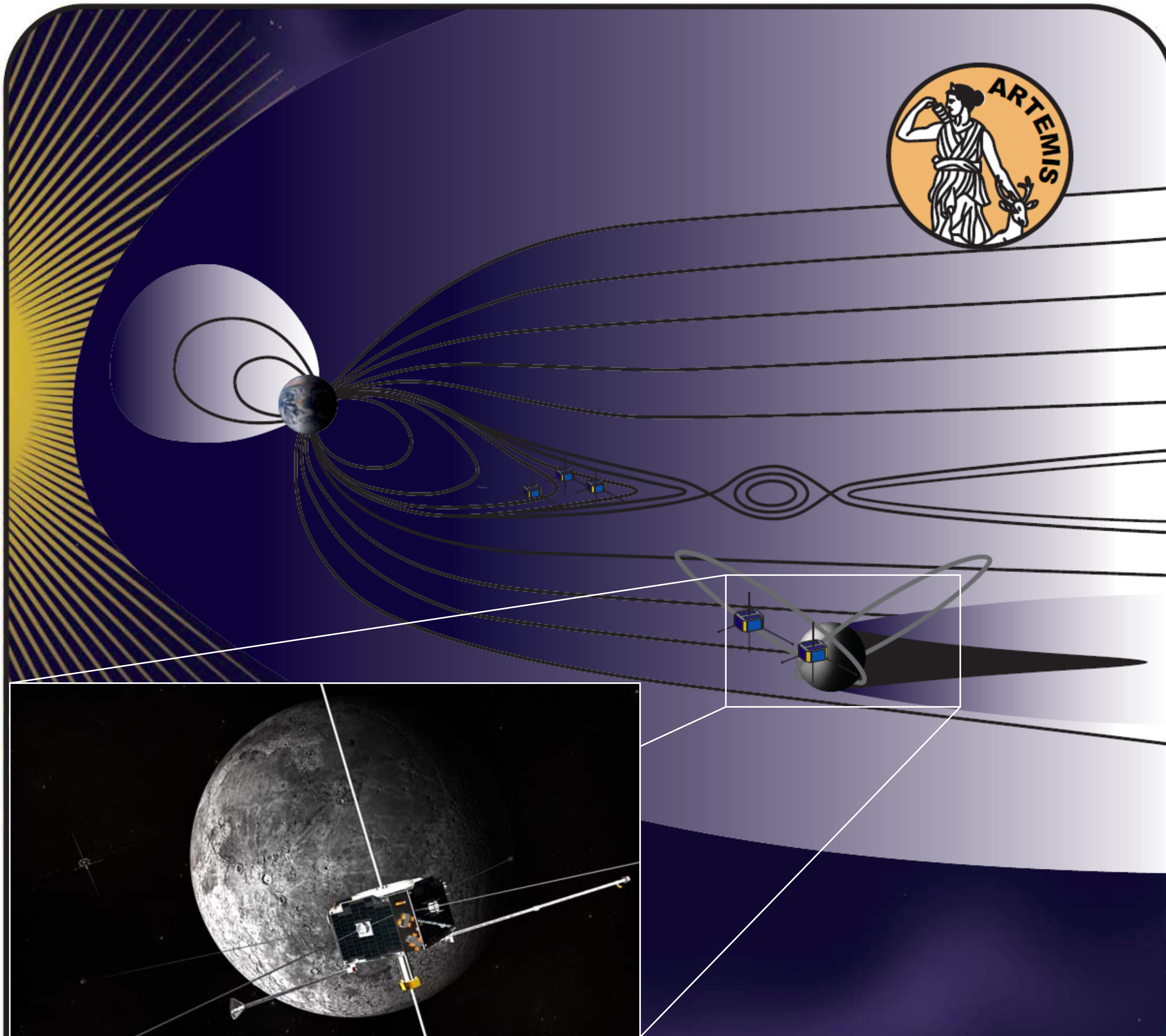

Acceleration, Reconnection Turbulence, and Electrodynamics of Moon's Interaction with the Sun:

ARTEMIS

PROPOSAL FOR:
SENIOR REVIEW 2010 OF THE MISSION OPERATIONS AND DATA ANALYSIS PROGRAM
FOR THE HELIOPHYSICS AND PLANETARY OPERATING MISSIONS
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1. Executive Summary

ARTEMIS, a two satellite mission to the Moon, provides entirely new scientific objectives for the two outermost THEMIS probes. THEMIS, a MIDEX-class heliophysics mission comprising five identical satellites (“probes”), was launched on February 17, 2007 to study magnetospheric substorms, solar wind-magnetosphere coupling and radiation belt electron energization. The mission objectives have been accomplished as of September 2009. THEMIS is a success story, a testament to the team’s capabilities and commitment to science. It has had >135 refereed publications, three special journal issues, 6 press releases and major stories in public media. Discoveries were a CNN most popular science story, aired as NOVA, Discovery and PBS programs, and ranked as a top-10 science story in 2008 in Astronomy Magazine.

In its proposal to the February 2008 Heliophysics Senior Review, the THEMIS team proposed an extended mission which, while retaining the three innermost probes, P3, P4 and P5, in Earth orbit to conduct critical near-Earth magnetosphere science it would send the two outermost probes, P1 and P2, into stable, lunar, near-equatorial orbits, where they would form the new mission ARTEMIS. The rationale was to conduct cutting-edge heliophysics science from the moon and simultaneously evade P1 and P2’s terminal shadows in March 2010 if still in Earth orbit.

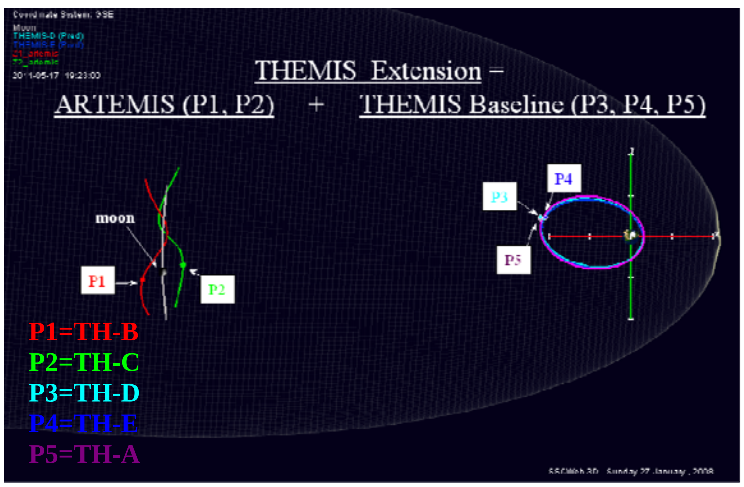

Figure 1.1. THEMIS extended baseline and ARTEMIS. Insert shows probe number assignments to probe letters, which was done after early checkout. Orbits are available for plotting at: http://sscweb.gsfc.nasa.gov/tipsod

The request was granted and thus ARTEMIS was born, to study “Acceleration, Reconnection, Turbulence and Electrodynamics of Moon’s Interaction with the Sun”. The two probes en-route to the Moon have already undergone several lunar flybys. One flyby in particular traversed the wake and has returned new and exciting information regarding the structure and dynamics of the wake at ~4R_L thanks to the highly capable instrumentation at hand. The probes will enter through a low-thrust trajectory the Earth-Moon Lissajous orbits in October 2010 (see Table 1.1) and will be inserted into stable, low inclination, highly eccentric lunar orbits in April 2011. From 100s of km to 20R_E separations at lunar distances, P1 and P2 will make the first systematic, two-point, comprehensve observations in the distant magnetotail. ARTEMIS will thus resolve outstanding questions regarding particle acceleration, reconnection and turbulence in the magnetotail and in the solar wind, and study the formation and dynamics of the lunar wake from two points at 1500km–30R_L separations.

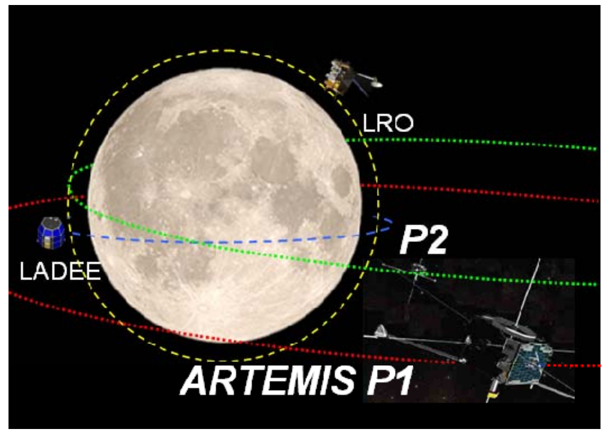

Figure 1.2 ARTEMIS will study with two identical, cross-calibrated spacecraft lunar exospheric ions and dust, crustal magnetism, and the lunar interior. One probe will measure the pristine solar wind driver, while the other will study the lunar environment’s response. ARTEMIS extends the Kaguya results into the next decade, and provides synergy with LRO, LADEE and the International Lunar Network.

From the moment ARTEMIS was conceived, the team realized that significant benefits to planetary science could also accrue from the two lunar probes with further, albeit small, orbit and instrument optimizations. Aside from the significant progress expected in understanding the lunar wake and radiation hazards at the Moon’s orbit (of interest to both Planetary and Heliophysics), ARTEMIS can address fundamental questions at the forefront of planetary science at the Moon (Figure 1.2): the sources and transport of exospheric and sputtered species; the charging and circulation of dust by electric fields, the structure and composition of the lunar interior by electromagnetic sounding; and the surface properties and planetary history, as evidenced in crustal magnetism. Additionally, ARTEMIS’ goals and instrumentation complement LRO’s extended phase measurements of the lunar exosphere and of the lunar radiation environment by providing high fidelity local solar wind data. ARTEMIS’ electric field and plasma data also support LADEE’s prime goal to understand exospheric neutral and dust generation and transport.

The health of the instruments is excellent: ARTEMIS’ state-of-the art electron and particle detector capabilities at the moon match or exceed electron reflectometry capabilities of Lunar Prospector. Highly sensitive, well-characterized magnetometers, electric field, and energetic particle instruments are ideally suited for the low field, low count lunar environment. ARTEMIS will provide the first simultaneous, comprehensive in situ measurements from locations near the lunar surface and in the nearby pristine solar wind with identical, cross-calibrated instrumentation. ARTEMIS will continue the successful THEMIS tradition to release its highest quality data, analysis code, and documentation and conduct software demos and training sessions at major heliophysics and planetary meetings. The ARTEMIS data are already SPASE-compatible, available through Virtual Observatories (VxOs), and will transition seamlessly in the Planetary Data System (PDS).

ARTEMIS orbits, to be adjusted in the second half of 2010 (if approved) for planetary, will generate dozens of low altitude periselene passes (~100km) and hundreds of out/inbound passes through the lunar exosphere and wake at altitudes ranging from 100s to beyond 10,000 km. The well characterized, identical magnetometers can conduct remote sensing of the lunar interior and crust, as well as exospheric species picked up by the solar wind. Stable for at least a decade, ARTEMIS will monitor exospheric constituents of the Moon over solar-cycle time-scales.

ARTEMIS complements other Heliophysics and Planetary missions: Most of the time upstream it will be an ideal, nearby solar wind monitor for THEMIS, Cluster and the soon to be launched RBSP; while it explores turbulence and reconnection at separations never before visited by Cluster or other spacecraft. Visiting the under-explored magnetotail at 55-65R_E, it will performing the first two point comprehensive observations there, resolving spatio-temporal ambiguities on tail structure and the extent of plasmoids. On the heels of the exciting discoveries from SELENE/Kaguya on lunar exospheric composition and transport, it possesses *in situ* DC electric fields and electromagnetic wave instrumentation that complements Kaguya's recent observations. ARTEMIS overlaps LRO's extended phase investigation and LADEE's prime investigation. It will therefore extend Kaguya's measurement capabilities into the LRO and LADEE era and will provide important synergies with these and future missions beyond 2014, such as the International Lunar Network, in need of magnetic field data from lunar orbit.

ARTEMIS is an interdisciplinary mission of discovery: It address key Heliophysics and Planetary science questions and does so at a very small fraction of the cost of a dedicated mission. It is aligned with the Heliophysics objectives: #1 (to understand the flow of energy and matter throughout the Heliosphere) as it is an ideal measure of the solar wind, when upstream, and of the storm/substorm outflows when in the tail; #2 (to understand the fundamental physical processes of space plasmas) as it addresses reconnection, acceleration, turbulence and wind-unmagnetized body interactions; and complements #3 (to define origins and societal impacts of variability) as it measures very precisely the solar wind input (when upstream) our reconnection output (when in the tail). The proposed investigation is also directly aligned with the findings of the National Research Council's (NRC's) 2003 Decadal Survey on "New Frontiers in the

Phase	Abbr	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	Mission Operations Only
P1 at LL2, P2 at LL1	**LL1,2 Phase**	Oct. '10-Jan. '11	d$\mathbf{R}_{P1-P2}$=20R_E at Moon d$\mathbf{R}_{P1-P2}$ along/across Wake & Sun-Earth dX^{GSE}_{P1-P2} ~ dY^{GSE}_{P1-P2} ~ 500km-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$\mathbf{R}_{P1-P2}$=5-20R_E at Moon d$\mathbf{R}_{P1-P2}$ along/across Wake & Sun-Earth dX^{GSE}_{P1-P2} ~ dY^{GSE}_{P1-P2} ~ 500km-20R_E		At Solar Wind (SW) wake or downstream: Pickup ions?
In Lunar orbit	**LO Phase**	Apr.'11-Sep. '12	d$\mathbf{R}_{P1-P2}$=500km-20R_L at Moon d$\mathbf{R}_{P1-P2}$ along/across Wake & Sun-Earth Periselene = ~ 100 km [trade TBD] Aposelene = ~19000km Inclination = ~10deg [trade TBD]		*In the Solar Wind (SW):* Wake/downstream: pickup. Periselene wake: Crust, Core Periselene dayside: Dust *Magnetotail:* Crust, core Periselene dayside only: Magnetotellurics, Dust
Lunar orbit (Prime)	**LO**	Oct.13-Sep.14	Same separations as above	Solar Max Studies & Tail extent and variability	
Phase	**Abbr**	**Interval**	**ARTEMIS and Ancillary Assets**	**Heliophysics Objective**	**Planetary Objective**
Lunar orbit (Prime)	**LO**	Oct.13-Sep.14	With THEMIS: Near- & mid-tail	Plasmoids, Rx, Shocks	
			With LRO: Instrument Complement		*UV and Dust + In-situ*
Lunar orbit (Extended)	**LO**	FY13/14	With RBSP + THEMIS	Storms: Plasmoids, CMEs	
			With LADEE		Exosphere sources/E-fields

Table 1.1: *ARTEMIS (FY11-14) Orbits and Mission Phases Versus Heliophysics and Planetary Objectives*

Solar System, An Integrated Exploration Strategy", which proclaimed the Moon as a high priority target for inner planet research. This is due to the special importance the Moon had in shaping our planet's past and the critical information it holds about the evolution of all the rocky planets. Amongst the top lunar science goals of the NRC Decadal Survey were the "determination of the [Lunar] internal structure, … and possible existence of an iron-rich core" (p. 62), both related to the goals of the ARTEMIS investigation. *By funding ARTEMIS to conduct cutting-edge Heliophysics from lunar distance and Planetary science that complements its upcoming missions, NASA expands the frontiers of knowledge in both disciplines with novelty and efficiency while providing cross-disciplinary benefits across NASA.*

2. ARTEMIS concept and team

The "Acceleration, Reconnection, Turbulence, and electrodynamics of Moon's Interaction with the Sun" (ARTEMIS) mission uses two-spacecraft ("probes") currently en route to the Moon. The mission has been optimized to address heliophysics questions related to acceleration, reconnection and turbulence in the (i) magnetosphere and (ii) the solar wind, and (iii) the electrodynamics of the lunar environment. From distances 100km to 120,000km from the Moon and at variable inter-probe separations optimized for Heliophysics science, the two ARTEMIS probes will address fundamental questions in Heliophysics related to the dynamics, scale size, and evolution of distant tail and solar wind particle acceleration and turbulence processes and the kinetic properties of the lunar wake. The probes are expected to reach Lissajous orbits (the Lagrange points of the Earth-Moon system) in October 2010 and enter into lunar orbits in April 2011 (see Table 1.1, Figure 2.2).

ARTEMIS's multi-point observations, orbits, and instrumentation are also uniquely suited to advance our knowledge on several key topics raised in the 2003 NRC Decadal Survey for Solar System Exploration and several prioritized science concepts listed in the 2007 NAS report "The Scientific Context for Exploration of the Moon". Specifically, with all its instruments operating flawlessly, ARTEMIS can contribute greatly to our understanding of the formation and evolution of the exosphere, dust levitation by electric fields, the crustal fields and regolith properties and the interior of the Moon from the achievable 100km perigee altitude, ~10° inclination orbit. By optimizing periselene to obtain low altitude passes below 100km and inclinations as high as 20° with a goal to reach the outskirts of the South Pole – Aitken basin, the ARTEMIS team can maximize the science return from the mission for Planetary science, without any adverse effect on the heliophysics mission objectives. ARTEMIS instruments (Figure 2.1, Table 2.1, or Table VI in Angelopoulos, T2008 for a detailed synopsis) can provide magnetic field, electric field, and particle distributions with state-of-the-art cadence, offset stability and sensitivity. Orbit and instrument optimization to address Planetary objectives can start immediately, be tested on flybys, and be in place by lunar orbit insertion in April 2011.

History: Late into the THEMIS mission's development cycle the team recognized that Earth shadows exceeding the bus design limit would threaten THEMIS probes P1, P2 during their third tail season (one year after the prime mission was over). Additionally, the angles between the lines of apsides for P1 and P2 would be 54^o and 27^o away from those of P3, 4, and5, rendering five-probe conjunctions less than optimal. It was recognized that by placing P1 and P2 into stable lunar orbits, their potential for scientific discovery would be maximized for heliophysics, while the risk of freezing would be avoided. This formed the genesis of both the ARTEMIS concept and the ARTEMIS science team. Orbits have been optimized for maximum Heliophysics science in collaboration with JPL since 2005, and were vetted during three THEMIS Science Working Team meetings.

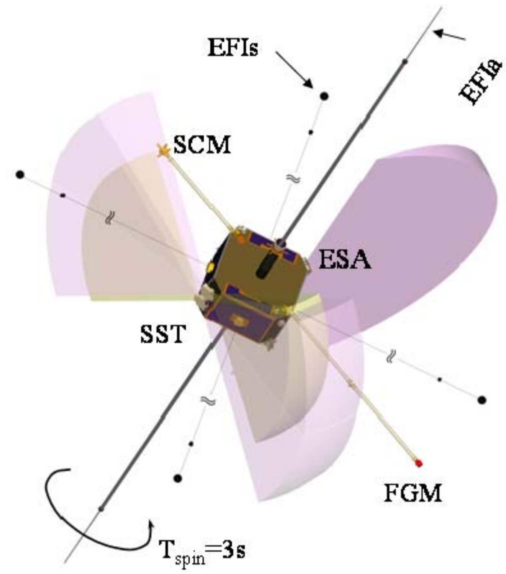

Figure 2.1 *One of two ARTEMIS probes shown with its instrumentation, in deployed configuration. The fields of view of the body-mounted particle instruments are highlighted. The spin-stabilized probe provides three dimensional particle information once per spin period (T_{spin}=3s). Electric Field Instrument spin plane booms (EFIs) are 40m long and 50m long tip-to-tip wire dipoles. EFIa (axial) stacer booms are ~7m tip-to-tip. FluxGate Magnetometer sensor (FGM) and Search Coil Magnetometer sensor (SCM) are mounted on 2m and 1m graphite epoxy booms.*

Mission Phases: 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 2.2). After 3 months P1 is brought onto the same side of the Moon, (*LL1 Phase*) resulting in smaller, 5-10R_E separations.

