Lunar Science with ARTEMIS:
A Journey from The Moon's Exosphere to its Core

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This white paper describes the planetary science objectives to be achieved by ARTEMIS, a two-spacecraft constellation en route to the Moon, and presents recommendations pertaining to future lunar science.

Motivation and Recommendations

The inner planets hold critical information regarding the origin of the solar system and habitable environments within it. A witness to 4.5 Ga of solar system history, the Moon's surface has recorded that history more completely and preserves it more purely than any other planetary body, since it is devoid of Earth-like plate tectonics, Venus-like planet-wide volcanism, and Mars-like surface-altering atmospheric processes. The layering of the lunar interior holds records of planetary differentiation of the early solar system. Understanding of the lunar surface and the stratification of the lunar interior provides a window into the early history of the Earth-Moon system, and can cast light on the evolution of other terrestrial planets such as Mars and Venus.

The Scientific Context for Exploration of the Moon (SCEM) advocated studies of the pristine state of the lunar atmosphere and dust environment before the surface is disturbed by future landers. The hazards posed by lunar dust to future astronauts and their equipment is a major concern and is slated to be assessed by missions such as Lunar Reconnaissance Orbiter (LRO) and The Lunar Atmosphere and Dust Environment Explorer (LADEE).

Field and plasma instruments have made fundamental discoveries on the composition and loss processes of lunar exosphere, dust environment of the Moon, the composition of lunar surface and its charging, and the interior structure of the Moon. ARTEMIS, a two satellite lunar mission carrying state-of-the-art field and particle instruments, will be captured into lunar orbit in April 2011. Designed to address Heliophysics goals (lunar wake, particle acceleration in the tail and the solar wind) using the moon as an anchor, ARTEMIS's multi-point observations, orbits, and instrumentation present (with minor modifications) an ideal opportunity to advance our knowledge on several key topics raised in NRC studies on Planetary Science. ARTEMIS can study the formation and evolution of the exosphere, dust levitation by electric fields, the origin of crustal magnetic fields, composition and physical properties of the regolith and the interior structure of the Moon. NASA does not have concrete plans to include such instrumentation in future missions or use ARTEMIS to address planetary goals. **We thus recommend that NASA:**

(1) *Pursue a balanced lunar exploration program which benefits from the extremely high inherent sensitivity of field and plasma instruments in characterizing the environment and the interior of the Moon.*

(2) *Exploit the power of simultaneous multipoint spacecraft observations to distinguish between temporal and spatial gradients and thus obtain unambiguous information on the exospheric, surface and interior properties of the Moon.*

(3) *In the interim, use the two spacecraft capabilities of ARTEMIS ("Acceleration, Reconnection, Turbulence and Electrodynamics of Moon's Interaction with the Sun"), in orbit around to the Moon to characterize its exosphere, surface and interior.*

(4) *Enhance the science return of future missions such as LRO and LADEE by exploiting the field and plasma measurement capabilities of ARTEMIS that these missions lack.*

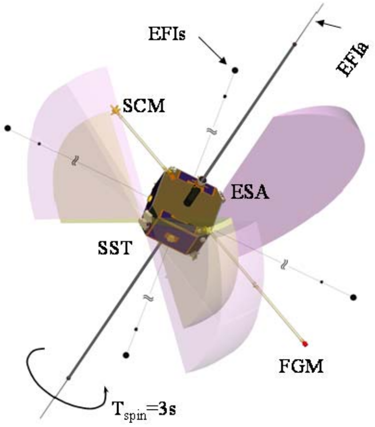
(5) *Recognize the potential for high science return per dollar from missions such as ARTEMIS; support analysis by instrument teams (to ensure proper instrument utilization) and the community at large, encourage open data policy, quick data release, open source software for analysis and encourage synergies with existing Lunar missions.*

(6) *Augment the electromagnetic sounding capabilities of International Lunar Network by obtaining continuous magnetometer measurements of the driver induction signal in the solar wind from spacecraft such as ARTEMIS.*

