situ dust detection

Based on current understanding, the lunar dust environment is dominated by submicron sized dust particles. Analysis of the Apollo photographs indicate a characteristic dust size of ~0.1 μm. However, at approximately 50 km altitude, the velocity of the dust impacts is dominated by the velocity of the spacecraft, $V < 2$ km/s, and the combination of relatively small impact speeds and small grain sizes represents a challenge in direct detection. Since impact ionization sensing varies with particle velocity as $v^{4\text{-}5}$, the slow speeds of lunar dust will yield relatively small signals. For example, a 0.1 micron grain incident at 2 km/s will create a fraction (few percent) of a fempto Coulomb (fC) of charge via impact ionization processes − a level at the limit of sensitivity for such instruments. However, the dust concentration at 10^{-4} /cc at 50 km will provide a dust flux of thousands of grain collisions per second for a 10 cm x 10 cm section of the spacecraft. Thus, the surface-lofted dust may possibly be detected via collective effects, as many grains simultaneously generate a small charge but collectively generate a sufficiently-large signal amplitude that can be amplified and detected via traditional methods. The analysis and interpretation of such a collective signal remains to be worked out in detail.

Table 4.3: Comparison of LADEE as a GRAIL co-manifested and an independent launch demonstrate the significant relaxation of constraints and science enhancement gained from an independent launch.

		
Launch Option	Secondary Payload with GRAIL	Independent Launch
Launch Vehicle	Delta II 2920H-10 (2 stage)	Minotaur V
Accommodation Development	Composite DPAF	Ø38.81" to 15" PAF
Science Payload Mass	27 kg	60 kg
Science Orbit	50 x 3300 km elliptical orbit	50 km circular orbit
# of terminator crossings	1150	3000
# of low-altitude sunrise terminator crossings	100-250	1500
Issues	Negative mass margin (~80kg) on total payload stack.	Positive mass margin for most heritage launchers except Taurus

4.2.4.2 Remote sensing

The optimal remote sensing dust observations are vertical scans in UV/Vis near the sunlit limb while the spacecraft is in shadow (i.e., just before sunrise or after sunset as seen by LADEE). This mimics the geometry of the lunar horizon glow observed by the astronauts (Figure 4.2). Vertical profiles taken with several broadband filters and at the sodium wavelengths could provide a key ability to detect the large-scale structure of the dust exosphere. Lunar dust will be distinguished by the deviation of its spatial profile from zodiacal dust, and by its expected spectral signature: lunar exospheric dust particles are expected to appear blue as they are probably dominated by submicron sized particles, while zodiacal light is more yellow due to the wide size range of interplanetary dust grains (1 – 100 μm). Dust may also be detected remotely by measuring the subtle extinction of sunlight or starlight as the source rises or sets as seen from the spacecraft.

Given the challenges in dust detection, the SDT finds that the measurement of lofted dust can be best achieved by a combination of in situ dust detection and remote sensing observations to disentangle spatial and temporal variability. Using both capabilities increases the likelihood of detection, especially given that the surface-lofted dust is expected to be small and slow, and hence difficult to detect via *in situ* sensor. A near UV-Vis instrument should have the capability to detect the broadband light-scattered emission associated with dust.

4.3 The LADEE Mission's Primary Trade Study: Payload Mass vs. Terminator Crossings

As suggested in Section 4.1.1 and 4.2.1, the LADEE mission is best served by a circular retrograde orbit at an altitude below 50 km and an inclination of 180° ± 20°. The SDT consensus view is that periselene at low altitudes (< 50 km) near the sunrise terminator should be a mission driver. Such an orbit would provide about 3000 terminator crossings for a nominal mission of 4 months at low altitudes – ideally suited for to achieve the LADEE mission's science objectives.

Based on analyses performed for the SDT by the ARC LADEE project team, it is apparent that this low altitude, circular orbit is incompatible with the constraints of a LADEE mission co-manifested with GRAIL − the large propellant mass required for capture into a circular orbit would not allow any science payload to fly.