Instrument	Specs	Reference
FGM: FluxGate Magnetometer	DC Magnetic Field Frequency: DC-64Hz Offset stability <0.2nT/12hr	Auster etal., T2008
SCM: SearchCoil Magnetometer	AC Magnetic Field Frequency: 1Hz – 4kHz	Roux et al., T2008 LeContel et al., T2008
EFI: Electric Field Instrument	3D Electric Field Frequency: DC – 8kHz	Bonnell et al., T2008 Cully et al., T2008
ESA: Electrostatic Analyzer	Total ions: 5eV – 25 keV Electrons: 5eV – 30 keV g-factor/anode: -ions: $0.875 \times 10^{-3} cm^2 str$ -electrons: $0.313 \times 10^{-3} cm^2 str$	McFadden et al., T2008
SST: Solid State Telescope	Total ions: 25keV – 6MeV Electrons: 25keV – 1 MeV	Angelopoulos, T2008 for mounting, and fields of view.

***Table 2.1** THEMIS instruments and their capability*

After another 3 months, both probes are inserted into stable, ~300km x 19000km (heliophysics plan), equatorial, ~1-day period lunar orbits with separations ~500km - $5R_E$ (*LO Phase*). P1 is on a retrograde and P2 on prograde orbit, resulting in a fast, 360^o relative precession during the 17 months of this phase for heliophysics science objectives – this aspect of the mission will also be retained. It is evident that the probe separations become progressively shorter as the probes move from one mission phase to another. These are ideal for measuring the solar wind and the magnetotail from a range of distances never before achieved with other missions.

Planetary modifications: In order to optimize the planetary aspects of the investigation, the team proposes to revise the inclination and periapsis of the orbit to get below 100km and at higher inclinations, to capture interactions between the solar wind and multiple anomalies. These are described in Section 6.

Since the Moon visits the magnetotail and solar wind once each 28 days, the two probes measure the response of the lunar environment under different drivers during each phase of the mission. Furthermore, as the probes travel around the Moon, they sample the exosphere and near-equatorial surface from a variety of altitudes and solar zenith angles.

As of this proposal, the ARTEMIS team has accomplished the translunar injection maneuvers that will eventually bring P1 and P2 into lunar orbit. The first dataset from the proximity of the Moon has occurred during a lunar flybys in early 2010 (closest approach = 4 R_L on a polar Sun-Moon plane pass) with very exciting new results currently being analyzed (Section 4); these will guide science orbit and instrument optimization, as well as data processing and science validation plans over the next year in anticipation of lunar orbit captures in 2011.

3. Heliophysics Science

ARTEMIS addresses the dynamics, scale size, and energy balance of distant tail particle acceleration and reconnection processes, solar wind and magnetotail turbulence, and the yet unknown kinetic properties of the lunar wake from multiple vantage points. ARTEMIS is a mission of discovery in support of the Heliophysics Great Observatory. Its lower energy particle measurements and comprehensive fields instrumentation complement LRO's higher energy measurements from the CRaTER instrument, and characterize the lunar electrodynamic environment to help interpret LRO's data. In addition, ARTEMIS serves as an accurate, near-Earth solar wind monitor ~ 80% of the time, working synergistically with STEREO's remote sensing of Solar variability and ACE's and Wind's early warning capabilities. The remainder of

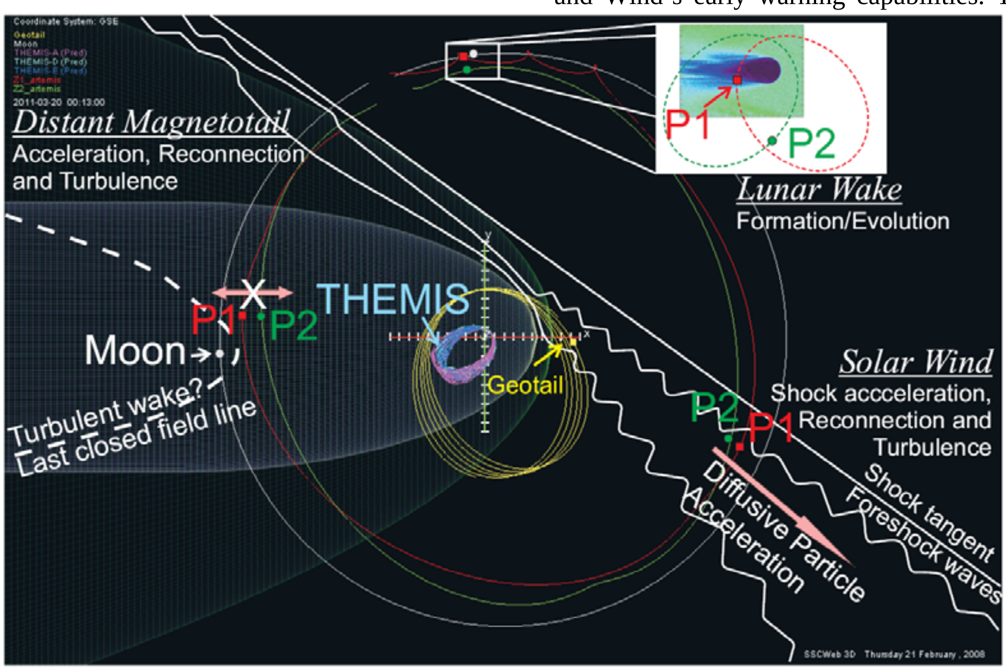

Figure 3.1 ARTEMIS depicted by science region. Every 28 days probes P1 and P2 traverse the magnetosphere, the solar wind and (multiple times) the lunar wake, addressing key questions in Heliophysics.

the time, ARTEMIS works in tandem with Geotail, Cluster, and the extended THEMIS baseline mission to study effects of near-Earth reconnection (plasmoids, flux ropes) in the distant tail.

ARTEMIS is the first multi-probe mission with the comprehensive field and particle instrumentation required to study the distant tail and the lunar wake. Its two probes, P1 and P2, will determine the shape and extent of plasmoids and reconnection lines, and expand our understanding of solar wind and plasma sheet turbulence by surveying these phenomena over hitherto unexplored spatial scales. Finally, with two probes, ARTEMIS will be able to disentangle temporal and spatial variations of the lunar wake and their relationships to upstream solar wind conditions.

Figure 3.1 shows the three regimes visited by the probes in lunar orbit and the science objectives within them. ARTEMIS addresses questions related to (i) Acceleration, Reconnection and Turbulence in the magnetosphere; (ii) Acceleration, Reconnection and Turbulence in the Solar Wind and (iii) the Electrodynamics of lunar environment. In those regimes ARTEMIS answers fundamental questions pertaining to the three primary objectives of the Heliophysics Discipline, as described Section 1. ARTEMIS is very relevant to the Heliophysics roadmap and NRC findings (Table 3.1).

3.1 In the magnetosphere.

Tantalizing, but brief passes of the “distant” magnetotail by ISEE-3, Geotail, Galileo, and Wind demonstrated that the region hosts diverse, fundamental plasma physics phenomena: quasi-steady reconnection resulting in heated plasma jets, beams of energized particles, twisted and/or unusually cold and dense plasma sheets and turbulence. The distant reconnection line is thought to reside at times at 55-65R_E from Earth, making the lunar orbit particularly interesting for global magnetotail circulation. The fundamental processes occurring there are common to other planetary and astrophysical systems (see Figure 3.2). Additionally, the magnetotail at lunar distances is an ideal vantage point from which to study the integrated output from the near-Earth processing of stored solar wind energy in the form of heated/accelerated flows and plasmoids. ARTEMIS will study these phenomena for the first time both comprehensively and systematically, from the unique perspective afforded by its two identical probes.

In the magnetosphere, ARTEMIS will address:

- How are particles accelerated up to 100s of keV?
- What are the nature and effects of reconnection?
- What are the drivers and effects of turbulence?

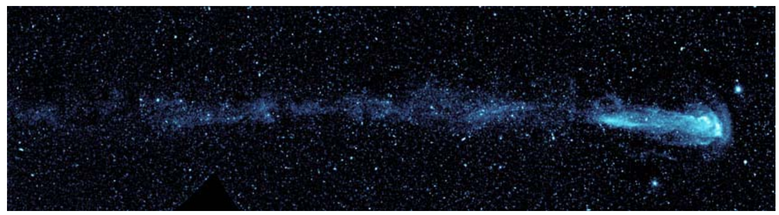

Figure 3.2. Supersonic motion of Mira, a mass-shedding red giant moving through the interstellar medium, creates a thirteen light-year long tail. The tail-length to standoff distance ratios for Mira and Earth are comparable. Plasma acceleration, reconnection and turbulence are basic processes controlling the dynamics of that stellar object’s tail, but only at Earth can we study them comprehensively using ARTEMIS’s dual, well-instrumented probes. http://www.galex.caltech.edu/MEDIA/2007-04/

3.1.1 Particle acceleration. Simulations show that particles in reconnection geometries gain energy as they drift along X-lines, but can also be Fermi-accelerated in the collapsing bubbles surrounding O-lines. Wind observations in the distant magnetotail provide evidence for electron energization up to 300 keV [Øieroset et al., 2002]. Two-probe ARTEMIS observations of flows and magnetic fields are needed to discriminate between (and track the motion of) X- and O-lines [Eastwood et al, 2005a]. Comparing observations of particle distributions by the ESA and SST instruments at X- and O-lines with models, *ARTEMIS will distinguish between the two acceleration mechanisms and determine the maximum energy obtainable under a variety of external conditions.* Additionally, the factors controlling ion heating by tail reconnection are presently unknown. Simulations suggest that this heating is proportional to the inflow Alfvénic speed. The distant magnetotail is an ideal, pristine laboratory to study these phenomena: the absence of a near-Earth high-field obstacle

	Heliophysics Roadmap Objective	ARTEMIS
F1	Understand Magnetic Reconnection	3.1, 3.2
F2	Understand the Processes that Accelerate and Transport Particles	3.1, 3.2
F3	Plasma-Neutral Interactions on Various Spatial Scales (Aurora/Ionosphere)	3.1, 3.2
H1	Understand the evolution of solar activity that affects Earth (Turbulence/Shocks)	3.2
H2	Determine changes in the Earth’s magnetosphere/ionosphere for specification/mitigation/prediction	3.2.4
H4	Understand role of magnetic shielding on evolution/habitability	3.2.4
J1	Characterize the variability of space environments for explorers	3.2.4
J4	Characterize space weather in planetary environments	3.2.4
	NAC/NRC Report Goal: Heliophysics Science and the Moon	
1.1	Characterize lunar electromagnetic and plasma environment	3.3
1.3	Magnetotail dynamics at lunar orbit	3.3
1.4	Interaction of plasmas with the Moon	3.3

Table 3.1 Mapping ARTEMIS to the Heliophysics roadmap & the NRC report on Lunar Science

there eliminates the possibility of heating by flow braking. Simultaneous inflow and outflow parameters are needed to ascertain the results of these models. *ARTEMIS will obtain simultaneous measurements of the reconnection inflow and outflow conditions to determine the mechanism of ion heating in the distant tail.*

3.1.2 Reconnection: Its nature and effects. ISEE-3, Geotail, and Wind observations built a statistical picture of large-scale quasi-steady reconnection line in the distant magnetotail, which appears to be bowed, with closest approach to Earth at the center of the magnetotail (Figure 3B). Some simulations indicate that both the north-south and dawn-dusk interplanetary field components control the cross-tail extent of the X-line. In the absence of multi-satellite observations we do not know the conditions favoring point- versus line- reconnection and the instantaneous shape of the distant reconnection line. Case and statistical studies combining observations by the two ARTEMIS probes will determine the occurrence patterns, orientation, and length of reconnection lines in the magnetotail at lunar distances as a function of solar wind and geomagnetic conditions.

Most of the plasma jetting from reconnection in the distant tail does not reach the near-Earth plasma sheet [Øieroset et al., 2004]. We do not know presently whether field line tension, boundary layer waves, flank-ward diversion, or plasma sheet turbulence decelerates these flows. Conversely, transient reconnection both in the near-Earth, as well as in the mid-tail regions, ejects anti-sunward moving plasmoids and Earthward moving flux ropes (see Figure 3.3). Plasmoids are expected to accelerate once reconnection reaches the last closed field line, but may decelerate when moving in the Earthward direction. In the absence of multipoint measurements, even the most basic characteristics of fast flows and plasmoids in the tail remain poorly understood. Understanding these phenomena is important for determining how the distant tail reconnection process affects global flux and energy circulation, as well as the amount and extent of particle energization in the near-Earth environment.

Radial separations of 1-10 R_E parallel to the Sun-Earth line enable the two ARTEMIS probes to track the evolution of high speed flows and plasmoids over short distances. ARTEMIS will work in conjunction with Geotail, Cluster and the extended baseline THEMIS probes, to determine the Earthward extent of sunward flows generated in the distant magnetotail and track the tailward motion of plasmoids generated by near-Earth reconnection. ARTEMIS will determine the conditions under and the means by which the latter structures accelerate and grow or decelerate and dissipate along the tail axis. Azimuthal probe separations enable ARTEMIS to determine the cross-tail extent, orientation, shape (using minimum variance analyses of the magnetic field), internal structure, and topology (using particle pitch angle distributions) of plasmoids.

ARTEMIS will define the characteristics and effects of reconnection in the distant magnetotail, from structural, magneto-hydrodynamic scales down to the ion gyroradius and ion inertial length scales. Together with Cluster, Geotail and the baseline THEMIS extended probes, ARTEMIS will define the evolution of reconnection jets and plasmoids from near-Earth to the distant magnetotail.

3.1.3 Turbulence: drivers and effects. Turbulent dissipation is an effective mechanism for heating fluids and transferring mass, momentum and energy. Turbulence in the near-Earth region has been studied using Cluster [Weygand et al., 2007]. Here, the dissipation range is on the order of the ion inertial lengths or gyroradius (~few hundred km) and the correlation coefficients diminish to zero beyond scales of $3R_E$. But unlike at the near-Earth tail, where the flow fluctuations are small relative to the sound and Alfvén speeds (except in dynamic conditions), in the distant tail and the fluctuation flows are comparable to the sound and Alfvén speeds and therefore the fluctuations are dynamically and energetically important. Theoretical work and global simulations point towards magnetotail reconnection and velocity shears at the flanks as likely drivers of plasma sheet turbulence. Both drivers can affect energy circulation and particle transport within the magnetosphere. Characterizing the nature of these fluctuations, and determining their origin and dissipation is therefore important for global circulation. It is quite likely that the distant tail also exhibits an inertial range of turbulence at 1-$10R_E$ scales and a dissipation range at 0.1-$1R_E$.

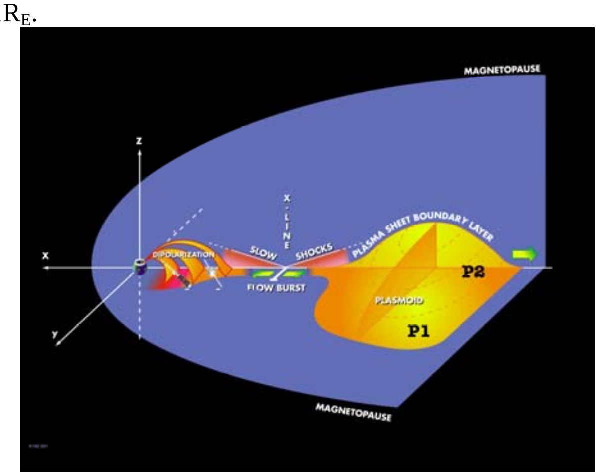

Figure 3.3. Until ARTEMIS's distant tail, two-point observations, the flow burst and plasmoid cross-tail extent, shape and structure will remain no more than an artists' conception, based on ephemeral visits by single satellites. Simulations cannot provide definitive answers due to the inclusion of numerical or artificial resistivity.

During periods of strongly northward IMF, the magnetosphere may close within lunar distance [Usadi et al., 1993], leaving a turbulent wake at greater distances.

We seek to identify and differentiate this wake, unrelated to magnetospheric convection, from inner magnetospheric or low latitude turbulence. To determine the drivers and effects of turbulence, the spatial and temporal variations of plasma and magnetic field measurements over a wide range of solar wind conditions and scale lengths must be measured.

ARTEMIS's two-point measurements at separations of a few hundred km to several R_E in directions transverse to the Sun-Earth line, can pinpoint the origin of the turbulence (reconnection flows versus boundary layer shear). Electron pitch angle distributions with the turbulent flows will determine whether field lines are open or closed, thus differentiating between a turbulent wake behind a closed magnetosphere or internal magnetotail turbulence. Ion-scattering in thin current sheets or secondary reconnection centers in turbulent layers will be studied as potential avenues to turbulent heating. *In conjunction with upstream solar wind measurements from ACE and Wind, ARTEMIS will establish the external conditions for, and characterize the nature of magnetotail turbulence.*

Turbulence is also expected to result in significant diffusion of plasma across the magnetopause boundary. Observations of a cold dense plasma sheet during northward IMF indicate that solar wind / sheath plasma has ready gains to the magnetotail even when no reconnection is expected on the dayside magnetopause. Such "cold dense plasma" is important for space weather because it intensifies the ring current under storm commencement immediately following strongly northward interplanetary fields.

The non-linear evolution Kelvin Helmholtz instability at the magnetopause may result in turbulent diffusion rates sufficient for solar wind plasma to cross the magnetopause boundary, and create the aforementioned cold dense plasma sheet. ARTEMIS's cross-tail conjunctions will detect the rolled-up waves driven by the Kelvin-Helmholtz instability and outward-oriented gradients in the plasma density expected for diffusion. Alternative hypotheses, e.g., solar wind entry due to high latitude reconnection, will be tested through searching for abrupt shear boundaries between recently reconnected and still open magnetic field lines. Wind and ACE data will be used to determine the upstream conditions and classify event occurrence patterns. ARTEMIS will determine the effects of turbulence on plasma sheet heating and mass circulation. Comparing these results with THEMIS's baseline studies at distances inside of $12R_E$ and Cluster's findings in the inner magnetosphere, plasma sheet turbulence and its effects can be studied as a function of magnetotail distance. *ARTEMIS will characterize plasma sheet turbulence over a previously unexamined range of spatial scales. It will determine, when, where and how turbulence originates in the magnetotail at lunar distances; and what its effects are for tail dynamics and magnetospheric circulation.*

ARTEMIS will spend four days per month, from October 2010 to September 2012, in the magnetotail. P1 and P2 will observe the plasma sheet from 20 to 30 hours per month, each collecting 2400hrs of magnetotail data, including 500-700hrs in the plasma sheet; more than enough to characterize this region of space and define its variability at unprecedented time resolution (burst mode) and with well inter-calibrated instrumentation. *From vantage points spanning kinetic to global phenomena, ARTEMIS will revolutionize our understanding of particle acceleration, the nature and effects of reconnection and the drivers and effects of turbulence in Earth's distant magnetotail.*

3.2 In the Solar Wind

Spending more than 80% of its time in the solar wind, ARTEMIS provides a unique opportunity to address long-standing questions concerning the physics of the solar wind and collisionless shocks. In the solar wind, ARTEMIS will determine:

- How particles are accelerated at shocks
- The nature and extent of low-shear reconnection
- The properties of the inertial range of turbulence

3.2.1 Particle acceleration: Collisionless shocks are sites for particle acceleration in a variety of astrophysical and heliospheric environments. ARTEMIS observations of both solar wind shocks and the Earth's foreshock will be used to address important questions regarding particle acceleration and heating.