ARTEMIS Mission Concept and Instrumentation

ARTEMIS is derived from the two outermost THEMIS probes. THEMIS, a MIDEX-class heliophysics mission comprising five identical satellites (“probes”), was launched on February 17, 2007 to explore the Earth’s magnetosphere (Angelopoulos, 2008) and has successfully completed its primary objectives. In its proposal to the 2008 Heliophysics Senior Review, the THEMIS team proposed an extended mission retaining the three innermost probes, P3, P4 and P5, in Earth orbit while sending the two outermost probes, P1 and P2, into lunar orbit. The scientific driver for the ARTEMIS mission design was to conduct cutting-edge Heliophysics and Lunar Science with the outermost two probes and simultaneously evade terminal shadows anticipated in March of 2010 if the spacecraft remained in Earth orbit. The two ARTEMIS probes, now en-route to the Moon, will be captured into Lunar orbits in April 2011. The Heliophysics technical implementation has been funded allowing for lunar capture and operations. No science funding has become available from Heliophysics for the science team. A proposal for mission modifications for Planetary goals is currently awaiting NASA review.

ARTEMIS instruments (Figure 1, Table 1, or Table VI in Angelopoulos, 2008 and references therein for a synopsis) provide magnetic field, electric field, and particle distributions with state-of-the-art cadence, offset stability and sensitivity and are all fully operational.



Instrument	Specs
FGM: Flux Gate Magnetometer DC Magnetic Field	Frequency: DC-64Hz Offset stability <0.2nT/12hr
SCM: Search Coil Magnetometer	AC Magnetic Field Frequency: 1Hz – 4kHz
EFI: Electric Field Instrument	3D Electric Field Frequency: DC – 8kHz
ESA: Electrostatic Analyzer	Total ions: 5eV-25keV Elec: 5eV-30 keV g-factor/anode: -ions: 0.875x$10^{-3}$$cm^2$str -electrons: 0.313x$10^{-3}$ cm^2str
SST: Solid State Telescope	Total ions: 25keV – 6MeV Electrons: 25keV – 1 MeV

***Table 1** THEMIS instruments and their capability*

Figure 1: One of two identical ARTEMIS probes shown with its instrumentation, in deployed configuration. The fields of view of the body-mounted particle instruments are highlighted. The spin-stabilized probe provides three dimensional particle information once per spin (T_{spin}=3s). Electric Field Instrument spin plane booms (EFIs) are 40m long and 50m long tip-to-tip wire dipoles. EFIa (axial) stacer booms are ~7m tip-to-tip. A Fluxgate Magnetometer (FGM) and Search Coil Magnetometer (SCM) are mounted on 2m and 1m graphite epoxy booms.

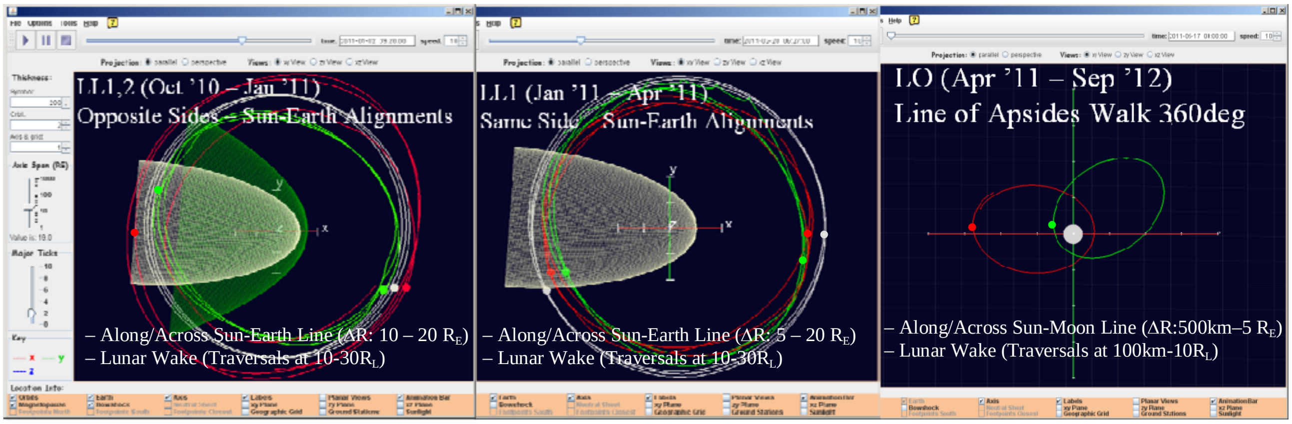
Mission Phases: The first three lunar flybys are expected in January-March of 2010. After trans-lunar injection (*TLI phase*), P1 and P2 are captured into opposite Earth-Lunar Libration points LL2 and LL1 respectively, resulting in 10-20 R_E separations (*LL1,2 phase*) along and across the Sun-Earth line (Figure 2). After 3 months P1 is brought onto the same side of the Moon, (*LL1 Phase*) resulting in smaller, 5-10R_E separations.