However, in the course of the SDT study, it became clear that a GRAIL co-manifested science payload mass could be increased at the expense of orbit eccentricity, which in turn is a trade of mass vs. the number of terminator crossings. For example, the SDT considered an option with the aposelene at 2350 km and periselene near the sunrise terminator at 50 km. In this case, less propellant is required for capture, thereby allowing a ~16 kg science payload mass. While encouraging, this mass was deemed as too limited to fly the instrumentation required to complete the LADEE measurement objectives in the traceabilty matrix (Appendix 2).

To fly a set of instruments that provide a detection of primary and trace atmospheric species, along with in situ and remote dust detection, the SDT estimates that LADEE needs to accommodate approximately 20 kg of payload mass (with 7-10 kg of mass margin). This mass could be accommodated on a GRAIL co-manifest provided the orbit remained highly eccentric with a ~50 km periselene over the lunar-sunrise terminator but with a highly extend aposelene of 3300 km (Table 4.3). Such a ~5-hour orbit makes about 1150 terminator crossings with 100-250 of these crossings at the lunar-sunrise terminator with altitudes below 50 km.

A possible orbital scenario to maintain a sunrise near-terminator periselene location is to have an initial sun-referenced longitude of periselene at -45°. In this scenario, perselene is then allowed to drift (about -1° per day) during the 4-6 week commissioning phase and the first few weeks of the science phase until it coincides with the sunrise terminator. Each day thereafter, while propellant lasts, the axis of the orbit is shifted eastward 1° per day, and the altitude of periapsis is corrected by an aposelene maneuver. This should keep periapsis over the terminator and at a fixed altitude for 40-60 days. For the remainder of the mission, periapsis resumes its natural drift into night. As shown in Figures 4.1 and 4.6, the periselene of LADEE would remain near the 5-10 hours local time region where desorbed atmospheric gas densities and lofted dust densities are expected to be the greatest.

A considerably more attractive option is to consider a launch independent from GRAIL. This option would provide ample mass margin to accommodate both the needed propellant for a circular, low altitude orbit and large science payload, but at the expense of added mission cost (separate launch vehicle, longer mission run-out time) that extends beyond the scope of the currently planned budget. The SDT finds that launching LADEE independently from GRAIL would significantly enhance LADEE science.

4.4 The LADEE Baseline Mission

Under the assumption that a mission option as a secondary payload (first column of Table 4.3) is available, a LADEE mission as a GRAIL co-manifest would have 20 kg of mass (plus 7-10 kg mass margin), with 100-250 low altitude spacecraft passes through the lunar-sunrise terminator region – the most active region for both exospheric gas emission and lofted dust.

Table 4.4: LADEE Baseline Science Mission Consistent with SDT Recommendations

	Baseline Science Mission
1	Neutral Mass Spectrometer, Dust detector, UV spectrometer that senses both neutrals and dust (20 kg of science payload)
2	Orbit retrograde, as close to circular, as low an altitude and low inclination as possible (but with periselene no higher than 50 km and inclination 180deg +/- 20) consistent with delivering a payload mass of at least 20 kg
3	Mission lifetime of 3-4 lunations
4	If more than 20 kg available, then additional IMS would greatly complement LADEE payload

The SDT has thus derived a baseline science mission for LADEE that is outlined in Table 4.4. While the SDT does not have access to the LADEE request for information (RFI) process (ongoing concurrently), the past experience of the SDT suggests that a NMS, dust detector, and UV system can all be accommodated within a 20 kg science payload envelope, and their measurements will be consistent with the instrument requirements listed in Appendix 2. A retrograde orbit is required to keep the sensitive sensor heads in the ram direction but out of sunlight during the lunar-sunrise terminator passage.