Solar Energetic Particle events with energies from 10's to 100's MeV, are one of the prime interests of Heliophysics. The largest, so-called "gradual events", occur at oblique interplanetary shocks and require a seed population of 50 keV – 5 MeV particles. It has been proposed that such particles are locally produced by shock undulations of a few hundred ion inertial lengths, i.e., a few R_E. Figure 3.4 shows the structure of an interplanetary shock inferred from in situ measurements on Wind [Bale et al. 1999]. Multipoint measurements of the average Rankine-Hugoniot conditions (e.g., the shock-normal angle, θ_{Bn} and the Alfvén Mach number, M_A), and the spatial scales of the curvature are needed to verify this hypothesis.

At separations ~1-20 R_E, ARTEMIS's two probes will determine shock jump conditions and identify shock undulations for comparison with models of particle acceleration at shocks, thus answering key questions regarding the seed population of solar energetic particle events.

Earth's bow shock and foreshock are also excellent locations for studying the fundamental processes of particle acceleration [e.g., Eastwood et al., 2005b]. A small fraction of the solar wind ions incident on Earth's bow shock is reflected and accelerates to energies of tens of keV. These particles then stream into the upstream region along magnetic field lines, generate waves, and the waves both scatter and continue to accelerate the particles to energies of hundreds of keV.

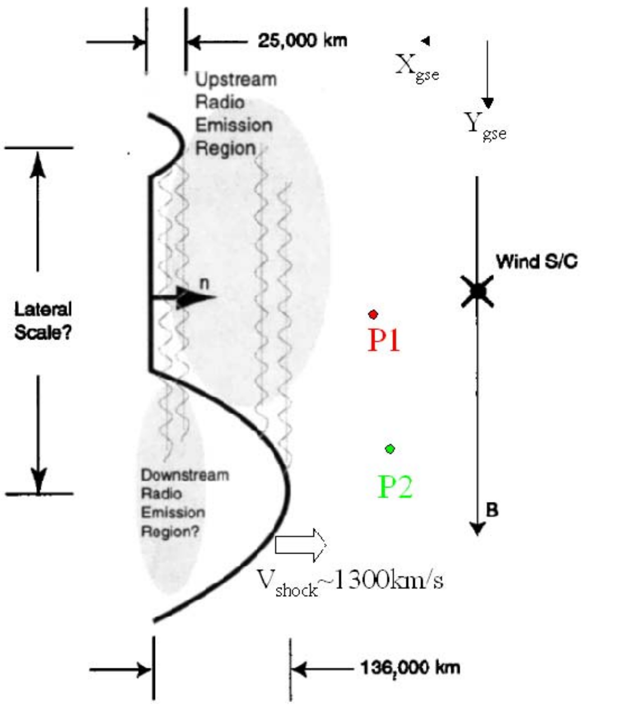

Figure 3.4. ARTEMIS, P1, P2, will make the first two-point measurements of shock undulations to determine how the 50keV-5MeV seed population for Solar Energetic Particles is accelerated at such structures, as predicted by theories. Shock undulations were inferred by Wind (as seen adapted from Bale et al., 1999) but never actually observed.

At lunar distances, where diffusively accelerated particles were first observed by the Apollo sub-satellites, the acceleration process continues at rates that depend on the spacecraft depth and distance to the point of tangency, as well as on upstream conditions. With distance from the bow shock wave amplitudes diminish, particle fluxes fall off at rates that diminish with increasing energy, and pitch angle distributions vary from isotropic to streaming. At ISEE-3 distances, 200 R_E upstream, observations indicate only streaming particle populations, as both scattering and acceleration has ceased. Single-spacecraft observations just outside the bow shock indicate that energetic ion flux e-folding distances are around 3.2 ± 0.2 R_E at 10 keV, but a recent two-spacecraft Cluster case study measured the e-folding distance to be an order of magnitude smaller: 0.5 R_E at 11 keV. The reasons for disagreement remain unclear. What is certain is that two-point measurements provide a far more reliable measurement of the e-folding distance, and that experimental tests of quasi-linear theory of diffusive acceleration at the Earth's bow shock have not yet been carried out.

ARTEMIS's direct inter-probe comparisons will provide a wealth of data regarding e-folding lengths over key distances (0.1 to 20 R_E). Their orbits sample the foreshock at various distances from the tangent line and solar wind conditions. Using ARTEMIS burst mode collection, triggered by crossings of the electron foreshock and bow shock, the plasma instruments will return the electron distribution functions needed to identify the electron foreshock beams to establish connection geometries; while high time resolution 3-D electric field observations will aid our understanding of how those beams are created. Results will then be compared with pitch angle distributions and wave amplitudes to validate or improve our theoretical understanding. Geotail, when properly situated, will help establish the homogeneity of the upstream wave field, and allow correlation lengths parallel and perpendicular to the field to be studied routinely, without the confounding effects of upstream variability. *ARTEMIS will accurately characterize the properties of diffusive particle acceleration at the foreshock.*

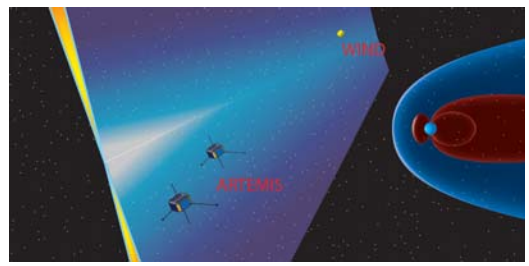

Figure 3.5. ARTEMIS P1 and P2 equipped with high-resolution plasma measurements will explore the properties of the low-shear reconnection exhaust, over scales of tens of R_E, and with WIND up to >100R_E.

3.2.2 Reconnection: Recent observations of reconnection "exhaust" regions have led to the identification of reconnection lines extending hundreds of Earth radii in the solar wind [Phan et al., 2006]. Such events enable detailed studies of reconnection under well-characterized conditions for comparing with simulations and theory. Examples reported thus far were accompanied by a large magnetic shear resulting in a wide exhaust fan. Lower shear cases of solar wind reconnection are interesting and far more common, but have yet to be reported due to the narrowness of the exhaust fan, which makes them more difficult to detect with the typical cadence of other solar wind monitors. High time resolution *plasma* measurements are essential to detect the narrower exhaust regions of low-shear reconnection. ARTEMIS's high time resolution accurate plasma moments and spin fits, as well as its Fast Survey and Burst mode collection, enable studies of the plasma structure within low-shear reconnection in the solar wind. Two-point ARTEMIS observations permit accurate, independent determination of shock normals at the exhaust and of the scale length of the reconnection region over 10-20R_E scales. Together with high-time resolution plasma measurements from Wind (Figure 3.5), and ancillary ACE and Geotail magnetic field data we can determine the extent of these reconnection lines at even larger scales (>100R_E). *ARTEMIS's two probe high cadence plasma measurements, both alone and combined with ACE, Wind and Geotail, enable fundamental studies of the most common, low-shear reconnection in the solar wind over scales ranging from tens to hundreds of R_E.*

3.2.3 Turbulence: The solar wind is an excellent laboratory for the study of turbulence. Understanding the properties of the inertial range is important for modeling solar wind evolution through the Heliosphere, and for providing constraints on kinetic theories of energy cascade and dissipation in space plasmas in general. Reliable knowledge about the correlative and Taylor scale values allows the effective magnetic Reynolds number in the solar wind to be determined. Only recently have multi-spacecraft measurements been used to examine turbulent fluctuations across space without the assumption of "frozen-in" flow. Fortuitous conjunctions between existing satellites were used to study scales above 20R_E, and Cluster was used at distances less than 1R_E (dissipation range) to study the magnetic correlative and Taylor micro-scale lengths. The crucial range, however, of the turbulent energy cascade at 1-20R_E has not been studied due to lack of appropriate satellite conjunctions. One intriguing finding from previous studies is that the correlative scale varies with respect to the mean magnetic field direction but the Taylor scale remains relatively constant. It is important to investigate if this finding extends over the full range of inertial cascade of turbulence, because the turbulence anisotropy affects acceleration and propagation of cosmic rays, and solar wind heating. Artemis will make high quality, prolonged, two-point measurements of the pristine solar wind with well inter-calibrated instrumentation. It will provide the first measurements over the previously unexplored inertial range and through the dissipation range, without the need to invoke the Taylor approximation. *ARTEMIS will determine the properties of turbulent cascade in the inertial regime and how critical turbulence scale lengths vary under different solar wind conditions.*

The energy contained in the turbulent cascade is deposited in the dissipation range. The power spectra of electric (E) and magnetic (B) fluctuations can be used to determine the properties of the dissipation process. E & B spectra have the same index in the inertial range, but diverge at small scales (high frequencies) in the dissipation range. E & B spectral ratios can be used to determine whether the turbulent energy is deposited into the whistler mode or the Alfvén/ion-cyclotron mode. Comprehensive 3-D DC electric and magnetic field observations will determine for the first time the relative importance of these two wave modes in the dissipation of collisionless plasma turbulence as a function of solar wind conditions. *ARTEMIS will complete past surveys of dissipation turbulence in the solar wind by providing observations over a previously unexamined range of spatial scales with unique and well intercalibrated instrumentation.*

3.2.4 Solar Wind Monitoring: ARTEMIS will be an excellent monitor of solar wind conditions for Heliophysics missions. Especially when near the Sun-Earth line, ARTEMIS will be closer to the Earth than ACE or Wind and provide reliable observations with less uncertain time delays. THEMIS will define the lunar environment, including radiation hazards in the solar wind, magnetotail lobes, and plasma sheet on a case and statistical basis. *If requested, ARTEMIS can serve as a space weather beacon.*

In summary, in the solar wind ARTEMIS will: determine how the energizartion of the seed population of solar energetic particles and diffusive shock acceleration operate, determine the nature and extent of the most common, but elusive, low-shear reconnection, and will characterize the properties of inertial turbulence (through the dissipation range) from two-point measurements with identical, well inter-calibrated instrumentation.

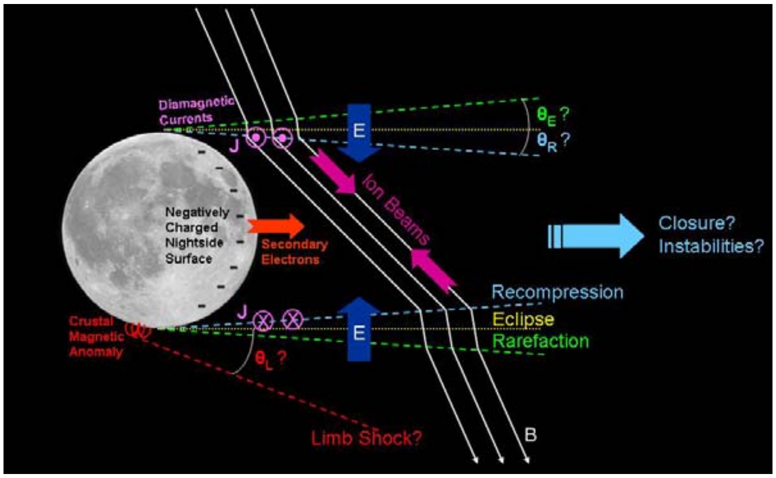

Figure 3.6. ARTEMIS, with its full complement of charged particle, magnetic and electric field, and wave measurements, can provide multi-point measurements of the wake over a wide range of downstream distances for varying solar wind conditions and to address the wide array of phenomena that occur in the lunar wake.

3.3 At the Lunar Wake

The interaction between the solar wind and the Moon forms a wake on the anti-sunward side of the Moon. The Moon is essentially non-magnetic, non-conducting, and has no ionosphere, so most solar wind plasma is absorbed on the dayside, leaving a plasma void on the nightside [Schubert and Lichtenstein, 1974]. The interplanetary field passes through the Moon practically unimpeded resulting in no upstream shock. Lunar wake refilling is a fundamental process and the Moon's easily accessible environment provides a unique opportunity to understand a wealth of basic physics questions pertaining to plasma expansion into a vacuum (see Figure 3.6). Knowledge gained at the Moon can be applied to plasma voids in torii around Earth, Jupiter, and Saturn and large objects in low earth orbit, e.g., the Space Shuttle, the International Space Station, and the Hubble Space Telescope.

Lack of *in situ* plasma measurements limits our understanding of the Lunar wake. Explorer-35 and the Apollo 15 and 16 sub-satellites, observed the wake extensively but carried limited instrumentation (low plasma resolution, in limited energy range). The Lunar Prospector (LP) mission had no ion detectors or electric field analyzers. Wind, Nozomi, and Geotail carried relatively complete plasma instrumentation, but made only a few passes. Extensive observations with the comprehensive ARTEMIS instrumentation offers a unique opportunity to:

- Determine the three dimensional structure and downstream extent of the lunar wake
- Identify the plasma acceleration processes and energetics in and around the wake
- Characterize wake formation and refilling under a wide range of solar wind and magnetospheric conditions.

3.3.1 Structure. Early studies treated the lunar wake as a magneto-hydrodynamic structure, i.e., a standing tangential discontinuity. As Explorer 35 identified no manifestation of the wake beyond 4 R_L (1 R_L = 1738 km), it was assumed that the lunar wake propagated as a magnetosonic disturbance, closing relatively rapidly within 3-10 R_L, depending on the interplanetary field orientation and Mach number, and that a trailing standing shock (never observed) would form at several R_L. However, Wind discovered a wake extending further, as much as 25 R_L [Clack et al, 2004] suggesting that the wake refills via an ion sonic mode. Wind observations of counter-streaming ion beams, large temperature anisotropies, and strong wave turbulence [Ogilvie, et al., 1996], as well as Nozomi observations of non-thermal ions and counterstreaming electrons indicate that the wake is far more kinetic. Figure 3.7 illustrates the predictions of a global hybrid simulation that a lunar wake extends well beyond 25 R_L downstream.

Asymmetries in wake structure are expected due to the IMF orientation being far from the wake axis or due to magnetosonic waves growing in the vicinity of crustal fields and propagating downstream. Observations do suggest asymmetric wakes, but with a single spacecraft they cannot be definitive. ARTEMIS's two probes will resolve spatio-temporal ambiguities, confirm relationships between wake structures and crustal features, determine how far downstream they propagate, and determine the degree to which they affect the interior of the wake.

Orbital configurations that place one or both of ARTEMIS' well-instrumented probes at the downstream wake will define the wake's extent and structure. Two-point measurements permit unambiguous determination of the asymmetries in the wake due to the perturbing influences of solar wind and crustal magnetic fields or other effects.

3.3.2 Energetics. Near the lunar limb, solar wind electrons diffuse rapidly across the low altitude wake boundary ahead of the slower ions, producing a charge separation electric field that slows the electrons and accelerates the ions. The resulting ambipolar electric field produces field-aligned beams of accelerated ions streaming into the wake from the flanks and can also cause pitch angle diffusion at the wake boundary [Nakagawa and Iizima, 2006]. Recent particle in cell simulations suggest that the charge separation between the 'electron cloud' and the trailing ion front can persist to several lunar radii downstream, forming a standing double layer with intense electric fields, as high as 0.1-1 V/m. These fields have never been measured directly before as no previous satellite carried the necessary DC electric field instrumentation. Hybrid simulations indicate that the density cavity should be filled by counter-streaming ion beams and large temperature anisotropies ($T_\perp > T_\parallel$), in general agreement with Wind observations [Travnicek et al., 2005]. *ARTEMIS will provide the first comprehensive measurements to determine both the large DC electric field at the lunar wake and its effect on the particle distributions.*

Secondary electrons from the surface provide another example of a fundamental acceleration process in the wake [Halekas et al., 2002]. LP commonly observed beams of secondary electrons produced at the lunar surface and traveling along magnetic field lines into the wake. It appears that these secondary electrons are generated at low energies at the surface, and then accelerated through the plasma sheath above the negatively charged nightside lunar surface. Typically these accelerated secondaries reach energies of only a few hundred eV. During magnetospheric plasma sheet passages and solar storms, however, the nightside surface charges up higher; at those times LP observed beams of upward-going electrons at several keV or higher. The beams have never been observed at higher altitudes and it is not known what altitude they reach before beam-plasma instabilities moderate them. The high fields and accelerated particles generated at the wake during solar events would have clear consequences for surface exploration or orbiting spacecraft.

The ion and electron beams and the temperature anisotropies produce waves. A broad wave spectrum was observed in and far upstream from the central wake on magnetic field lines connected to the wake boundary [Kellogg et al., 1996]. Simulations predict waves generated by two-stream electron instabilities in the central wake, bump-on-tail instabilities from particles passing all the way through the wake, ion acoustic-like beam instabilities that slow the ion beams in the central wake, flute instabilities, and low frequency electromagnetic turbulence with frequencies near the local proton gyrofrequency. This veritable zoo of plasma waves has barely been explored, and all the wave generation mechanisms and interactions between waves and particles remain unknown.

ARTEMIS's comprehensive suite of field and plasma instruments enables a detailed study of the plasma physics occurring within the lunar wake that leads to acceleration and energization. This includes the first DC electric field observations ever made in that region, direct observations of non-neutral plasma effects near the wake boundary, the extent of secondary electron beams, and their interaction with plasma refilling of the wake from the flanks.

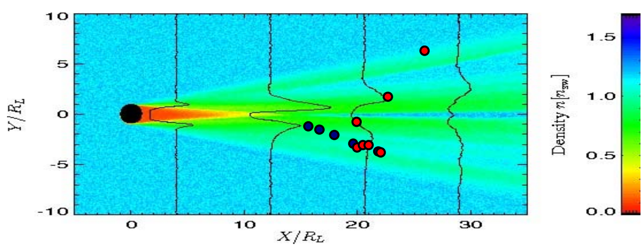

Figure 3.7. ARTEMIS will provide an extensive survey of lunar wake properties as shown by the Lissajous phase probe crossings (red: P1; blue: P2) of a simulated wake (hybrid simulation by Travnicek, et al., 2005: kinetic ions; fluid electrons). Color is density relative to SW and anisotropy profiles are lines at select X distances downstream. Another ~1000 crossings occur inside of 10R_L during lunar orbit phase of ARTEMIS (Figure 3.1).