After another 3 months, both probes are inserted into stable, ~300km x 19000km orbits. Periselene can be further gradually lowered to 100 km to achieve planetary goals. P1 is on a retrograde and P2 on prograde orbit, resulting in a fast, 360° relative apsidal precession during the 17 months of this phase. Probe separations become progressively shorter as the probes move from one mission phase to another. Table 2 summarizes the Heliospheric and Planetary Science to be carried out by ARTEMIS in these mission phases. Lunar orbits are stable for decades.

Phase	**Abbr**	**Time Interval**	**ARTEMIS: probes P1, P2.**	**Heliophysics Objective**	**Planetary Objective**
Translunar Injection	**TLI**	Oct. '09-Oct. '10	Translunar orbits to capture into LL1,LL2	Lunar Flybys: Build tools, experience	Lunar Flybys: Build tools, experience
P1 at LL2, P2 at LL1	**LL1,2 Phase**	Oct. '10-Jan. '11	$d\mathbf{R}_{P1\text{-}P2}=20R_E$ at Moon $d\mathbf{R}_{P1\text{-}P2}$ along/across Wake & Sun-Earth $dX^{GSE}_{P1\text{-}P2} \sim dY^{GSE}_{P1\text{-}P2} \sim 500\text{km-}20R_E$	*In the Magnetotail:* Rx, SW-magnetosphere interaction, tail turbulence *In the Solar Wind (SW):* Foreshock, shock acceleration, Rx, SW turbulence *In the Wake (SW or Tail)* Kinetics and dynamics of lunar wake in SW, sheath, tail	At Solar Wind (SW) wake or downstream: Pickup ions?
P1,P2 at Lunar Libration 1	**LL1 Phase**	Jan. '11-Apr. '11	$d\mathbf{R}_{P1\text{-}P2}=5\text{-}20R_E$ at Moon $d\mathbf{R}_{P1\text{-}P2}$ along/across Wake & Sun-Earth $dX^{GSE}_{P1\text{-}P2} \sim dY^{GSE}_{P1\text{-}P2} \sim 500\text{km-}20R_E$		At Solar Wind (SW) wake or downstream: Pickup ions?
In Lunar orbit	**LO Phase**	Apr.'11-Sep. '12	$d\mathbf{R}_{P1\text{-}P2}=500\text{km-}20R_L$ at Moon $d\mathbf{R}_{P1\text{-}P2}$ along/across Wake & Sun-Earth Periselene = ~ 100 km [trade TBD] Aposelene = ~19000km Inclination = ~10deg [trade TBD]		*In the Solar Wind (SW):* Wake/downstream: pickup ions. Periselene wake: Crust, Core Periselene dayside: Dust *Magnetotail:* Crust, mini-magnetospheres, core Periselene dayside only: Magnetotellurics, Dust

Key: T=Tail; Rx= Reconnection; R_L =Lunar radii = ; R_E =Earth radii

Table 2: *ARTEMIS (FY10-12) Orbits and Mission Phases Versus Heliophysics and Planetary Objectives*


LL1,2 (Oct '10 – Jan '11)
Opposite Sides – Sun-Earth Alignments
– Along/Across Sun-Earth Line (AR: 10 – 20 R_E)
– Lunar Wake (Traversals at 10-30R_L)

LL1 (Jan '11 – Apr '11)
Same Side – Sun-Earth Alignments
– Along/Across Sun-Earth Line (AR: 5 – 20 R_E)
– Lunar Wake (Traversals at 10-30R_L)