4.5 Expectations from the LADEE Baseline Mission

Figure 4.7 gives a comparison of simulated mass spectrometer data for ^{40}Ar, CO, and CH_4 from the circular (50x50 km) and eccentric 5-hour (50x3350 km) orbits. The gray shaded area marks the period between sunset (i.e., spacecraft sunrise) and noon when sunlight impinges on the ramside of the spacecraft, and when mass spectrometers and other ram-pointing instruments, such as a dust impact detector, cannot operate. The afternoon location of the instrument dead zone is due to the retrograde direction of the orbit. A prograde orbit would prohibit study of the lunar-sunrise gas pocket.

The red curves (circular orbit) in Figure 4.7 mimic the Apollo 17 observations of the diurnal variation of argon. The utility of repeating the same observations each orbit lies in the opportunity to learn more about the variability of the sources and sinks of lunar exosphere, as well as the possibility of long integration times in the search for minor species.

The blue curves in Figure 4.7 represent the data that could be expected from the most likely scenario, that is, a 5-hour orbit (Table 4.3, column 1). Each of the blue curves is a 22-minute segment of data near periapsis. The longitudes of periapsis progress in 10° steps from -40° (mid-morning) to -150° where the nighttime exosphere is depleted. Unattended, the apparent precession of the orbit would span this range in 110 days, and, if the exosphere were static (which unfortunately is not true), the peaks of the data at periapses would give the same diurnal variation as the red curve of the circular orbit. It is important to note that the sharp peak of the signal over the sunrise terminator is mainly due to the narrow extent of the sunrise gas pocket (see Figure 4.1); it is only slightly affected by the vertical descent and ascent of the spacecraft through a barotropic exosphere.

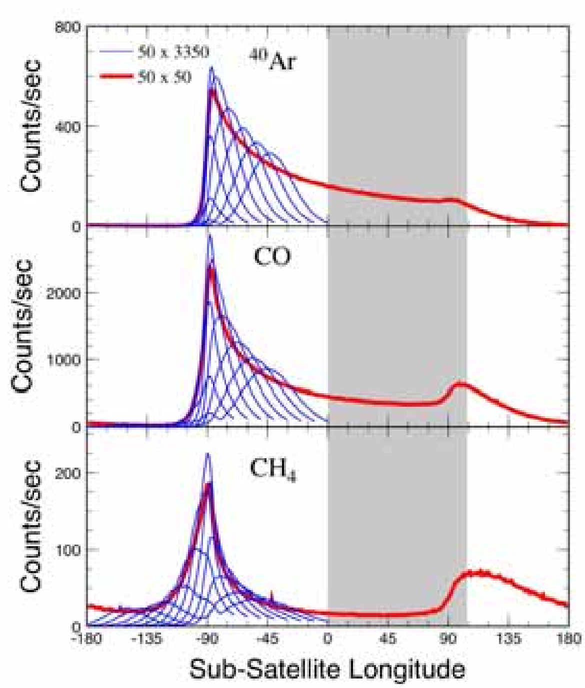


Figure 4.7: The expected counts from a simulated mass spectrometer with a closed source and conversion factor of 0.01 counts/sec/particles/cc. Note that while a 50 km x 50 km would allow detection throughout the dayside, there is still substantial detection of species per orbit on a 50 x 3300 km orbit with a sunrise terminator periapsis. Each of the blue curves is a 22-minute segment of data near periapsis, for periapsis locations that progress in 10° steps from -40° (mid-morning) to -150° [Provided by D. Hodges].

As described in Section 4.3, the preferred strategy for mass spectroscopy in a 5-hour retrograde orbit includes using the apparent westward drift of the orbit axis to obtain some data from periapses in daytime at the start of the mission and some at the end of the mission over the night side to aid in understanding the role of adsorption in transport processes and the dynamics of helium. The middle of the mission should be spent with periapsis within ±1° of the sunrise terminator as long as possible to study exospheric variability as well as bulk composition, and especially to search for minor species by prolonged integration at the peak of the sunrise gas pocket.