3.3.3 Statistics. The wake structure varies in response to external drivers. Statistical studies provide tantalizing hints on how the wake responds to changing or transient solar wind conditions, but incomplete instrumentation and orbital coverage has limited our knowledge of this response. *ARTEMIS will provide an unprecedented wealth of routine observations of the wake under a variety of solar wind conditions.*

Additionally, ARTEMIS will be able to show how transient solar wind features interact with the Moon itself (e.g. shocks). At the magnetosphere, reconnection-accelerated fast Earthward flows emanating from beyond 60 R_E produce generally subsonic, sunward-oriented wakes at the Moon. These conditions can be highly variable, and are likely resulting in magnetospheric lunar wakes, with intense charging and particle acceleration conditions very different from those in the solar wind. To fully characterize those phenomena in support of ARTEMIS, 3D hybrid simulations, laboratory simulations and visualizations will be carried out to provide a global context for ARTEMIS's ground-truth observations. Lacking an unperturbed upstream monitor, previous single spacecraft observations of the lunar wake inside the magnetosphere have been difficult to interpret. With one probe in the unperturbed flow and the other in the wake ARTEMIS will make the first comprehensive observations of the lunar wake interior to the magnetosphere and fully characterize its formation, physics and particle acceleration within it. *ARTEMIS will provide the first detailed measurements of the lunar wake plasma environment within the terrestrial magnetosphere.*

4. Preliminary results from the lunar wake

On February 13, 2010 probe P1 (TH-B) traversed the lunar wake from a distance of ~4R_L at the closest approach to the wake center. The results obtained bespeak of both an instrumentation suite that is ideally equipped to obtain the proposed data, and of an instrument and science team that works efficiently together to optimize the instruments. Figure 4.1 shows the orbit on an XZ Selenocentric Solar Ecliptic (SSE) coordinate system (available at NASA/SSCWeb via tipsod specifically for ARTEMIS needs through efforts at SPDF in coordination with the ARTEMIS science team).

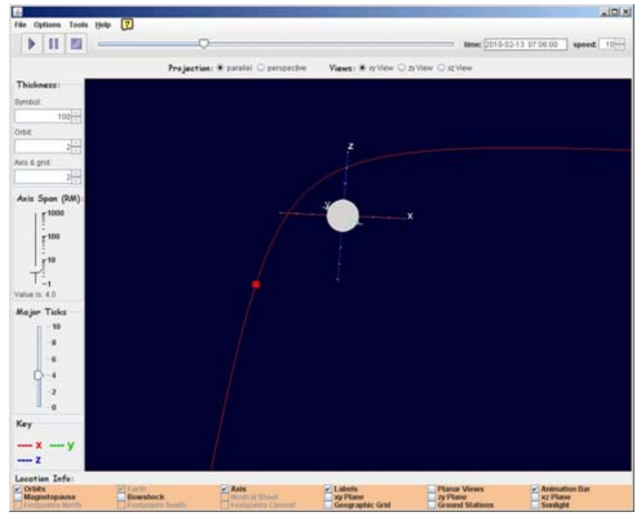

Figure 4.1. ARTEMIS P1 (TH-B) lunar flyby trajectory in XY SSE coordinates (Red is X_{SSE}, with Sun to the right; Blue is Z_{SSE} with top being North). The traversal was nearly through the middle of the wake, just to the West.

The instrument team recognized that this wake crossing would provide an ideal opportunity to calibrate the instruments for their lunar phase. The two main aspects of the experiment were to (i) prove that the spin phase information can be obtained adequately in the absence of Sun-sensor sun pulses, and (ii) prove that the electric field instrument can provide useful information in the wake, i.e., when sphere biasing cannot be done as in sunlight since the spacecraft charges negative in the shadow. During typical shadow crossings at Earth the data are ignored because the spacecraft charges to 100's of Volts (up to a kilovolt) rendering electric field measurements unusable. Also the absence of Sun-pulse information results in loss of spin-period data, and the cooling spacecraft spins up (i.e., the Spin-period does change significantly) resulting in loss of directional information on the magnetic field and particles.

The FGM team developed and tested software that models the exponentially decreasing spacecraft inertial moment (from the cooling) and fits the spin-phase error resulting in accurate spin-period and spin-phase knowledge. Further, the EFI team applied reverse bias conditions on the spheres and this resulted in moderate spacecraft potentials, reasonable operation of the EFI instrument (no power supply saturation) and correct wave signatures from the antennas.

Applying the correct despining resulted in Figure 4.2. The data shows the magnetic field was along the YZ_{GSE} direction (close to SSE) i.e., the field was not crossing the moon but was near-perpendicular to the wake axis with a component pointing towards the Sun. Additionally the electric field instrument showed high frequency waves just below the plasma frequency, consistent with electron acoustic mode fluctuations.

It is expected that electrons will accelerate toward the wake center, and this is seen in the flow velocity as well as in the solar wind beam spectra: Fig. 4.2 shows that the ion beam decreases in energy inbound towards the center, and increases outbound. In fact, there are alpha particles showing as a second peak in the spectra. Those are also seen to decelerate. In fact right at the center all four ion components are seen (Figure 4.3). Accel-/Decelerated protons, and alphas, presenting a unique opportunity of determining the electric field resulting in the electrostatic acceleration through modeling.

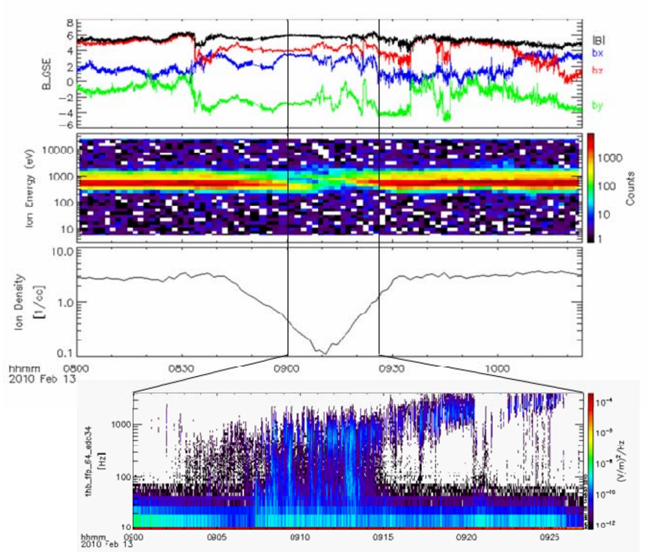

Figure 4.2. Magnetic field (top), ion energy spectrum (2nd panel) and ion density (3rd panel) through the wake crossing. The wake center is at the density minimum. The shadow did result in spurious magnetic field rotations but application of the correct phase in shadow cleans up the data. Also the spacecraft did not charge up significantly, thanks to a reverse bias application on the electric field, resulting in correct density computation and wave measurements within the wake.

Moreover, electrons respond consistently to the electric field at the wake and accelerate the opposite way. As a result, an electron beam (likely reflected strahl electrons) is seen in the electron distributions on the outbound leg of the flyby (Figure 4.4). It is those electrons that are then interacting with the ambient plasma resulting in the unstable electron acoustic waves of Figure 4.2 (bottom), seen to correlate with the beams in the outbound leg. The electron beam energy correlates with the magnetic field, which is due to the fact that the electrostatic potential changes with field-line depth to the wake. This can be used to map the potential structure of the wake with future flybys as far in as 100s of km and as far out as tens of R_L from the prime ARTEMIS mission.

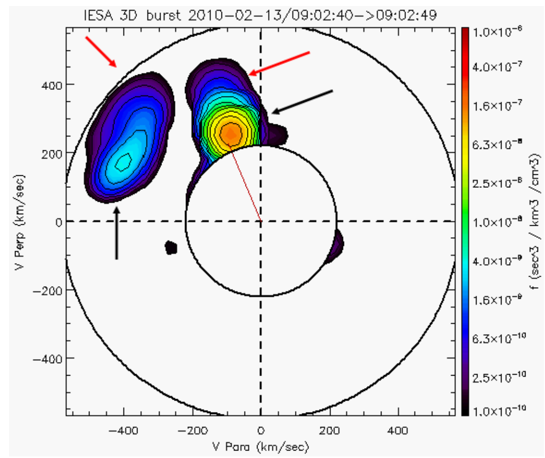

Figure 4.3. Ion distribution functions in Parallel, Perp plane (Perp includes the antisunward direction). The black arrows show the solar wind protons (accelerated and decelerated). The red arrows show the solar wind alphas (also accelerated and decelerated but at different speed and energy due to their

It is evident that more detailed observations of the wake refilling are possible than ever before even with a single spacecraft thanks to the ARTEMIS instruments and a team that is highly capable of optimizing the science that can be obtained from the moon. The presence of a second ARTEMIS spacecraft adds to the mission's potential for ground-breaking discoveries in the next few years.

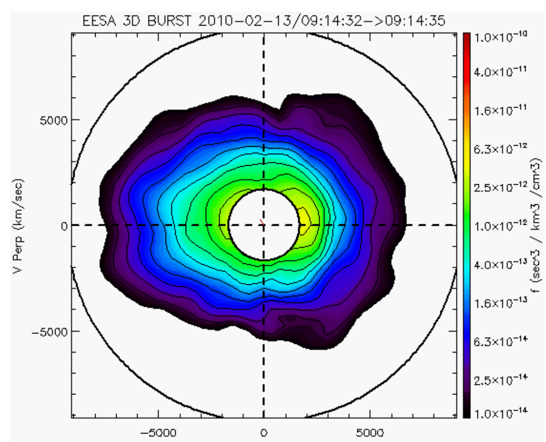

Figure 4.4. Electron distribution in the same coordinates as the ions (3sec, field aligned vs. perp). Solar wind core, halo and strahl are recognized to the left, which a 50-100eV beam streaming along the field (toward the sun) was likely accelerated at the wake and is clearly seen moving to the

5. ARTEMIS – Planetary Science

The inner planets (Mercury, Venus, Earth and the Moon) hold critical information regarding the origin of the solar system and habitable environments within it. The Moon, together with Mercury, preserves records of past events which have been largely erased on Earth and Venus. A witness to 4.5 billion years (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 preserves records of the differentiation of planetary bodies in 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 shed light on the evolution of other terrestrial planets such as Mars and Venus.

In 2003, the National Research Council's Decadal Survey on "New Frontiers in the Solar System, An Integrated Exploration Strategy" identified the critical importance of understanding: (1) the core, mantle and crust evolution, and the characteristics of the metallic core of inner planets; (2) the history and role of early (3.8-4.5 Ga) meteoritic impacts and (3) the history of water and other volatiles at inner planets. The Moon specifically and its South Pole-Aitken Basin in particular were singled out as high-return targets for further studies and for sample return, in order to address these questions, since understanding our closest planetary body and the chronology of its oldest large crater exposing material elevated from the early lunar mantle holds clues on inner planet evolution and differentiation.

Since 2003, the time of the last NRC Decadal Survey, several international and US lunar missions have been launched (SMART-1, SELENE/Kaguya, Chang'e, Chandrayaan-1, LRO and LCROSS) and two are currently in the planning for launch in 2011-2012 (GRAIL and LADEE). The 2007 NRC study on "The Scientific Context for Exploration of the Moon" (herein refered to as "SCEM") incorporated the results and expectations from the current lunar missions, addressed the scientific challenges and opportunities in the period 2008-2023, and put forth a set of goals and recommendations independent of programmatic implementation but also are on par with NASA's Vision for Space Exploration. Intended for near-term guidance to NASA, NRC's recommendations were prioritized by three criteria: scientific merit, opportunity and technological readiness. The top eight science goals were prioritized and discussed in Table 5.1 of the NRC report. Since the report, NASA mission LADEE has been accepted for flight in 2012, aimed at studying the lunar exosphere with in-situ instrumentation from low altitude, and ARTEMIS has been approved to commence ascend operations to conduct Heliophysics observations around the Moon. Moreover, the Japanese mission SELENE/Kaguya's results on the lunar exosphere have reshaped our understanding of lunar atmosphere populations and interactions with the surface and the environment, sparking renewed interest in conducting planetary science via remote sensing of exospheric and surface charged particle populations, and paving the way for ARTEMIS. Equipped with charged particle detectors and electromagnetic sensors, ARTEMIS will make significant contributions to 4 of the top 8 lunar science goals identified in the NRC report, as shown in Table 1. At the same time it will provide synergistic information to the extended LRO, and the upcoming LADEE mission.

ARTEMIS Planetary Science Goals and Means	**Primary relation to NRC prioritized concepts**
A. Sources and transport of exospheric and sputtered species, in relation to surface features, as revealed in the charged particle environment	SCEM# 8. Processes involved with the atmosphere and dust environment of the Moon, accessible while the environment remains in a pristine state.
B. Dust charging and circulation by electric fields.	
C. Structure and composition of lunar interior as revealed by electromagnetic sounding from orbit.	SCEM # 2. The structure and composition of the lunar interior provides fundamental information on the evolution of a differentiated body.
D. Surface properties and planetary evolution as revealed by crustal magnetism and space weathering.	SCEM # 3. Key planetary processes are manifested in the diversity of lunar crustal rocks. SCEM # 7. The Moon is a natural laboratory for regolith processes and weathering…

Table 5.1 ARTEMIS planetary goals and relevance to concepts and goals of NRC report "Scientific Context for Exploration of the Moon"

ARTEMIS Science Goals and Means. The first two goals of the ARTEMIS investigation deal with the lunar atmosphere, i.e., the tenuous lunar surface boundary exosphere. Individual atoms rarely collide there (thus no chemistry is involved) and ions move subject to the electromagnetic fields of the ambient environment. Ions and dust are constantly sputtered from the surface and then circulate in the exosphere until they either escape into the solar wind or they are trapped in permanently shadowed polar regions. Interactions of sputtered and ionized particles, or reflected solar wind ions, contribute to the dynamics of the lunar wake. Similar atmospheres may surround Mercury, Europa, Ganymede and other bodies, but the lunar atmosphere is the only surface boundary atmosphere accessible enough for detailed study in the next two decades. Therefore this goal is highly rated by the NRC report. Based on the availability of the ARTEMIS orbits (i.e., an opportunity) and the health and status of the ARTEMIS instrumentation (i.e., the technical readiness) this goal is rated even more highly in the list of ARTEMIS goals.

Recent Kaguya results have confirmed the presence of Na^+ ions and also revealed the presence of C^+, O^+, and K^+. Ions with differing masses are expected to be "picked up" by the solar wind and attain the same (solar wind) average velocity, but can be distinguished further downstream by the ARTEMIS energy-angle ion spectrometers due to their different energies. Kaguya has demonstrated excellent agreement between modeled particle motion in the presence of known electric and magnetic fields and measured particle populations far from the source. *ARTEMIS will use its energy-angle spectroscopic capability and its full electric and magnetic sensors to determine motion, source and flux of exospheric ions.* Additionally, dust particles are controlled (i.e., lofted and transported) by surface electric fields, which can be remotely sensed using electron reflectometry or measured directly from altitude. *ARTEMIS will use its unique electromagnetic field measurements to determine the forces acting on dust populations and their acceleration and deposition or loss in the lunar environment. The ARTEMIS dataset of solar wind, exospheric species and electromagnetic fields will provide important synergies to LRO's UV spectroscopy of the exosphere using LAMP and to LADEE's neutral mass and UV spectroscopic measurements of dust using NMS and UVS.*

The third goal of the ARTEMIS investigation deals with the structure of the lunar interior as determined by electromagnetic sounding from orbit. By studying differentiation of the lunar interior we can better understand the origin of all inner solar system planets, including our own. Analysis of Apollo-era data indicates that the Moon formed by impact of a Mars-sized object with the early Earth, and later differentiated into primary crust, mantle residuum, and possibly a small iron-rich core. The Moon's temperature and composition radial profiles, as well as their lateral variability today hold important clues regarding lunar differentiation history and by inference that of Earth and inner system planets. Broadband (<<10mHz to 10Hz) electromagnetic sounding including novel use of the magnetotelluric methods at higher frequencies will improve knowledge of these state variables for the core, mantle and crust. These are high priority goals of the NRC report.

ARTEMIS is equipped with magnetic sensors of 3pT sensitivity and <100pT/12hr stability. The probes are on orbits that will bring them, one at a time, within ~100km from the surface or lower, i.e., at an altitude close enough to detect the core response but least perturbed by crustal anomalies. Cross-calibration during times prior to closest approach enables offset removal. By comparing the periselene signal from one probe to the driver signal from the other probe further away we expect to achieve far greater sounding sensitivity than possible in the Apollo era: this is due to the stability of ARTEMIS magnetometers, and the accurate removal of geophysical plasma currents by use of concurrent plasma measurements.

Furthermore, the highly sensitive electric field experiment on ARTEMIS provides a state-of-the-art measurement of the horizontal electric field at 1-10Hz, which enables, for the first time, magnetotelluric investigations from orbit. *ARTEMIS presents new capabilities for planetary investigations at the Moon, which can further constrain the radial profiles of lunar composition and temperature, unraveling the mystery of lunar formation and differentiation.*

Finally, ARTEMIS will study the interaction of lunar crustal magnetic anomalies with the solar wind using its comprehensive particles and fields sensors. Initial Kaguya observations have already provided significant new information on an ion sheath, electron heating and solar wind reflection around magnetic anomalies at 100km (Saito et al., 2009), but waves properties and solar wind particle flow around the strong field region remain poorly understood. ARTEMIS will study the magnetic anomalies to infer properties of the ancient, seed magnetic field and to determine the accessibility of the solar wind to the surface and the effect it has on lunar surface ageing. Electric field and plasma wave data, together with ion and electron measurements in the vicinity of the mini-magnetosphere that forms around the crustal anomaly (the first comprehensive plasma measurements attempted at the Moon) promise exciting new science with possibly significant ramifications for planetary evolution.

Relevance to NASA's Solar System Exploration goals. Although ARTEMIS was primarily designed with several of NASA's Heliophysics Division goals in mind, its unique instrumentation can address key Lunar science questions, important for Planetary Sciences. Many aspects of the Lunar environment remain poorly understood, even though the Moon is our nearest neighbor. Notably, this includes the lunar exosphere, which the recent NRC SCEM report prominently identified as a science priority. The species that populate the exosphere originate in the solar wind, the surface, and subsurface, and are lost to the surface and to space by a variety of pathways. The relative importance of the many exospheric source and loss processes is still under debate, and likely differs for each exospheric species. Both source and loss processes couple the exosphere to the surface, so that one cannot fully understand the exosphere without some knowledge of the surface. Similarly, many source and loss processes are externally driven by photons and solar and magnetospheric plasma, and one cannot understand the exosphere and its coupling to the surface without understanding the space environment around the Moon. *ARTEMIS, with its full plasma instrumentation, elliptical orbit spanning a large range of observational vantage points, and two-point measurement capability, provides the means to simultaneously explore the drivers and products of exospheric source and loss processes, allowing us to* *constrain the importance of each process and obtain information about the composition and structure of the lunar exosphere and its coupling to the surface.* These investigations are critical to the science questions on surface-plasma interactions and will help us understand surface-bounded exospheres encountered on many other solar-system bodies (e.g., Mercury, asteroids, outer planet satellites).