LO (Apr '11 – Sep '12)
Line of Apsides Walk 360deg
– Along/Across Sun-Moon Line (ΔR:500km–5 R_E)
– Lunar Wake (Traversals at 100km-10R_L)

Figure 2: ARTEMIS by phase (Phases LL1,2 and LL1 are shown in GSE coordinates. Phase LO is shown in Selenocentric Solar Ecliptic, SSE, coordinates. Acronyms in Table 2). P1 is red, P2 is green and the Moon gray. Phases are designed to permit progressively smaller inter-probe separations in all regions visited. These orbits are publicly available for plotting at: http://sscweb.gsfc.nasa.gov/tipsod . For probes P1 and P2 select: Artemis_P1 and Artemis_P2; for the Moon select: "Moon".

Lunar Science with ARTEMIS

Exosphere and plasma pick-up

Newly created ions, produced by surface sputtering or ionization of exospheric gases are generated at relatively low energies (0.01-10 eV) but immediately feel the effect of solar wind magnetic and electric fields. Ions are then accelerated in cycloidal trajectories (i.e. "picked up"). ARTEMIS will use charged particle measurements from the ESA and SST instruments as an extremely sensitive detector of the surface and exospheric properties, by back-tracing the pickup ion trajectories, allowing the ARTEMIS team to accurately determine the source region [Hartle and Killen, 2006]. These measurements can be combined with the other, nearby ARTEMIS probe's ESA and SST pristine solar wind data, and with GOES solar EUV measurements of the solar activity to determine the relative variability of exospheric source and losses and their dependence on external drivers.

Using such techniques, SELENE/Kaguya observations have shown that (1) solar wind ions reflected off the lunar surface and from crustal magnetic fields are accelerated by the solar wind electric field to speeds as high as 3 times that of the solar wind [Saito et al., 2008], (2) ions originate partly from the exosphere and partly directly from the surface. Surface ions are able to obtain the full energy resulting from the electric field imposed by the solar wind; while exospheric ions, which commence their orbits midway between the surface and the detector, obtain less energy. Thus energy differentiates the source of those ions and finally (3) the ions on the day side are composed of He^+, C^+, O^+, and K^+ in addition to Na^+.

Although ARTEMIS will generally be further away from the Moon, the large geometric factor of the ESA instruments and the long integration time (hours) afforded by the 27hr-long, eccentric orbit will enable sensitive measurements of the pickup ions under stable solar wind conditions. The technique will first be tested on lunar flybys in January through March of 2010. When applied as function of lunar phase the technique can determine the dependence of the lunar exosphere on lunar longitude undergoing illumination, thereby providing estimates of the ion composition as function of selenographic longitude.

Lunar Dust and Transport

It is generally accepted that ambient solar and plasma conditions play a central role in dust motion on airless bodies, via electrostatic levitation of charged grains. For example, images obtained by the Surveyor landers showed a glow along the western horizon after sunset [Rennilson and Criswell, 1974]. The Apollo 17 Lunar Ejecta and Meteorite (LEAM) experiment may have yielded direct evidence for the electrostatic transport of lunar dust. LEAM detected highly-charged dust grains of lunar origin moving at < 1 km/s with impact rates up to 100 times greater than anticipated [Colwell *et al.*, 2007]. More recently, a dust fountain model [Farrell *et al.*, 2007] has described how charged lunar dust can become electrostatically "lofted" to high altitudes when the forces due to surface charging effects are able to overcome gravity and cohesion. The charged dust is then rapidly accelerated through the plasma sheath and subsequently follows a ballistic trajectory where it could be readily detected from orbit. Finally, observations by Apollo astronauts from orbit of a "lunar horizon glow" (LHG) above the terminator is thought to be due to the scattering of sunlight by an electrified exospheric dust population extending to altitudes in excess of 100 km [Zook and McCoy, 1991]. McCoy [1976] used coronal photography from Apollo to estimate dust concentrations ranging from $\sim 10^5/m^3$ near the surface to $\sim 10\ /m^3$ at 100 km.