Figure 4.8 shows the resulting column density from the model exosphere used to derive the atmosphere shown in Figure 4.1 for limb-grazing viewing from LADEE altitude for ^{40}Ar, CO, and CH_4 for both a 50 x 50 km and 50 x 3300 km orbit. The geometry is illustrated in Figure 4.2.

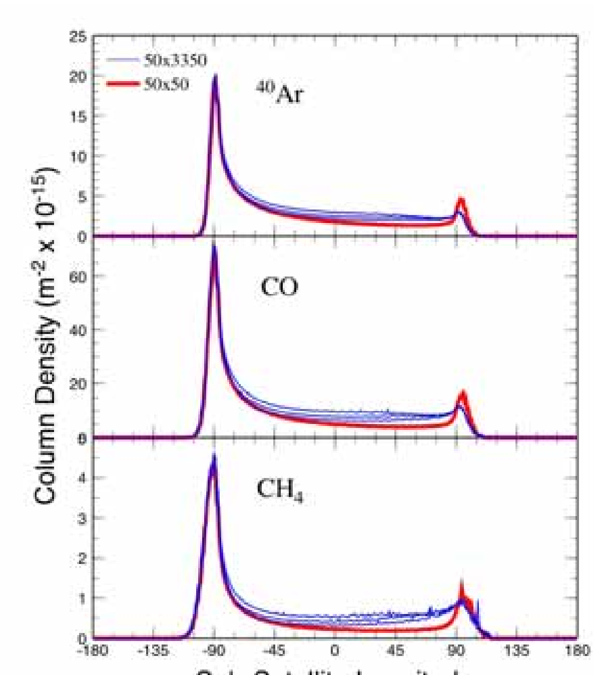


Figure 4.8: Column density from a model exosphere for limb-grazing viewing (i.e., like that for a UV sensor). Note that because the gas species near the limb are measured by remote-sensing, the column density along the line of sight is less sensitive to the orbital eccentricity than in-situ measurements [Provided by D. Hodges].

Table 5.1: Instrument Loss and Science Impact

Instrument Loss	LADEE Science Impacts
In situ Dust Detector	Science Objective 2 (dust) is seriously degraded. While a remote-sensing UV/Vis sensor or sunlight/starlight extinction measurements provides some model-dependent information on dust, no *in situ* "ground truth" of particle size and concentration is obtained. Complete loss of micro-meteoroid impactor detection.
UV	Science Objective 1 (atmospheres) is highly degraded with the loss of species consistent with each source category. The loss of UV leaves atmosphere detection to NMS, which will detect Ar, He, but possibly not be sensitive enough to detect species of trace concentrations, like Na/K.
NMS	Science Objective 1 (atmosphere) is highly degraded with the loss of *in situ* Ar and He measurements, which are the primary mass constituents of the lunar atmosphere. These primary species are the markers for atmospheric variability, especially spatial variability at the sunrise terminator desorption region. Far UV sensor could pick up Ar and possibly second order He emission.

Note that for limb remote sensing via UV/VIS, the selected orbit has less of an impact on the expected column density.

5.0 PROGRAMMATIC ISSUES

5.1 A Reduction in the LADEE Baseline Mission: The Scientific Impact

The SDT recommends that the LADEE baseline mission include a NMS, a dust detector, and UV instrument, since this set provides the strongest connection to the instrument requirements that trace back through to the completion of the LADEE measurement objectives. The SDT concludes that all three instruments are required to properly complete the LADEE science objectives as stated in the Traceability matrix (see Appendix 2). The impact on science from the loss of each payload element is shown in Table 5.1.