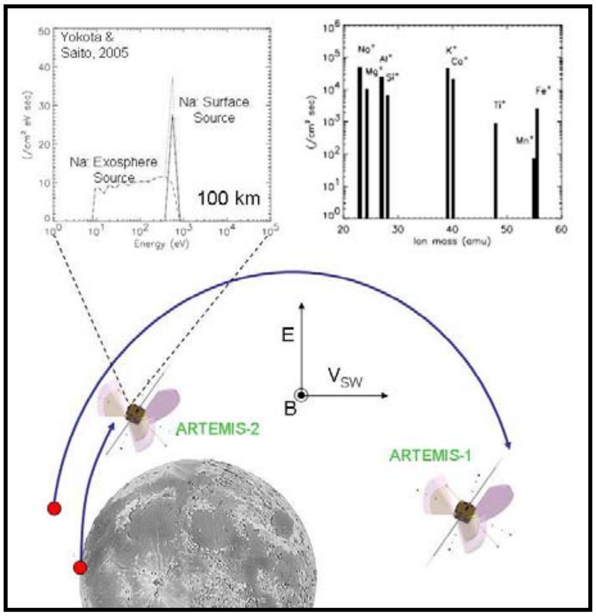

Figure 5.1 *A schematic showing the trajectories of recently picked-up ions and the expected measurements of the fluxes (top left) and composition (top right) of the picked-up ions.*

Another highly rated science concept of the 2007 NAS report concerns the: "processes involved with the atmosphere and dust environment of the Moon while the environment remains in a pristine state". As a solid body surrounded by a tenuous exosphere, the Moon's surface lies directly exposed to the space environment, including solar UV and X-rays, solar wind and magnetospheric plasmas, and energetic particles. In an effort to maintain current equilibrium among these various populations of incident and secondary charged particles, the Moon acquires a dynamic electric field over its surface. As with most objects in space, to first order the lunar surface charges positive in sunlight and negative in shadow, reaching potentials that vary over many orders of magnitude in response to changing solar illumination and plasma conditions. The changing surface electric fields are suspected of transporting charged dust via electrostatic forces, thus providing a possible link between solar/plasma conditions and dust dynamics observed in the lunar environment. *The comprehensive field and plasma instrumentation of ARTEMIS and simultaneous two-point measurements will help us understand the origin and dynamics of lunar electric fields.*

The 2003 NRC Decadal Survey noted that the bulk compositions of the inner planets and the Moon remain poorly known, yet that knowledge is essential in understanding the formation history of the inner planets and their satellites. For example, the models of the impact generation of the Moon by the collision of a Mars-sized object with the Earth would be further constrained if the bulk composition of the Moon were known more precisely. ARTEMIS studies of the deep Lunar interior from electromagnetic induction take advantage of the first simultaneous two-point magnetic field measurements of the nearby pristine solar wind and its effect on the Moon. This enables unique separation of the measured signal into a primary and an induction field. The technique is expected to provide new information on the structure, composition and temperature of the deep lunar mantle and lunar core.

5.1 Exosphere and plasma pick-up

Charged species discrimination: ARTEMIS will use charged particle measurements from the ESA and SST instruments as an extremely sensitive detector of the surface and exospheric properties, by measuring ions produced at the surface or in the exosphere and accelerated by solar wind electric fields. 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 (which ARTEMIS will also determine). Ions are then accelerated in cycloidal trajectories (i.e. "picked up") as shown in Figure 5.1.

Pickup ions are unique since their orbits have a well defined energy and direction as a function of gyrophase. Therefore, the pickup ions of a given species and flux detected at ARTEMIS at a given location near the Moon will be well-collimated and nearly mono-energetic (beam-like). By measuring the pickup ion beams' energy and direction and using EFI, ESA, and FGM measurements to determine the solar wind magnetic field and convection electric field, we can back-trace the pickup ion trajectories, allowing the ARTEMIS team to accurately determine the source region and differentiate between surface and exospheric sources [Hartle and Killen, 2006].

In addition, ARTEMIS will roughly determine the ion mass, since both the ion energy and the size of the cycloidal trajectory scale with mass. ARTEMIS can therefore use pickup ion measurements to remotely probe the properties of neutral gases produced in the exosphere or at the surface. These measurements will then 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.

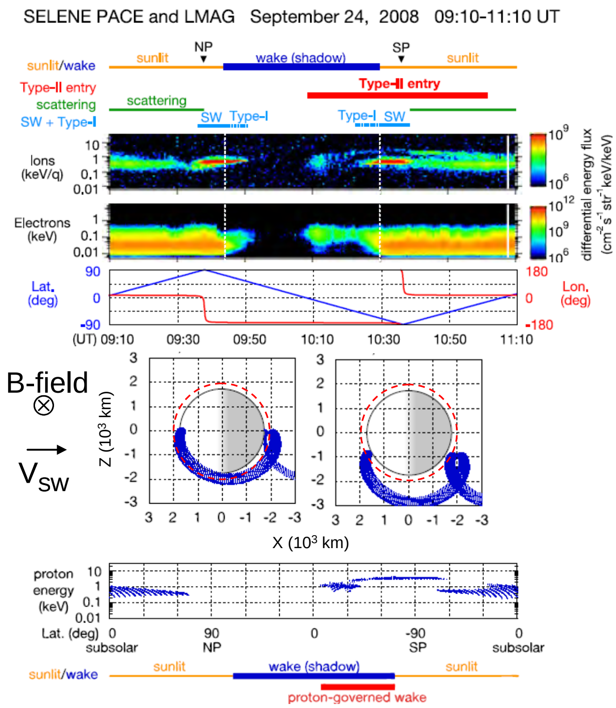

Figure 5.2 *(From Nishino et al., 2009) Ion and electron energy spectrograms from the downward-looking SELENE (Kaguya) detectors. Kaguya (red-dashed circle in middle panel), is on a polar, 50-100 km lunar orbit. It observed reflected solar wind ions at the dayside, some of which can make it to the nightside equator, i.e., deep within the wake. Computer simulations reproduce the observations.*

Recent Kaguya findings have advanced significantly our understanding of the solar wind interaction with the lunar surface as well as the near-Moon wake. Solar wind ions are reflected off the lunar surface and from crustal magnetic field regions and are then accelerated by the solar wind electric field to speeds as high as 3 times that of the solar wind [Saito et al., 2008]. The picked up ions find access to not only the high latitude wake, but also to areas deep within the wake at low latitudes and altitudes, through fully kinetic processes (Figure 5.2). The solar wind magnetic field and electric field can reconstruct the observed proton spectra fully, assuming a reflected proton source on the dayside.

Yokota et al., 2009 used SELENE/Kaguya's *in situ* mass spectrometry and confirmed the presence of Sodium in the Lunar exosphere. Sodium had previously been detected from the ground using a solar coronograph to occult the illuminated lunar surface (Figure 5.3). Kaguya's observations from orbit have shown that the 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 can differentiate the source of those ions. The ions were observed by Kaguya at 100km altitude on the sunlit lunar hemisphere side that is favorably located for acceleration by the solar wind electric field. Moreover, Kaguya has shown that these dayside ions are composed of He^+, C^+, O^+, and K^+ in addition to Na^+. Traces of Al^+ were previously reported by WIND observations further from the Moon, and other species may also be present. The heavy ion flux varied with solar zenith angle but not with solar wind flux or meteor shower occurrences, suggesting a stable driver for the sputtering process.

Within a distance of 2 gyroradii the ions can be discriminated in mass based on their energy and gyrophase by reconstructing their cyclical motion, shown in Figures 3.1 and 3.2, in external fields. Further away, a distinct, ion mass-dependent ring distribution in velocity space is expected.

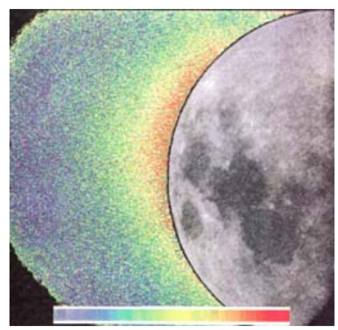

Figure 5.3. *Lunar exospheric Na, observed via remote sensing on a fortuitously clear night [Potter and Morgan, 1998]. Kaguya has recently measured the ionized Sodium. ARTEMIS will extend Kaguya's results into the LRO and LADEE era and establish their variability with solar activity.*

The principle of operation and geometric factor of the ARTEMIS ESA instrument [McFadden et al., 2008] are similar to those of the IEA (total ion) instrument on Kaguya [Saito et al., 2008]. These total ion instruments have a geometric factor 10 times larger than the IMA (ion mass analyzer) instrument on Kaguya (Yokota). Figure 5.4 shows IMA instrument observations of accelerated ions from the lunar surface. ARTEMIS will provide information concerning the continuous evolution of the energy spectra as function of altitude from 100km to several thousand km.

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 will determine the dependence of the lunar exosphere on lunar longitude undergoing illumination, thereby providing the ion composition versus selenographic longitude.

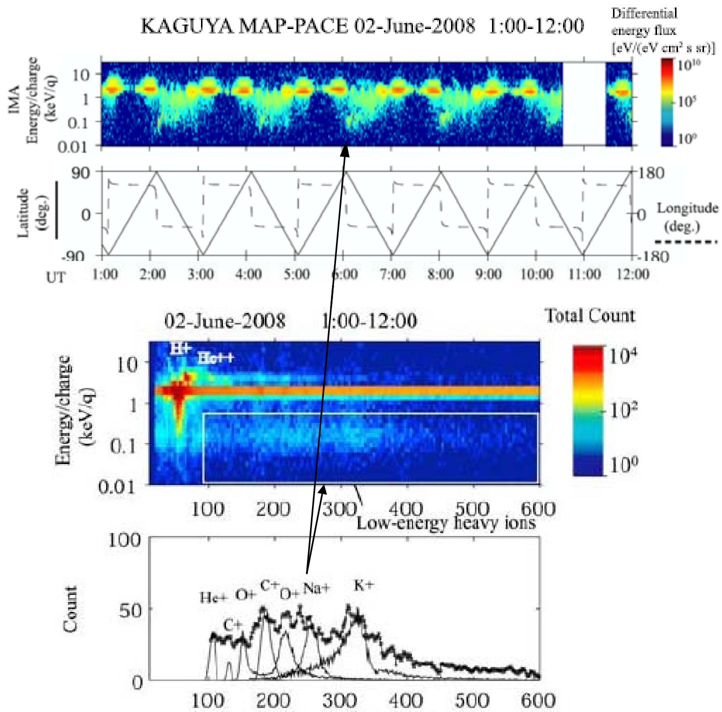

Figure 5.4. *[Yokota et al., 2009] Observations of sputtered ions from the lunar surface using the IMA sensor on Kaguya. The ions have sufficient flux to be seen in the energy /charge spectrograms by IMA.*

<u>Feasibility.</u> Many authors have demonstrated the utility of pickup ion measurements in the way proposed by ARTEMIS to probe surface and exospheric properties at the Moon [Cladis et al., 1994; Yokota and Saito, 2005; Hartle and Thomas, 1974; Hartle and Killen, 2006; Hartle and Sittler, 2007]. Though previous measurements of lunar pickup ions at large distances from the Moon required very sensitive mass discrimination and background rejection [Cladis et al., 1994; Hilchenbach, 1993; Mall et al., 1998], fluxes of pickup ions near the Moon are both larger and more collimated. Indeed, the geometric factor and energy resolution of ARTEMIS suffice to measure these sources easily: For the three species in the lunar exosphere which are currently best understood (Ar, He, Na), convolving the exospheric neutral density with expected photoionization rates (both from Stern [1999]) gives ion production rates of 10^{-3} - 10^{-2} cm^{-3} s^{-1}. Integrating ion production over a reasonable source region leads to a prediction of pickup ion fluxes of $>10^3$ - 10^4 $cm^{-2}s^{-1}$ near the Moon. This agrees with the more detailed particle tracing simulations of Yokota and Saito [2005], which predict pickup ion fluxes on the order of $\sim 10^4$ cm^{-2} s^{-1} for most major species near the Moon (see inset in the upper right corner of Figure 5.1) and Kaguya's direct observations of such fluxes at 100km [Yokota et al., 2009]. Sputtered ion fluxes from the surface are similar [Cladis et al., 1994; Yokota and Saito, 2005]. For example, the upper left inset in Figure 5.1 shows the expected differential fluxes at ~100 km altitudes from Na sputtering and photoionization. The ions from the surface are nearly monoenergetic, while those from the atmosphere are still spread out in energy because the source is extended and the observation altitude is very low. At higher altitudes, the ions will be accelerated further, producing a much more monoenergetic spectrum and much higher ion energies for both surface and exospheric sources (with little reduction in flux unless significant scattering occurs in one ion gyroperiod). Using the two-point measurements and highly elliptical ARTEMIS orbits, we can observe both exospheric and sputtered ions over a range of altitudes, allowing us to determine their source properties quite accurately. Due to their collimated and nearly monoenergetic nature the ion fluxes can be easily observed above background by either the ESA or SST instruments (depending on ion energy), especially when the ions reach their peak energies near the apex of their cycloidal trajectory. Near the Moon, trajectories will be affected, to some degree, by: (1) magnetic perturbations due to crustal magnetic fields [Halekas et al., 2001; Hood et al., 2001] (2) wake boundary currents [Halekas et al., 2005a], (3) electric perturbations due to lunar surface charging [Halekas et al., 2002, 2008] and (4) wake ambipolar electric fields [Halekas et al., 2005b]. However, most of these perturbations are small, and all of them can be measured directly by ARTEMIS and/or determined from previous studies. Indeed, ARTEMIS's ability to measure these perturbations is a key advantage in understanding the details of pickup ion trajectories.

Synergistic Measurements – SELENE/Kaguya, which was in orbit around the Moon until a few months ago, has an ion mass spectrometer. It could therefore detect pickup ions with better mass discrimination than ARTEMIS. However, the highly elliptical orbit of ARTEMIS enables high altitude pickup ion measurements that Kaguya could not make. Furthermore, the unique two-point capability of ARTEMIS will enable very accurate measurements of upstream parameters and of local electric and magnetic fields, allowing better back-tracing of ion trajectories for appropriate orbital geometries. Since ARTEMIS is in a similar part of the solar cycle, results from the two missions can be compared and cross-validated.

ARTEMIS also complements LRO and LADEE, being concurrent to both (also see Sections 3.6 and 3.7). 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 its understanding of the lunar exosphere, the exospheric coupling to the lunar surface and its escape rate into space.

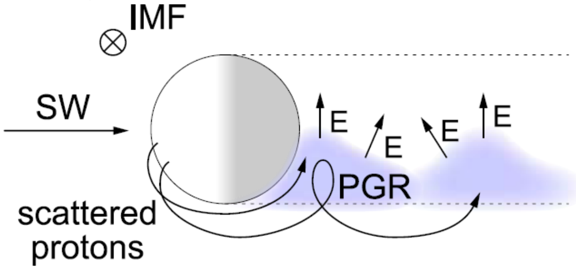

Figure 5.5 *Kaguya measurements [Nishino et al, 2009] in the proton-governed region (PGR) indicate that the wake electric field may be severely distorted from its anticipated inward direction due to proton concentrations moving ballistically there, after their generation by solar wind scattering at the dayside. Measured ion and electron concentrations confirm that the nightside wake at 100km is quite dynamic. Due to such plasma interactions the wake is expected to host significant electric fields that likely map to the surface.*

5.2 Lunar Dust

The lunar surface electric field has been shown to respond closely to solar and magnetospheric plasma and energetic particles [Halekas *et al.*, 2007; Halekas *et al.*, 2005b], 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 [Manka, 1973; Stubbbs *et al.*, 2007]. In turn, lunar electric fields affect the lunar ionosphere and exosphere, and may also control the distribution of charged lunar dust transported near the surface. Recent experimental results confirm the bulk properties expected of lunar electric fields, and have also yielded some surprises.

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.*, 2008, 2009]. On the dayside, surface potentials are small, and for much of the time below the sensitivity of the reflectometry technique. On the nightside LP data indicate potentials of –100 V or less in the wake and the magnetospheric tail lobes [Halekas *et al.*, 2002]. A more startling result was the measurement of negative potentials occasionally as high as –4 kV in the tail plasma sheet [Halekas *et al.*, 2005b] and during SEP events [Halekas *et al.*, 2007, 2009].

More recently, Nishino et al., [2009] used the solar wind velocity measured on Kaguya to infer the motional solar wind electric field. In conjunction with the observed solar wind protons back-scattered from the sunlit side, this field provides a good prediction for ion signatures observed near the poles and the equatorial wake (Figure 5.5). Contrary to the anticipated preponderance of electrons on the nightside, there are occasions when positive ion fluxes accumulate, pulling the electrons in from the wake, resulting in local electric field concentrations or distortions of the inward electric field at the wake.

The plasma and fields instrumentation on ARTEMIS is far more comprehensive than that flown on previous missions, enabling significant strides forward in our understanding of the origin and dynamics of lunar electric fields: LP measurements lacked direct knowledge of the spacecraft potential. Although the potential has been modeled on LP (Figure 5.6), ARTEMIS will be capable of measuring the spacecraft potential directly using its EFI instrument, and thus validate the model-dependent LP results. The lack of an ion analyzer on LP made measurements of small positive dayside potentials either extremely difficult or impossible. On ARTEMIS, the combination of electron and ion measurements will allow the extension of the reflectometry technique to consistently measure a wide range of both positive and negative potentials, and to determine all plasma currents incident on the surface, thus facilitating accurate modeling of the charging process.

The ESA and SST combination on ARTEMIS will also help determine the mechanism that causes high lunar electrostatic potentials during Solar Energetic Particle (SEP) events. These potentials likely result from charging due to either energetic particles or changes in the (lower energy) solar wind plasma distributions that may accompany some of these events. By directly measuring particle fluxes over a wide energy spectrum, ARTEMIS will directly confirm or refute this hypothesis and identify the solar wind particle population driving electrostatic charging.

Finally, ARTEMIS will explore the efficacy of other surface electric field generation mechanisms, which eluded detection by the low altitude orbit and incomplete instrumentation of LP. For example, large negative potentials are predicted within an "electron cloud" region in the wake expansion region [Farrell *et al.*, 2008; Farrell *et al.*, 2007]. Complete plasma measurements on ARTEMIS from a range of altitudes in the sunlit regions of the wake expansion, just behind the terminator can reveal the predicted "electron cloud" and study its interaction with the surface.

5.3 Dust Transport

Dust transport is believed to occur on all airless bodies in the solar system -- such as the asteroids [Colwell *et al.*, 2005], Mercury [Ip, 1986] and many of the Moons of the outer planets -- and in some cases may be a significant process in determining the evolution of their surface regolith. The development of surface electric fields discussed in the previous section may transport charged dust via electrostatic forces, thus providing a possible link between solar/plasma conditions and dust dynamics in the lunar environment. These processes may be responsible for the presence of dust at high altitudes; for example, 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 ~10^5/m^3 near the surface to ~10 /m^3 at 100 km.