The lunar surface electric field has been shown to respond closely to solar and magnetospheric plasma and energetic particles [Halekas *et al.*, 2007], and also to vary with inclination with respect to the Sun. The largest lunar potentials occur on the nightside, in the absence of photoemission, where surface charging is primarily driven by ambient plasma currents [Stubbbs *et al.*, 2007]. Electron reflectometry techniques have been used on Lunar Prospector (LP) to measure the potential drop between LP and the surface [Halekas *et al.*, 2002], and more recently to determine the absolute surface potential [Halekas *et al.*, 2009].

The field and plasma instrumentation on ARTEMIS is more comprehensive than that flown on previous missions ensuring future progress on our understanding of the origin and dynamics of lunar electric fields. By using both electron and ion measurements, the reflectometry technique can be extended to both positive and negative potentials, and can be used to determine plasma currents incident on the surface, facilitating accurate modeling of the charging process.

ARTEMIS is expected to play a key role in ongoing and future efforts to understand dust dynamics in the lunar environment. Maps of the lunar surface potential obtained using the reflectometry techniques described above can reveal average and extreme charging conditions that contribute to dust dynamics.

Interior Structure and composition of the Moon from Electromagnetic induction

Determining the interior structure of the Moon provides a key constraint on the history and evolution of the Moon. EM sounding techniques determine conductivity profile of its interior providing major insights (e.g., radius of lunar core, Hood et al., [1999] or the allowable mineralogy and temperature profile of the mantle, Khan et al., [2006]).

Two independent pieces of information are needed to derive the EM impedance at each frequency. The principal approach during the Apollo project was to use the magnetic transfer function between a distant satellite (source field) and a surface magnetometer (sum of source and induced fields). The alternative approach uses correlation of orthogonal electric and magnetic fields, i.e., the magnetotelluric (MT) method (Vozoff, 1991). MT is not subject to spatial aliasing at high frequencies, and is therefore optimal for relatively shallow probing of the outermost parts of the moon. ARTEMIS can use both methods—transfer function, and MT—to sound the lunar interior using ambient geophysical signals. A broad spectrum of frequencies is available for lunar EM sounding in the ambient solar wind such as turbulent waves, shocks and other structures. The supersonic solar wind confines the Moon's inductive signal near the surface on the dayside. However, in the near-vacuum cavity on the dark side, the magnetic induction signal propagates far away and can be sensed from orbit. Additionally, for ~4 days each month, the Moon passes into the Earth's geomagnetic tail, consisting of two near-vacuum magnetic lobes, sandwiching a dense sheet of plasma moving at subsonic speeds. There the lunar induced response in the tail is symmetric on the dayside and the nightside. As the Earth's dipole brings the Moon from one lobe to the other twice per day, the Moon will see very low frequency (50μHz to 50mHz) external drivers, ideal for probing at great depths. In the magnetotail, traveling compression regions and shocks have well characterized electric and magnetic signals, and provide high frequency drivers (0.05-10 Hz) well suited to MT investigations.

Though great strides were made during the Apollo era in our understanding of the lunar interior using EM and more recently from Lunar Prospector data, limitations in those data sets (e.g., zero level drifts for Apollo and its companion Explorer 33, and single point measurements from LP etc.) has hampered inversion of data at all depths (see Grimm and Delory, 2008 for a recent review). Thus, the lunar core remains compatible with either metallic or silicate composition. ARTEMIS can measure the external, driving magnetic field with one spacecraft and the response of the lunar interior to that field from the probe near the surface. Differencing the highly sensitive magnetometer signals on the two spacecraft under various external driver frequencies would yield the interior conductivity of the Moon as a function of frequency, and hence depth. For the first time the technique will be applied using nearby spacecraft, bearing identical sensors with very stable offsets, that can be cross-calibrated just hours prior to each pass, and can benefit from on board plasma measurements to remove localized space currents.

The ARTEMIS periselene altitude can be modified to be approximately 100km (exact altitude depends on results of orbit stability analysis). This altitude is ideal for making induction measurements from orbit, because with the exception of few known, localized magnetic anomalies, all other variances from the input signal can be attributed to induction effects. Preliminary analysis indicates that a geophysical signal ~0.1mV/m/sqrt(Hz) at 1-10Hz is expected at an orbital platform (e.g.,ILN SDT, 2009, p. 38); this signal is ~5 times the sensitivity limit of ARTEMIS' EFI instrument from its 40m and 50m tip-to-tip radial sensor pairs.