5.2 Supporting Needs for LADEE Science

To extract the greatest possible science return from LADEE, more than "instrument providers" are needed. LADEE should utilize a science team with a breadth of expertise covering both the instrumentation and data interpretation portions of the mission. In addition, the mission should support concurrent ground-based observations of the lunar environment to tie the LADEE measurements to past and future remote sensing observations. Finally, to properly interpret the LADEE measurements, scientists with expertise in exospheric modeling are needed. The SDT feels that these science investigations can and should be acquired through a competitive process, even if the instruments are not. To maximize the benefit of this science expertise as LADEE is being designed and build, the science teams should be selected as soon as possible.

Interpretation of the LADEE data will be dramatically enhanced by the availability of space weather monitoring data sets, most likely from satellites such as WIND, that are upstream from the Moon. Every effort should be made to continue to have such measurements available during the time of the LADEE mission.

APPENDIX 1: LADEE Science Definition Team

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APPENDIX 2: Tracing LADEE Requirements to NRC SCEM Recommendations

SCEM Objectives	LADEE Science Objectives	LADEE Measurement Requirements	Mission Requirements	Instrument Requirements
8a. Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity	Determine the composition of the lunar exosphere and investigate the processes that control its distribution and variability, including – sources, sinks, and surface interactions	• Measure spatial and temporal variations of known species (Ar, He, Na, K) on time scales of hours (fraction of orbit) to beyond a lunation (many orbits) • Derive a new lower limit or a direct discovery detection for those gases strongly suspected to be in the lunar atmosphere (CH_4, CO, CO_2, H, H_2O, N, C, S, Si, Al, Ca, Fe, Ti, Al Mg, OH) • Obtain a direct measurement or new upper limit for gases in each source category: solar wind, regolith, and radiogenic	• Periselene at low altitude (<50 km) in near-vicinity of sunrise terminator • As close to circular as possible • As low an inclination as possible (180o +/- 20o) • Retrograde orbit • Mission duration of at least 1 lunation	• Ar and He at levels of > 1000/cc with tens of percent certainty on time scales of tens of minutes • Na or K at levels of tens per cc with tens of percent certainty on time scales of tens of minutes • Lower know limits of other species by a factor of 5-10 • He (solar wind), Na (regolith), and Ar (rediogenic) as a required minimum dataset
8b. Determine the size, charge, and spatial distribution of electrostatically-transported dust grains and assess their likely effects on lunar exploration and lunar-based astronomy	Characterize the lunar exospheric dust environment and measure any spatial and temporal variability and impacts on the lunar atmosphere	• Obtain a lower limit or direct detection of the lofted dust from the lunar surface • Determine the rate and size of micro-meteor impactors • Obtain a lower limit or direct detection of ejecta from micro-meteor impactors • Determine variations in grain concentration and size as a function of driving plasma and micro-meteor environment		• Dust detection at submicron levels • Obtain integrated dust flux

APPENDIX 3: Acronyms

ALSEP	Apollo Lunar Surface Experiments Package
Ar	Argon
ARC	NASA Ames Research Center
CU	University of Colorado
CUA	Catholic University of America
GRAIL	Gravity Recovery And Interior Laboratory
GSFC	NASA Goddard Space Flight Center
He	Helium
HQ	NASA Headquarters
IMS	ion mass spectrometer
JHU	Johns Hopkins University
K	Potassium
kg	kilogram
LACE	Lunar Atmospheric Composition Experiment
LADEE	Lunar Atmosphere and Dust Environment Explorer
LAMP	Lyman-Alpha Mapping Project
LCROSS	Lunar CRater Observation and Sensing Satellite
LEAM	Lunar Ejecta and Meteorites Experiment
km	kilometer
LRO	Lunar Reconnaissance Orbiter
mm	millimeter
Na	Sodium
NAS	National Academy of Sciences
NMS	neutral mass spectrometer
RFI	request for information
SCEM	Scientific Context for Exploration of the Moon
SDT	Science Definition Team
SMD	NASA Science Mission Directorate
UTD	University of Texas at Dallas
UV	ultraviolet
Vis	visible

APPENDIX 4: References

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