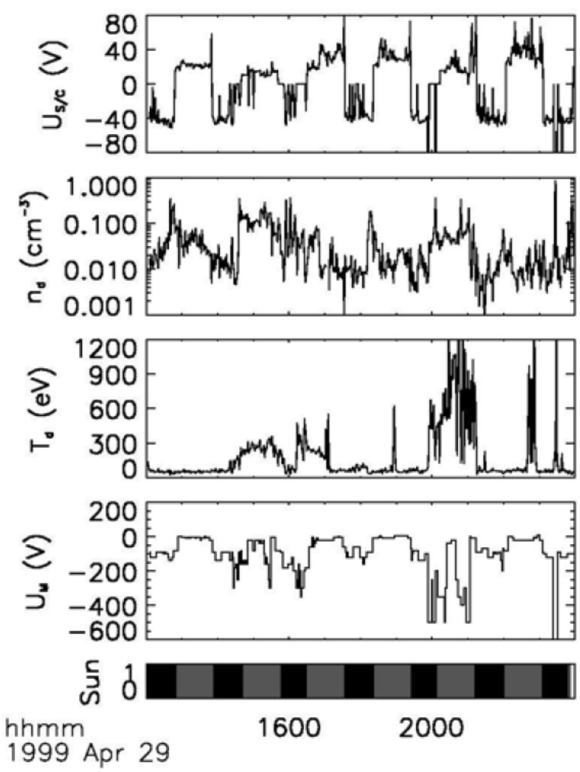

Figure 5.6 *Measurements of the potential of the lunar surface (U_m), corrected for the LP spacecraft potential ($U_{s/c}$) when the Moon is in the terrestrial magnetosphere, in sunlit and shadowed regions. ARTEMIS will enable the direct measurement of positive potentials in sunlight and establish which particle populations dominate surface charging over a broad range of solar and plasma conditions.*

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. This is known to occur at low altitudes on the Moon: images obtained by the Surveyor landers showed a glow along the western horizon after sunset [e.g. Rennilson and Criswell, 1974]. The phenomenon of dust levitation in a plasma sheath has also been reproduced in the laboratory [Sickafoose *et al.*, 2002]. The Apollo 17 Lunar Ejecta and Meteorite (LEAM) experiment may have yielded direct evidence for the electrostatic transport of lunar dust. LEAM was designed to detect hyper-velocity meteoritic impacts and associated ejecta (> 10 km/s); however, it instead detected highly-charged dust grains of lunar origin moving at < 1 km/s with impact rates up to 100 times greater than anticipated [Berg *et al.*, 1976; Colwell *et al.*, 2007]. This activity peaked at the terminators, which strongly suggests that it is associated with the LHG. More recently, a dust fountain model 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 [Farrell *et al.*, 2007; Stubbs *et al.*, 2006].

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 in the previous section will reveal average and extreme charging conditions that contribute to dust dynamics.

Equally important is gaining an understanding of the dominant currents involved in the charging process, enabling predictive capabilities to be put in place for future missions. Currently, knowledge of the Moon's location and average plasma properties of different regions (solar wind, magnetosphere, geotail) is not sufficient information to predict lunar surface charge. The LP results underscore the need for continual monitoring of the plasma conditions and electric fields around the Moon, which can be highly variable due to episodic SEP events combined with passages through the dynamic magnetotail plasmas. ARTEMIS' complete characterization of ion and electron plasma currents incident on the surface over a broad energy range will reveal the missing cause-and-effect relationship of plasma conditions to surface potentials in these varied plasma environments, including the episodic extremes. In addition, the role of the wake in surface charging and subsequent dust trajectories is, at present, only speculative. The ARTEMIS wake investigations, aiming to characterize the electric field structure and loss of neutrality in the low-altitude wake expansion region will determine how these processes are linked to the lunar surface [Farrell *et al.*, 2007].

5.4 Interior Structure and composition

Determining the interior structure of the Moon provides a key constraint on the history and evolution of the Moon. Electromagnetic (EM) subsurface sounding using natural energy is one of the oldest branches of geophysics, which can be used for lunar sounding. EM sounding techniques seek to determine the conductivity structures of solid-body interiors, which is often sufficient to provide major insights regarding the interior (e.g., radius of lunar core or existence of Galilean satellite internal oceans). Further knowledge is gained in turn by using laboratory measurements of conductivity [Duba et al., 1974; Constable et al., 1992; Xu et al., 1998; Yoshino et al., 2006] to constrain allowable mineralogy and temperature.

EM sounding exploits the fact that eddy currents are generated when a conductor is exposed to a changing external magnetic field. The eddy currents generate their own magnetic field called the induction field, which is readily measured by ground or space instruments (see Figure 5.7). The depth to which a signal can penetrate depends on its frequency and the conductivity of the probed material. By using multiple frequencies, electromagnetic sounding has been used successfully to probe the upper mantle of the Earth [see Parkinson, 1983; and references therein] and the deep lunar mantle, placing limits on the size of the lunar core [Dyal et al., 1974; Russell et al., 1981; Hood et al., 1982] to be ~ 500 km in radius. More recently EM induction was used to discover liquid water oceans in the icy Galilean satellites of Jupiter [Khurana et al., 1998; Kivelson et al., 1999, Kivelson et al., 2002].

Two independent pieces of information are needed to derive the EM impedance at each frequency (see Grimm and Delory, 2009, for a review). 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). In special cases where the source field is known, a single magnetometer can be used (though having accurate measurements of the driver field is certainly preferable). The motion of the Galilean satellites in Jupiter's main field (Khurana) and the near-uniform field in the earth's geomagnetic tail (Russell et al., 1981, Hood et al., 1999) are two examples of the latter. The only other way that the impedance can be determined from a single platform is by correlation of orthogonal electric and magnetic fields, i.e., the magnetotelluric (MT) method (see Vozoff, 1991, for a review). As a single-platform measurement, MT is also not subject to spatial aliasing that may hamper transfer functions at high frequencies, and hence MT is optimal for relatively shallow probing of the outermost parts of the moon. ARTEMIS will use both methods—transfer function, and MT—to sound the lunar interior. Both methods rely on ambient geophysical signals to sound the interior.

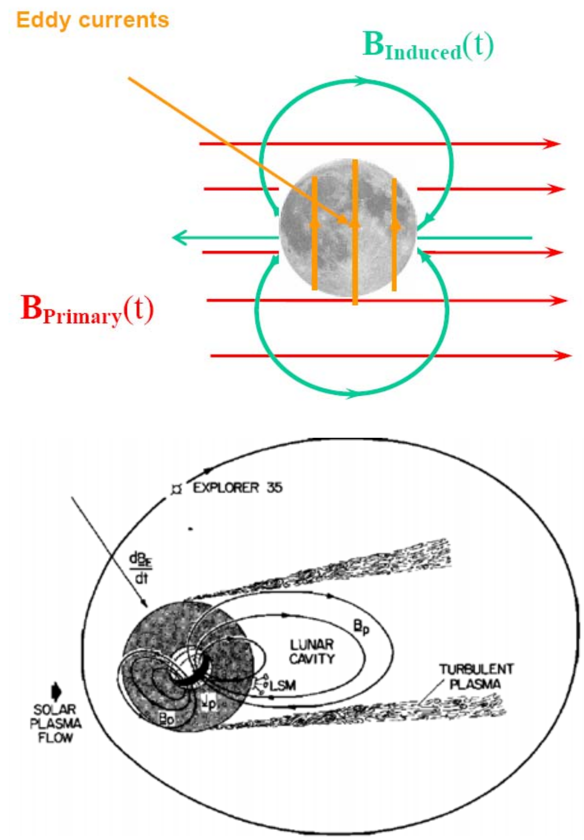

Figure 5.7 *Top: Principle of planetary scale electromagnetic induction. A time-varying primary field (red) induces a multipole secondary field (green lines; only dipole response shown) that is directly related to the electrical properties of the interior. Bottom: In practice, dayside response is confined when the moon is in the solar wind. Both this geometry (Sonett et al., 1972) and the near-vacuum nightside and magnetotail responses (Dyal et al., 1974) were exploited for whole-moon soundings. The magnetic-transfer approach between a distant satellite (Explorer 35) and the Apollo 12 Lunar Surface Magnetometer (LSM) is also illustrated; Artemis will use this technique between near and distant probes with higher fidelity magnetic data accompanied by excellent characterization of the plasma environment from plasma data. Additionally, ARTEMIS will test the magnetotelluric method, which relies on correlations between electric and magnetic fields at a single probe.*

<u>Driver signals.</u> A broad spectrum of frequencies is available for lunar EM sounding as the Moon orbits about Earth. The largest fraction of the lunar month is spent in the solar wind and the magnetosheath, where turbulent waves, shocks and other structures can be used for sounding. The supersonic solar wind results in confining 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 tha 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 interplanetary shocks, have well characterized electric and magnetic signals, and provide also high fidelity, high frequency drivers (0.05-10 Hz) well suited magnetotelluric investigations.

EM transfer function sounding. Using the transfer function method, Apollo and Lunar Prospector (LP) data has constrained the radius of a highly conducting lunar core to < 400 km (e.g., Hood et al., 1999) and determined the deep mantle conductivity (e.g., Hood et al., 1982, Hood and Sonett [1982]) and its relation to the geothermal gradient and thermal evolution of the Moon. However the transfer function is not very well constrained at depths less than 500km from the surface or radial distances less than 500km from the center (Figure 5.8) because at high frequencies the planar approximation breaks down and at low frequencies there are uncertainties in distinguishing the induction signal due to instrument offsets or noise. For example, Explorer 35 data, used to determine the driver in the Apollo era, had significant offset fluctuations; while the lack of simultaneous plasma measurements prohibited identification and removal of ambient, space currents. Lunar Prospector studies did not have a nearby monitor of the driver signal. Hood (1984) and more recently Grimm and Delory (2008) argued that previous datasets are still inadequate for constraining the conductivity profile at all distances, and that the lunar core remains compatible with either metallic or silicate composition. Grimm and McSween (2009) recently calculated that tens of ppm H_2O (Saal et al., 2008) can best explain the deep mantle conductivity, in lieu of high-alumina pyroxene.

ARTEMIS will measure the external, driving magnetic field with one spacecraft and the response of the lunar interior to that field with probe near the surface. Differencing the highly sensitive magnetometer signals on the two spacecraft under various external driver frequencies is an ideal way to sound the interior conductivity of the Moon as function of frequency. 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.

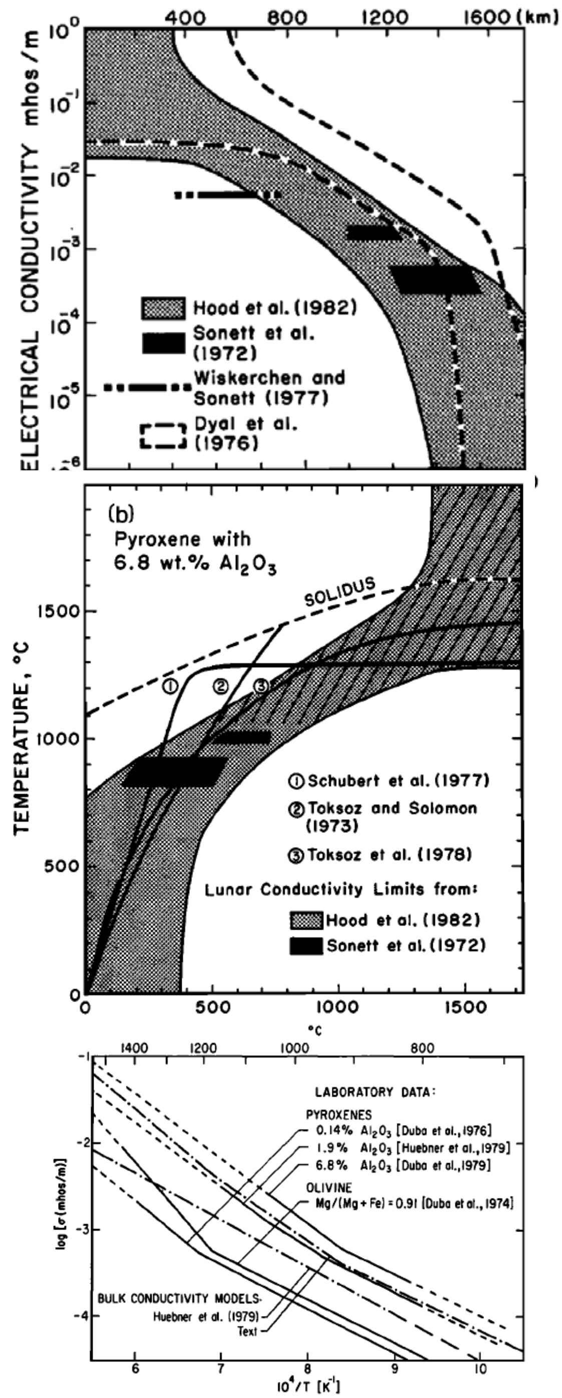

Figure 5.8 *Top: Apollo-era electromagnetic sounding of the lunar interior: Electrical conductivity versus radial distance from Moon's center (km) inferred from various sources, including Hood et al., 1982. Dashed line corresponds to anhydrous basalt. Middle: Temperature-depth profile inferred by Hood and Sonett [1982] using laboratory data, assuming conductivity is dominated by high-alumina pyroxene. Bottom: Laboratory measurements of mineral conductivity vs. temperature.*

The ARTEMIS periselene altitude will be approximately 100km (exact altitude depends on results of orbit stability analysis optimizing for planetary goals). This altitude is ideal for making induction measurements from orbit, because with the exception of known, localized magnetic anomalies all other variances from the input signal can be attributed to induction effects. The technique can be applied both in the solar wind at the nightside and in the tail/magnetosheath/lobes on either side of the terminator.

Magnetotellurics. EM sounding using the transfer function method is valid at low frequencies (<10 mHz) where wavelengths are large relative to the lunar radius, and the lunar response is well represented by a dipole. In that case, assumptions regarding spherical symmetry of the conductivity apply. Beyond 10mHz and up to 40mHz it is possible to extend the theory using a multipole approximation [Sonett, 1982; Sonett et al., 1972] though this requires assumptions on the wave-front propagation direction and speed. However, above 40mHz it is no longer possible to use magnetometer data alone, because phase velocities and speeds are only local and uncorrelated with the far away driver signal monitor. In that case a complete electromagnetic sounding can only be performed with the magnetotelluric method: The ratio of orthogonal magnetic and electric signals at a single point results in the apparent conductivity as function of frequency; this can be inverted to a conductivity-depth profile (Vozoff, 1991; Simpson and Bahr, 2005).

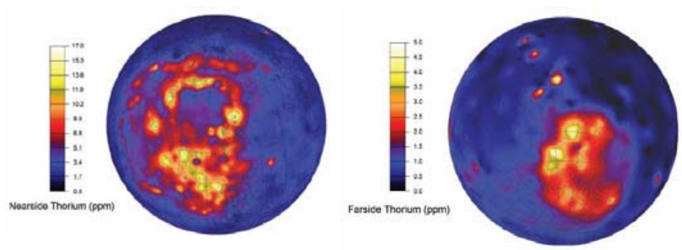

Figure 5.9 *The asymmetric distribution of Thorium and (by inference) of other incompatible elements (Potassium "K", Rare Earth Elements "REE", and Phosphorus "P", otherwise known as KREEP) bespeak of heterogeneity in the formation of the lunar crust that cannot be explained currently.*

Although routinely used at Earth, magnetotelluric sounding has never been attempted at the Moon, because never before have there been electric field instruments flown in the lunar environment. The method is most valuable at higher frequencies (1-10Hz), which are least affected by spatial aliasing of an orbiting satellite. ARTEMIS coIs Delory, Halekas and Grimm have been independently funded by NASA to analyze existing datasets and determine detectability limits of conductivity at various depths from ground or space platforms. Preliminary analysis indicates that a geophysical signal ~0.1mV/m/sqrt(Hz) at 1-10Hz is expected from 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 (Bonnell et al, 2008)). ARTEMIS periapsis measurements lasting for 10s of minutes, at a cadence of 128Hz will be captured in burst mode and will enable sounding of the lunar interior accurately over a broad frequency range. On board plasma instrumentation allows diagnosis of the ambient environment and culling of intervals affected by ambient plasma effects (e.g., tail current sheet crossings, sputtered ions at the nightside, neutralizing electron currents).

An important benefit of magnetotelluric sounding is that at shallow depths conductivity profiles are local. Given the near-equatorial orbits of ARTEMIS probes, this enables determination of the lateral heterogeneity of conductivity, i.e., primarily as function of selenographic longitude. Such information could take the field beyond the spherically symmetric lunar magma ocean hypothesis formulated in the 1970's thanks to Apollo era data. Evidence for such heterogeneity in the lunar differentiation process has been found in the Lunar Prospector measurements (Figure 5.9), and it is quite possible that ARTEMIS may characterize further this heterogeneity in the lunar magnetotelluric response.

In summary, ARTEMIS will perform EM lunar transfer sounding measurements of unprecedented quality. Using state-of-the-art instrumentation and extremely high knowledge of the driver field, it will establish improved bounds on the deep subsurface conductivity profile, and has the potential of distinguishing between the silicate versus ferrous core hypotheses. ARTEMIS' comprehensive fields and particles instrumentation, data collection capability and mission design allow us to utilize for the first time the technique of magnetotellurics from lunar orbit, to determine the subsurface conductivity at shallower depths than previously possible. Correlating that information with known features in surface composition and age can result in a more thorough understanding of the asymmetric mantle development during lunar differentiation.

5.5 Surface properties and planetary evolution.

Crustal magnetism preserves ancient records of planetary and surface evolution. At Earth, study 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 (the lunar dynamo is at least 8 orders of magnitude less than that of Earth's if it exists at all [Russell et al., 1978]). 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, thermoremanent magnetization is expected to have magnetized igneous lunar samples during that period. However, lunar magnetic fields are stronger over highlands than over maria, in agreement with the absence of a recent strong lunar dynamo to magnetize recent lava flows (Coleman et al., 1972). Lin (1988) showed that the largest concentration of crustal fields is diametrically opposed to the Imbrium, Serenitatis, Crisium and Orientale impact basins (Figure 5.10) as confirmed by Lunar Prospector and modeled empirically (Mitchell et al., 2008). Shock remanent magnetization may have magnetized the metamorphosed breccias in these impact basin antipodes, and possibly also in basin ejecta terranes.

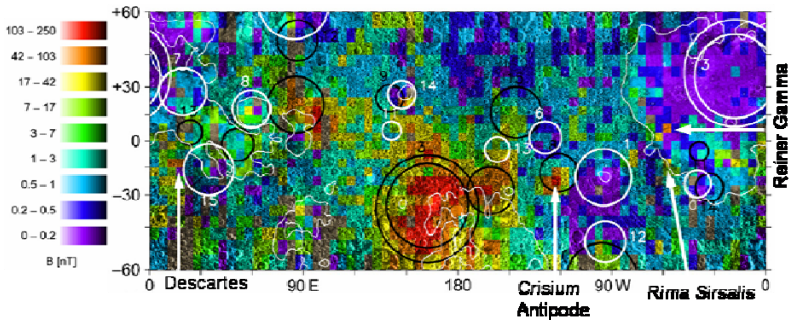

Figure 5.10 *Impact basin rims (white circles, for Imbrium interior ring also shown) and their antipodes (black circles), superimposed on a map of total surface field intensity averaged on 5x5deg bins (Mitchell et al., 2008).*

Highland breccias carry the strongest permanent magnetization of all lunar samples today (Fuller and Cisowski, 1987). These rocks are more efficiently magnetized because they contain more metallic iron grains (likely produced by meteoritic impacts). Mare basalts, on the other hand, contain less nanophase iron and generally have weaker remanent magnetization. Shock remanent magnetization requires the combination of an impact-generated shock and the presence of a magnetizing field, either from the lunar core or from the solar wind of 3.6-3.9 Ga ago. The magnetization may be enhanced in the antipodal regions by compression of the field by an ionized plume originating at the impact site (Fig. 3.11).