Surface properties and planetary evolution as revealed by crustal magnetism and space weathering.

Crustal magnetism preserves ancient records of planetary and surface evolution. At Earth, studies of crustal fields revealed polarity reversals of the core dynamo and established a chronology that ultimately confirmed the plate tectonics hypothesis. The origin of lunar magnetism is less clear because of the absence of a present day dynamo. Lunar sample measurements indicate the possible presence of a lunar dynamo from 3.6-3.9 Ga (Cisowski et al., 1983) with an order of magnitude decrease before and after that period. Like at Earth, thermo-remanent magnetization is expected to have magnetized igneous rocks during that period. However, lunar magnetic fields are stronger over highlands than over maria, in agreement with the absence of a recent dynamo to magnetize recent lava flows.

The correlation between regions with high albedo and crustal magnetization [Nicholas et al., 2006] may imply that strong surface magnetic fields are responsible for prohibiting the optical maturation of the regolith, otherwise known as "space weathering". On the Moon, spectral darkening was originally believed to be caused by the accumulation of agglutinates, glass-rich aggregates formed by melting as a result of micrometeorite impacts. These complex structures were known to contain a reduced form of iron (nanophase Fe – npFe0), generated by impact melting of solar wind hydrogen-enriched regolith. However, recent work has identified npFe0 itself and not the agglutinate particles as the darkening agent, which also explains the spectral reddening seen on the Moon and more importantly on other weathered bodies (Hapke, 2001; Pieters et al., 2000). ARTEMIS possesses the complete set of plasma instrumentation necessary for studies of crustal magnetization and weathering. ARTEMIS can measure lunar fields from 100km or less, depending on the periapsis and longitudes that will be attained, at a 10° inclination or greater (goal ~ 20°). It will study the interaction of near-equatorial magnetic anomalies with the solar wind and the magnetotail. Near equatorial anomalies which have been observed already by SELENE/Kaguya at 100km altitude include Reiner Gamma (8N, 58W), Rima Sirsalis (12 S, 58W), Descartes (11S, 16E) and Crisium antipode (20S, 124W). The equatorward portion of South Pole – Aitken (20-50S, 150-180E) may also be measured.

ARTEMIS and other concurrent missions

ARTEMIS complements LRO and LADEE, being concurrent to both. While LRO's LAMP instrument will observe the vertical scale heights of species such as Ar, H, OH and H_2 to understand volatile transport, ARTEMIS will measure the ionized fraction of those species, a result of photo-ionization by solar UV radiation. LADEE's UV spectrometer (UVS) and Neutral Mass Spectrometer (NMS) instruments will also observe exospheric constituents both directly as neutrals, and remotely via UV measurements. LRO and LADEE thus measure gases before ionization, while ARTEMIS measures them post-ionization. With the solar UV flux known from other concurrent space-borne instruments (e.g., GOES) it is possible to correlate the ARTEMIS measurements with those on LRO and LADEE and directly follow atmospheric constituents from their source on the surface to their loss in the solar wind. By coordinating ARTEMIS measurements with those from LRO and LADEE the community will greatly advance our understanding of the lunar exosphere, its coupling to the lunar surface and its escape to space.

ARTEMIS and International Lunar Network.

A major element of NASA's lunar flight projects is the International Lunar Network (ILN), comprised of small geophysical nodes on the lunar surface. These nodes are expected to be deployed in the next decade by NASA and international space agencies, with the goal to improve our understanding of the interior structure and composition of the moon (ILN SDT, 2009). One of the goals of the ILN is to perform lunar EM sounding from the surface with both electric and magnetic sensors. ARTEMIS can provide continuous magnetometer measurements of the driver signal to meet the needs of the measurement floor of the ILN network EM sounding goal. ARTEMIS' magnetotelluric observations from orbit, over various spatial and temporal locations would complement the magnetotelluric measurements of the ILN network.

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