Whatever the origin of these magnetic anomalies, they are expected to stand off the solar wind or the magnetosheath plasma, possibly forming a mini-magnetosphere, i.e., a density cavity [Omidi et al., 2002; Harnett and Winglee, 2003]. Lunar Prospector has observed features suggestive of such an interaction, including shock-like signatures in the electron and magnetic field data [Lin et al., 1998; Kurata et al., 2005; Halekas et al., 2008]. In addition, recent observations from SELENE/Kaguya have identified the anomalies both in the magnetic field data at 100km [Tsunakawa et al., 2008] and, more readily, in the plasma data [Saito et al., 2009].

A mini-magnetospheric interaction should result in solar wind density enhancements at the front and at the edges of the anomaly, but density depletions in the center (where solar wind ions are excluded). Indeed, shock-like features consisting of plasma density and magnetic field increases are often observed by LP over crustal magnetic anomalies in the solar wind; however, the expected density decrease is seldom observed in the electrons, even at very low altitudes [Halekas et al., 2008]. We note that the LP mission did not have a solar wind or ion spectrogram monitor. On the other hand, the ion spectrometers on SELENE/Kaguya did observe deceleration and reflection of ions from crustal magnetic anomalies [Saito et al., 2009].

The two strongest anomalies on the near side, Reiner Gamma and Descartes, and the strongest one on the far side, Crisium antipode, have surface fields that likely exceed 1000nT [Hood and Williams, 1989; Richmond et al., 2003] and all three anomalies provide typical examples of the general correlation between crustal magnetic field regions and high albedo "swirl" features [Hood et al., 1979; Hood and Schubert, 1980; Richmond et al., 2003, Nicholas et al., 2006] (see Figure 5.12). Reiner Gamma modeling results in magnetizations of 1-10A/m for layers of 1000 – 100 m respectively, with the source being very close to the surface. This suggests the magnetized layer was due to ejecta from nearby Imbrium impact, and material that was subject to ageing. Similar analysis at Descartes shows that the magnetization there is also likely concentrated in ejecta from nearby Imbrium or Nectaris.

The correlation between regions with high albedo and crustal magnetization may imply that strong surface magnetic fields could be 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 (Adams & McCord, 1971a,b). 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). Moreover, the npFe0 is now believed to be formed by a fractionation process from solar wind sputtering, vapor released by energetic micrometeorite impacts, or both (Pieters et al., 2000).

Reiner Gamma is an ideal feature to study in the context of space weathering, and has the potential to reveal the importance of the two competing weathering processes on the Moon: micrometeorites or the solar wind. There is a close correlation between the albedo morphology and the anomalous magnetic field, including dark and light bands that may indicate open and closed field line topologies. LP results also imply that the Reiner Gamma anomaly may indeed effectively shield the surface from the solar wind

(Kurata et al 2005), and thus be classified as a "mini-magnetosphere." Simple fluid MHD models (Hood & Schubert, 1980) and 2-D fluid simulations with multipole field structures (Harnett & Winglee) indicate that RG and other small-scale anomalies can form mini-magnetospheres.

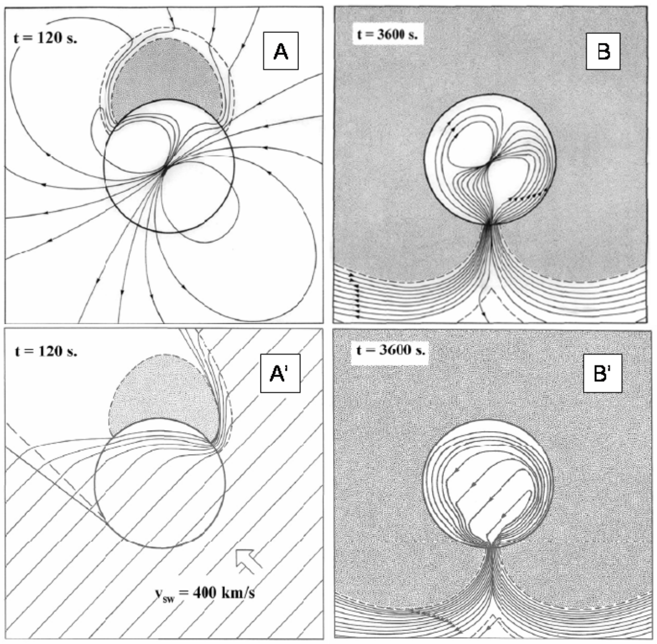

Figure 5.11 *Adapted from Hood and Artemieva [1987]. A possible antipodal magnetization mechanism takes advantage of a global field from an early lunar dynamo (top, A and B) or an enhanced solar wind field (bottom A' and B'). The transport of partially ionized impact ejecta from the impact site excludes this initial magnetic field, resulting in a field concentration at the impact antipode an hour to a few hours later. If this field compression is contemporaneous with enhanced shock pressures from antipodally focused impact ejecta and/or seismic energy, strong shock remanent magnetization can be impressed into both the local material and the transported debris from the impact site. The depth, intensity and orientation of the crustal field holds, therefore, key information regarding the seed magnetic field 3.6-3.9 Ga, at the time of formation of these magnetic anomalies.*

Despite this ongoing research, there is as yet no consensus on the relative importance of fluid or kinetic effects in these features, or whether they form shocks or whistler wakes such as suggested by Omidi et al (2002). While LP results are suggestive, other workers have stopped short of characterizing these features as mini magnetospheres (Lin et al., 1998) ARTEMIS, together with recent Kaguya data, possesses the complete set of plasma instrumentation necessary to help resolve this question. If RG is found to form an effective shield against the solar wind, this would imply that solar wind ion sputtering is an important or perhaps even dominant process for space weathering when compared with the micrometeorite contribution alone. These results can then be applied to other swirl features in order to explore the pervuasiveness and importance of this process over the lunar surface, and by extension other airless bodies throughout the solar system.

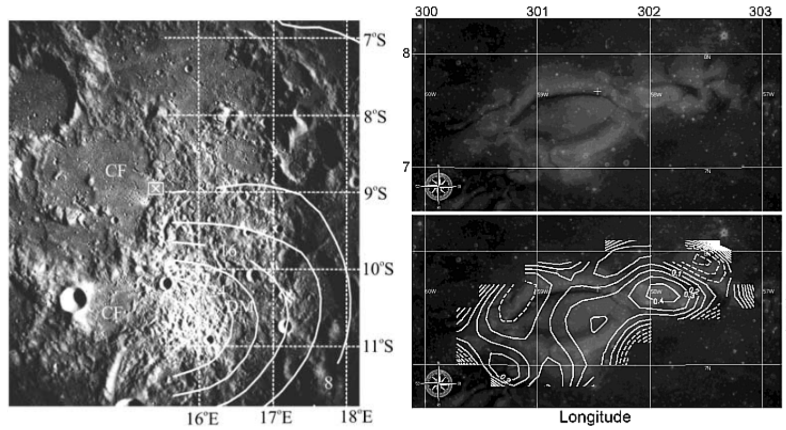

Figure 5.12 *Left: Descartes mountains albedo and its correlation with magnetic field magnitude at 19km, near the Apollo 16 landing site, shown in a box at the center (from Richmond et al., 2003). Right: Reiner Gamma albedo (top) and its correlation with the Northerly magnetization (bottom) shown as contours at 0.1 A/m atop a 40km thick magnetized layer (from Nicholas et al., 2006).*

Although recent impacts that bring up fresh material are also accompanied by high albedo, it is possible to use albedo information and the knowledge gained from observations of intense anomalies observed on orbit to understand other anomalies with higher order poles that may not extend as far into the solar wind, yet are still able to fend the solar wind off at lower altitudes. This can provide further information about surface magnetic topologies that cannot be accessed by magnetic field measurements from high orbit or remotely sensed using electron reflectometry.

In fact, the Kaguya plasma team has recently reported observations of solar wind ions reflected from magnetic anomalies, with the typical surface backscattering observed over the unmagnetized surface absent in the vicinity of such anomalies. Electron heating due to turbulent electric fields is expected and observed at the interface of solar wind and the magnetic anomaly [Saito et al., 2009]. That interface is expected to be a host of numerous plasma instabilities and electron populations that can remotely sense the entire field line. These observations suggest that significant knowledge regarding the properties of the lunar crustal anomalies can be obtained from orbit, by the study of the crustal field's interaction with the ambient plasma. Specifically, the extent of influence of these interactions into the environment (solar wind, magnetosheath or magnetotail) can provide information on the strength, multipole order, depth and orientation of the underlying dipole. This information, in turn, is related to the conditions at the time of magnetization and can be used to constrain the initial driver field. For example, random polarities at nearby sites would favor a solar wind seed, whereas polarities organized at a great circle, or meridian, could favor an internal dynamo theory.

ARTEMIS will 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°), depending on the communications link budget and fuel margin available. 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. These anomalies deflect and shock the solar wind plasma and cause electron heating and wave turbulence. Even from 100km altitude and from inclination below 10°, the comprehensive instrumentation on ARTEMIS will measure the magnetic properties of Reiner Gamma and the interaction of this mini-magnetosphere with the Solar Wind and the Earth's magnetotail.

5.6 FY11/12: ARTEMIS/Planetary and LRO

Because it overlaps with LRO's extended investigation in FY11 and FY12, the ARTEMIS mission is in a unique position to support LRO's prime and extended mission science objectives. LRO will study the lunar atmosphere and its variability with the LAMP instrument, and particle acceleration mechanisms and their radiation effects on tissue with the CRaTER instrument.

The LAMP EUV spectrometer's observations of the lunar atmosphere and its variability are key LRO objectives during the main mission. In the extended mission these objectives expand into the study of the structure and variability of the exosphere, the horizon glow and the search for active outgassing regions. LAMP will probe the vertical scale heights of constituent species, such as Ar, H, OH and H_2 to understand volatile transport processes with dedicated campaigns. Understanding the path of those species requires correlating their occurrence patterns and characteristics with external drivers such as the solar wind and magnetotail plasma fluxes and field orientations, parameters readily provided by ARTEMIS.

ARTEMIS can support LAMP observations of the exosphere by providing accurate measurements of solar wind and magnetotail drivers. For example, if the Moon has a Lyman alpha corona, it is possible that it varies with solar wind electron flux or external electric field intensity/magnetic field topology. Topographic measurements of source regions with LAMP can also be directly compared with charged particle surface sources from the ARTEMIS' investigation, reinforcing the findings or providing salient differences between the two techniques. Comparisons of ARTEMIS's in-situ charged species loss rate measurements and exospheric source determination, when compared with LAMP's observations of these species' neutral source populations from the same epoch provides a very strong synergy relating the exospheric constituent losses directly with their source population. Observations during the overlap period between LADEE and ARTEMIS can be used as calibration points to relate the statistical studies that will be done independently by the two missions.

CRaTER's objective to study Galactic Cosmic Ray (GCR) and Solar Energetic Particle (SEP) populations to constrain radiation transport models and determine the temporal variation of radiation effects at the Moon is particularly well facilitated by the presence of ARTEMIS as a nearby solar wind monitor. Variations in GSRs and SEPs at lunar distance depend on the location of the Moon relative to the magnetosphere and solar wind, the interplanetary magnetic field orientation and connection to the Sun, and variations in flux of solar wind plasma. This is particularly true for SEPs with ~100 keV energies, whose flux can vary by orders of magnitude as the Moon moves through the magnetotail plasma sheet and lobes, the magnetosheath or the solar wind. As these magnetospheric regions are very dynamic, only a lunar solar wind monitor can determine them accurately and provide the necessary input to model and interpret the CRaTER measurements.

5.7 FY13/14: ARTEMIS/Planetary and LADEE

By measuring both upstream solar wind and local plasma conditions near the Moon, ARTEMIS is in a unique position to support the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission, slated for a mid-2012 launch. LADEE carries instrumentation to study the dynamics of the lunar exosphere and dust environment, much of which will be tied directly to the ambient plasma conditions at the Moon and in the solar wind. Sputtering by the solar wind has been proposed as a possible mechanism for the generation of neutral exospheric species such as Na [Potter & Morgan, 1994], along with photon-stimulated desorption (PSD) and micrometeorite impacts [Mendillo *et al.*, 1999]. Although recent Kaguya results suggest that the solar zenith angle is the dominant effect on the observed Na^+ flux, distinct changes in the exosphere have been observed when the Moon enters the magnetotail [Potter *et al.*, 2000; Wilson *et al.*, 2006], indicating the importance of the local plasma environment on exosphere dynamics. Most recently, correlations between Lunar Prospector plasma data and ground-based observations indicate that ion impact may enhance PSD efficiency [Sarantos *et al.*, 2008], possibly due to the introduction of crystalline lattice defects in the regolith. This recent discovery is a preview of the synergies possible between ARTEMIS and LADEE, in which one spacecraft measures the complete plasma inputs to the system, while a second monitors the exospheric response. Since LADEE lacks any plasma instrumentation, the presence of ARTEMIS will enable a more direct linkage to be made between the specific plasma processes and the resultant exospheric variability measured by LADEE. Similarly, ARTEMIS plasma measurements will cast light on the processes causing any dust activity measured by LADEE. To first order, LADEE measurements will confirm or refute some of the more obvious potential sources of lofted dust, such as the photoemission-related day-night asymmetry at the terminator region where the surface potential of the Moon is known to change on a regular basis [Farrell *et al.*, 2008; Halekas *et al.*, 2005b; Manka, 1973; Stubbs *et al.*, 2006]. It is also possible that dust activity is rare on the Moon, occurring only during extreme charging events [Halekas *et al.*, 2007, 2009] or follows unexpected temporal or spatial patterns. In this case ARTEMIS measurements of the plasma conditions and surface potential could revolutionize our understanding of the underlying physical mechanisms at work which would have otherwise gone unnoticed with LADEE measurements alone.

The LADEE launch is currently planned for mid-2012, and thus will overlap with the nominal ARTEMIS mission during its low-altitude phase (~100 km) about the Moon. The synergy is immune to a launch delay because the ARTEMIS probes will be in stable orbits for many years. The LADEE deputy project scientist, Dr. G. Delory, is also an ARTEMIS co-I, ensuring early and effective scientific and operational coordination between these two missions prior to their lunar conjunctions.

5.8 Beyond 2014: ARTEMIS/Plantary and the ILN.

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. Magnetotelluric measurements are baseline ILN measurements to achieve a desired goal of the ILN, however magnetometers alone could provide an ILN measurement floor, assuming a low-orbiting magnetometer was available. 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 also complement the magnetotelluric measurements of the expanding ILN network of nodes during the next decade.

6. Planetary Science Trade Studies

The ARTEMIS team will optimize the science return for the Planetary investigation of the mission without affecting its Heliophysics commitments and without posing risk to the probes or undue burden on operations. The mission design and instrument operations trade studies are as follows and will occur in 2010 and early 2011.

6.1 Periselene reduction

The ARTEMIS orbits are affected most by Earth perturbations, and less by lunar perturbations. Orbits are predictable with the periapsis altitude exhibiting periodic behavior dominated by an oscillation at 1/2 the lunar orbital period with a secondary oscillation at four times the lunar month (Figure 6.1). Both modes of the periselene oscillation can be reduced by lowering aposelene, and the orbit can be further optimized to "graze" the surface in the <100km domain once a month. By expending maintenance fuel on the order of a few m/s it is possible to maintain a stable orbit at low periselene. The operational aspects of this optimal design will figure prominently here including: position knowledge accuracy; fidelity of long-term orbit predicts from models; and burn targeting accuracy.

6.2 Inclination adjustments

An inclined orbit increases the gravity gradient torque on the spin axis away from its optimal orientation of 3-13° (8° nominal). This affects communications as there are significant signal losses below 15° from the spin plane. Spin axis station-keeping results in a 225gr/yr fuel expense assuming 26° inclination, which is equivalent to 5m/s/year and should be gauged against ~5 m/s/year needed for periselene station keeping. Further inclination increases or fuel reductions are also possible assuming data can be lost from a small part of the orbit whose location depends on the time of year and the evolution of the inclination/spin axis as function of mission elapsed time. The trade space includes thermal considerations (top deck illumination runs the spacecraft hotter), boom shadow effects (for solar incidence angles greater than 10° the magnetometer booms shadow the solar array resulting in spin tones in the magnetometer measurements during one portion of the year). The study will culminate in a recommendation for an inclination/spin axis attitude that will optimize science at low additional operational costs for the fuel available.

6.3 Instrument planetary rates and modes

The instruments on ARTEMIS can be run in ways that optimize planetary objectives without reducing their efficacy for heliophysics science. We will consider the following: (i) Averaging particle distributions rather than capturing snapshots, to increase counting statistics at no volume expense, needed for high quality measurements of exospheric species. (ii) Time-based perigee burst mode collection for magnetotelluric and crustal fields/space weathering science. (iii) Apportionment to slow versus fast survey modes, and data products returned will have to be revisited to optimize exospheric science versus low altitude science.

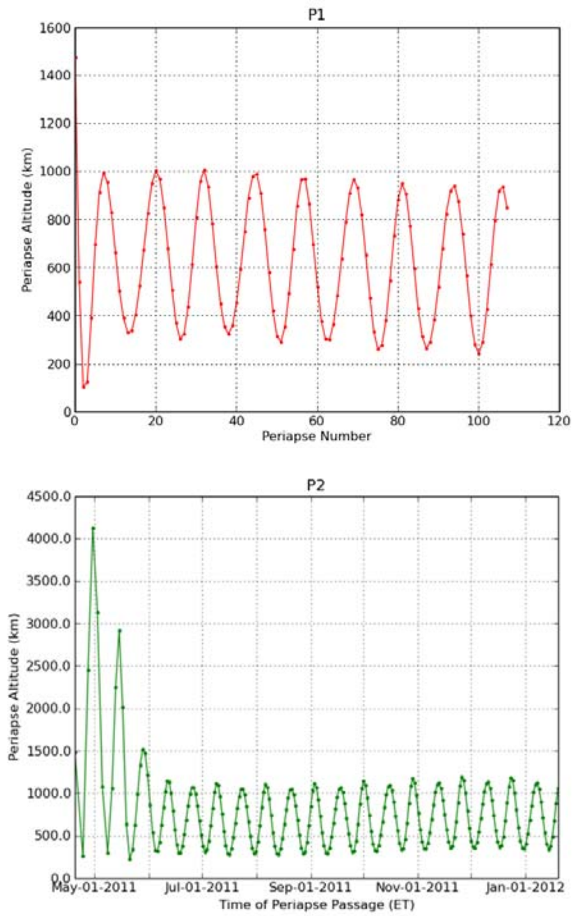

Figure 6.1 *Current periapsis altitude of ARTEMIS probe P1 and P2, were selected for heliophysics. For Planetary science, a <10m/s burn (margin is available, see Section 7) or optimization of orbit insertion maneuvers can result in lower periapsis (<100km). Lowering of apoapsis can further reduce the periapsis spread from Earth perturbations. Orbits are expected to result in ~ a dozen "grazing" lunar encounters per probe per year, or about three dozen low altitude passes in the period 2011-2012, and continue with minimal maintenance thereafter.*

6.4 Particle instrument mode changes

The ESA instrument (McFadden et al., 2008) operates in the magnetosphere and in the solar wind in two separate modes. The solar wind mode increases angle resolution to 5.125^o producing accurate solar wind plasma moments but reduces the energy resolution to only 50eV-5keV and angle resolution everywhere else by along the solar wind direction. These two separate modes suffice for doing heliophysics science at the Moon. Planetary science, however, requires capturing both the solar wind input to the lunar environment and the spectroscopic differentiation of species, many of which are expected to occur at higher energies due to their greater masses. The method requires energy detection up to (and beyond) the maximum energy of the ESA detector (30keV) and into energy range of the SST instrument. The plan is to develop a special mode for the ESA, which preserves energy range and angle differentiation for solar wind directional information. An alternate but operationally more complex scenario would be to develop mission design tool automated scripts that would switch the instrument between solar wind and magnetospheric modes based on lunar wake predicts and entry/exit into the magnetosphere.

7. Potential for future discoveries

The ARTEMIS team of scientists, software engineers, instrument team and operations personnel is highly integrated. The team works efficiently on delivering its scientific promises, fulfilling the aspirations of the Heliophysics discipline by maximizing the scientific return from the probes. A prime example of this efficiency is the rapid redesign of the 2nd year of its orbits, to accommodate the unusually thin plasma sheet thickness observed in the 1st tail season, with minimal fuel costs, on target and on-budget. Below are the top reasons for THEMIS's potential for future discoveries in FY11-14:

- **Location.** ARTEMIS is visiting an under-explored region of Geospace by Heliosphysics spacecraft. ISEE 3, and more recently WIND and Geotail have made infrequent passes of the region 55-65R_E, but none completed a systematic study of what is arguably the most likely location of the last closed field line, and the best place to observe lobe energy transfer into the plasma sheet. With two spacecraft, another first, ARTEMIS will be able to systematically characterize the region, and study fundamental physics of reconnection and turbulence possible only at that location, far enough from the strong influence of Earth's field. Moreover, no other spacecraft has had the systematic wake traversals from a range of distances that ARTEMIS will make, and no other mission has had the pristine solar wind measurements right upstream to recognize and interpret even minute changes of field and particles. Finally, from a vantage poing of ~100km and likely as low as 50km, ARTEMIS will be able to observe and interpret small changes of fields and particles due to lunar influences better than any other missions due to the presence of the second spacecraft measuring exactly the pristine solar wind input.
- **Relevant science.** ARTEMIS science lies at the cutting edge of magnetospheric research: In FY11/12 (Sec. 4) it will study fundamental processes with global consequences during substorms, while in FY13/14 it will add many storms in its studies of reconnection and turbulence. In that period it will be a pristine local solar wind monitor right upstream and its 2 point measurements will enable studies of shocks and CMEs (in parallel with

RBSP) making relevant complementary studies of the space environment to NASA's LWS spacecraft.

- **Orbits and instrumentation.** The proposed probe separations are unique, never achieved before by Cluster or fortuitous conjunctions by other spacecraft. The comprehensive ARTEMIS particles and fields instruments are working flawlessly on both spacecraft.
- **Enabling community science.** The power of the ARTEMIS constellation lies not just in its team but also in the community's ability to fully utilize its data, software and human resources. In recognition of this doctrine, the ARTEMIS is providing its highest resolution data openly, as well as machine-independent software for seamless data downloads, highly advanced analysis (http://themis.ssl.berkeley.edu/software.shtml) and recipes ("crib sheets") on how to conduct research with the data.

In summary, the ARTEMIS mission's prime location, the cutting-edge science questions that it will address, its unique orbit design, its 100% operational and fine-tuned instrumentation and its pro-active embrace of the entire science community point towards its promise for future discoveries. Past performance is a solid indicator that ARTEMIS will deliver on its promises. ARTEMIS is leading NASA on a journey of exploration of fundamental physical processes at the Earth and Lunar space and planetary environment.

8. Technical/Budget

8.1 Technical

8.1.1 Probe and instrument status. As of this writing, the ARTEMIS probes are in excellent health and performing nominally. After the Orbir Raise Maneuvers (ORMs) have been accomplished they are on their way to enter their Lissajous orbits in October 2010. Remaining maneuevers are placeholder correction "Deep Space Maneuvers" (DSMs) and 2 minor orbit adjustments to avoid umbra shadows at end of March. The thermal design is extremely robust, the power systems maintain significant margins such that the transmitters can essentially operate all the time, exceeding design requirements. Probe and instrument status is updated in real-time during pass-supports. The last recorded status is seen at: http://soleil.ssl.berkeley.edu/ground_systems/themis_constellation_status.html. Minor contamination effects that have been addressed by ground software: (1) As anticipated, sunlight affects two sectors per spin of the SST. Analysis tools that remove the sun pulse and associated electronic noise have been devised and are widely disseminated to the team and the community. (2) Spin harmonics and 32 Hz noise affect the SCM and have been corrected by ground software, now part of the standard calibration. (3) An 11 Hz noise affected the FGM (at ~30pT level, only minor). This has been recently diagnosed as interference from particle sectoring and has been fixed with an operational workaround: By changing the spin rate by a few msec the noise is "tuned" beyond the FGM cutoff frequency.

Instruments operate in Slow Survey (SS) mode most of the orbit and in Fast Survey (FS) mode during conjunctions. Horizontal bars indicate fast and slow survey mode intervals in overview plots from past Earth orbits of P1, P2 at **http://themis.ssl.berkeley.edu/summary.php**. There is effectively no science telemetry in the present, coast phase as signal strength is too weak for meaningful data return. Upon lunar capture, a 3hr FS with 1-2 bursts per orbit and full orbit SS are envisioned. A trade study to determine optimal Helio- vs Planetary operations is proposed. Automated operations support routine passes with BGS, and this is the planned operations strategy after a few months into lunar insertion in April 2011. Operator-supported passes with DSN are planned till then, as has been the norm now for the last 8 months, once per day per probe. Approximately 17000 passes have been completed to date in lights-out mode on THEMIS.

8.1.2 Status of ground systems. All data processing and software continue to function reliably. All flight dynamics systems are nominal. Mission design runs with the latest orbit solutions are run months in advance with nominal planned maneuvers with a quick turnaround reaffirming conjunctions, shadows, and fuel budget. Product generation based on updated ephemeredes is fully automated. GSFC flight dynamics provide backup orbit solutions for each probe. Telemetry files are transferred post-pass from the ground stations to UCB, checked and archived. Level 0, 1 and 2 data processing is automated. Instrument scientists ("tohbans") review survey plots ~1 day after receipt of data on the ground. See http://sprg.ssl.berkeley.edu/~themistohban/ for tohban functions. The Berkeley ground station continues to function well. NASA Ground Network stations continue to support THEMIS nominally, while USN and HBK stations have been certified and also support THEMIS. The NTR T-1 line from GSFC to the MOC over the Open IONet and 3 voice loops continue to function nominally.

8.1.3 Mission operations in FY11/12

Lissajous Phase (Q1,Q2 of FY11): After several lunar and Earth flybys the probes will be inserted into weakly stable orbits at the two Earth-Moon Lagrange points, LL1 and LL2 at the start of FY11. At that point science operations commence while the probes execute Lissajous orbits with ~14 day periods. The Lissajous orbit phase design has a dual goal: Operationally, it prepares the team for accurate, low risk orbit insertion, while orbit evolution flattens the orbit of P2 after its previous out-of- (ecliptic) plane motion (Figure 6.1). Scientifically, this phase is important for Heliophysics science, as it results in a wide range of large inter-probe separations (10-20 R_E) and Sun-angles, suitable for studies of large-scale phenomena in the magnetotail, solar wind, and lunar wake. There are two Lissajous orbit sub-phases, driven by heliophysics science reasons (above): From late October 2010 to early January 2011 the probes are on opposite sides of the Moon; from

January 2011 to early April 2011 the probes are on the same side.

After the 5-month residence at the Lagrange points, the probes are inserted into stable, 27hr period, near-equatorial lunar orbits. The orbit insertion times and inclinations are flexible and chosen to optimize the lunar orbits for heliophysics science. Once the sequence commences and the closest approach is reached, a series of critical operations, namely periselene and aposelene burns, result in orbit capture. Planetary science would benefit from a higher inclination and lower periapsis, assuming orbit stability and fuel margins are maintained. (See Section 6.) Orbit insertion to the resultant new elements will be implemented by the operations team at no appreciable additional effort.

The near-equatorial lunar orbit design, currently aimed towards heliophysics goals, simultaneously optimizes science return and reduces mission operations complexity: P1 is retrograde and P2 is prograde, such that the orbits precess ~360^o relative to each-other in FY11/12, providing a wide range of inter-probe separations and longitudes as needed for the science objectives. The fast relative precession of P1 and P2 removes the inertial longitude of insertion (and time of LOI) from the design considerations. The team has found implementation options that even-out the fuel margin (shown in Table 8.1) between the two probes and has fine-tuned the DSN contact schedule.

Orbit optimization for planetary objectives was discussed in Section 6. End of mission re-entry requirements (10m/s) are well within margins (Table 8.1). Operationally, an inclined orbit (optimal for planetary) results in gravity-gradient torques (15deg/year worst case for a 26deg inclination orbit) which perturbs the spin axis away from the science attitude. This requires 225grams of fuel per year to correct, which is equivalent to 5m/s per year of ΔV and can be afforded for a number of years by both P1 and P2. This tentative planetary mission design concept also leaves sufficient fuel to ensure stationkeeping maneuvers, which may be needed for an extremely low periselene (~50km). The long term orbit stability and inclination/APER drifts remain part of the trade study.

The ARTEMIS probes will be operated in the standard SS, FS, PB and WB modes used for THEMIS. Planetary science requires approximately 0.5hrs of FS mode data at periselene, whereas heliophysics science requires 2.5 hrs in the wake. Nominally two PBs are envisioned per orbit: one time-based at periselene and one on-board-trigger-based closer to aposelene. Burst selection will occur at ARTEMIS mission and science operations meetings, incorporating a planetary scientist and a heliophysics scientist, the mission tohban, and the instrument scientists. Planetary requirements will be accommodated and adjusted as a result of these deliberations.

ARTEMIS is using the DSN 34m BWG antennas for communications at 3.5 hrs/probe/2 days. At a maximum lunar range of 64 R_E with the known G/T of the DSN 34m BWG stations, we collect:

- DSN, science: 65.536 kbps / 3.2 dB margin
- DSN, ranging: 16.384 kbps / 2.1 dB margin

Assuming that 32kbps represents a worst case scenario for reasonable lunar orbit view-angles from Earth (~5^o to ecliptic), and spin-axis tilts planed for science operations (~8^o to ecliptic) regardless of orbit inclination, we observe that we can collect ~337.5 Mbits / 3 hr contact. This exceeds mission requirements by more than a 50% margin.

Mission Design and Navigation. The ARTEMIS science and mission implementation teams (UCB, JPL, GSFC) are holding weekly telecons to execute the ARTEMIS mission heliophysics design. Maneuver validation, navigation error characterization, and insertion of additional trajectory correction maneuvers are currently under way at both GSFC (for proof of principle and spot-checking) and UCB (for detailed design) with identical tools and JPL in advisory role owing to the mission design contribution. Planetary objectives require re-targetting the Lunar Orbit Insertion (LOI), as explained in Sections 6.1 and 6.2. This has negligible operational effects for insertion, the choices of inclination and apo/periselene affect probe stationkeeping at the Moon. Orbit / attitude determination tolerances have to be considered and routine orbit forecast runs are needed to plan low periapses. Fuel budget and management of other mission resources (power, thermal, data volume, observation time, geographical coverage) are also importane. Early science trades can mitigate risk, and will be looked at very carefully while also optimizing science return. Efficient operations factor highly in the overall cost- science-benefit analysis of the mission.

ARTEMIS Mission (P1, P2): ΔV Overview				
Phase	Interval	Maneuvers	dV P1	dV P2
TLI	Oct. '09 - Oct. 10	Orbit raise, Lunar fly-by	104	255
		Declination, Gravity Losses	included above	
		Deep Space Maneuvers	5	29
LL1,2	Oct.'10 - Jan. 11	Maintenance	15	12
LL1	Jan. '11 - Apr. '11			
LO	Apr. '11 - Sept. 12	Lunar transfer initiation, LOI	121	106
		Declin., Gravity, Steering	included above	
all	all	Trajectory Correction Man's	10	17
Total required for probe			254	419
Total available at end of prime mission:			336	457
ΔV available ARTEMIS margin [m/s]			82	38
ΔV available ARTEMIS margin [%]			32%	9%

Table 8.1 *P1, P2 have started their journey to the Moon. The insertion scenario can be further optimized, but has sufficient margin for either de-orbit (~10m/s) or for operational use for planetary objectives.*

Flight operations and scheduling. As the probe apogees increased, the Berkeley Ground Station is now only used for probe health and safety contacts, whereas nominal tracking has transitioned into using the DSN antennas. In the current, translunar phase, routine operations on a best effort basis by DSN will continue, to maintain proficiency of operations personnel until the prime science phase at the start of 2010. Apart from Lunar Orbit Insertion there are no major critical maneuvers in the mission. It is important, however, to maintain backups and contingency plans for several correction and all insertion maneuvers because the mission design is based on a “Return to Nominal Trajectory” plan, which relies on successful plan execution with accurate targeting (<1%). This is accomplished by scheduling at least one backup ground station, and ensuring that schedule information and console personnel are in place a few hours prior to each planned pass.

Flight operations for planetary require accommodating the new instrument modes (or revised regions of interest, see Section 6.3) and burst collection and ensuring that temperature and sun-angle limits are not violated in slightly inclined orbits. These require flight software changes, flatsat testing and spacecraft uploading and verification by instrument personnel to ensure that the science return from reconfigured instruments satisfies the needs of the proposed ARTEMIS planetary investigation.

In summary, the FY11/12 mission operations tasks for heliophysics are well under way and planetary implementation has an identified tentative solution in line with current heliophysics operations plans, and within the fuel capabilities of the ARTEMIS probes. It will be vetted with the ARTEMIS science team, composed of leading experts in planetary and lunar science. The team will:

- Implement shadow spin phase recovery
- Orbit detailed redesign of LOI for planetary
- Spin axis reorientations / periapsis tweaks
- Planetary modes test/implementation
- Instrument operations/mode validation

8.1.4 Mission operations in FY13/14

Significant savings from operational simplicity, automation and familiarity of the team with instrument operations will reduce mission and science operations personnel in FY13/14. There will be a need to forward run projected orbits to ensure orbit stability, attitude control and execute orbit maintenance maneuvers, but overall the benefit of the stable orbits chosen is optimal science at low operational costs, and this benefit will be clearly seen in FY13/14. Instrument operations outside of nominal scheduling of instrument and spacecraft modes, requires interfacing with LRO and LADEE, as well as Heliophysics missions (e.g., RBSP) to optimize data collection in the upcoming solar maximum.

8.2 Budget

8.2.1 Project Financial Status. Since the start of the nominal extended phase in October 2009, THEMIS (which contractually includes ARTEMIS) has been operating under extension to the prime mission contract. Our new extension is through April 30, 2010. Given the fact that the Phase E contract took 15 months to award, it is imperative that all interested parties do their best to ensure rapid issuance of the new contract and project stability that will result in optimal science. The THEMIS prime contract ended on-target, despite the addition of significant ARTEMIS operations planning work, which was absorbed through early personnel reductions in the summer of 2009. All portions of THEMIS project under the visibility and control of the PI team have been, and remain, on-time and on-budget. The ARTEMIS heliophysics implementation budget is currently bare-bones and success-oriented. The traditional co-I funding for heliophysics science first look at data, Space Science Reviews publication on the ARTEMIS is absent. Such science activities by the science team that brought the mission concept to life are important both to showcase the mission capabilities and to encourage and stimulate the community to benefit from the dataset.

8.2.2 FY11/12 budget explanations. The budget spreadsheet shows the budget request to conduct the combined ARTEMIS Heliophysics and Planetary implementations. Specifically, under: “II. 5-way functional breakdown”, Item: “1. Development” describes the required operations, navigation to conduct the nominal Heliophysics mission, plus the science trades, science operations software and instrument work and mission operations preparations activities related to the Planetary aspects of the ARTEMIS mission in FY10 and the first half of FY11, i.e., until Lunar Orbit Insertion (LOI). After that time operational work transitions into items “2”, “3”, and “4”. A community training program of $20K/year (plus modest travel) is requested to develop and conduct software tutorials, distribute 50 bundled IDL licences for ARTEMIS analysis software, and support the community through a “hot line” in software bug reports and data questions. Public Affairs is funded to create visualizations of lunar encounters or orbits, and help relay to the public the excitement of ARTEMIS.

Under: “III. Instrument team breakdown”, the instrument support corresponds to mode changes pre-LOI and validation of the data after LOI.

Category “IV. … in-kind contributions” refers to the technical contributions that are required for the success of the project, but excludes the significant benefits from the THEMIS mission operations, upon which the success of ARTEMIS has been based. Specifically: Item: “2.a Space Communications Services” refers to the DSN anticipated costs for ARTEMIS tracking, and SSMO Project Management and Services (T1 Line).

Category: “V. …Optimal Budget” is a repeat of II.

8.2.3 Other major budget items: *Space Communication Services*: This includes pass scheduling, flight operations, and ground system support, as well as maintenance and minor upgrades to the Mission/Science Operations center as most are covered under THEMIS; *Mission Services*: This includes UCB and GSFC mission navigation, orbit and attitude determination and UCB and JPL mission design; *Science Operations*: Science Data processing, documentation and archival for the specific operational modes and data products of this mission, including ground based observatories, community support, software help line and tutorials; *In-kind contributions* include SSMO Project Management and Services (Ground Network, T1 Line to Berkeley).

8.2.3 FY13/14 budget explanations. The budget benefits from transition of Navigation error analysis to UCB and routine UCB and DSN operations due to increased operator familiarity with the mission. The workhorse of contacts for health and safety continues to be BGS whereas DSN is the primary way of obtaining the data at a rate of 1 pass per day, alternating between the two ARTEMIS probes.

Figure 9.1 *NOVA series aired a story on THEMIS discoveries and magnetic storms with footage from the UCB Mission Operations Center.*

9. Public Affairs

A vigorous public affairs program at NASA/GSFC with the help of the Scientific Visualization Studio, has achieved remarkable successes during the past 2 years. The THEMIS launch was covered extensively by the media and the launch video was advertised by www.nasawatch.com and received more than 21,000 hits on "YouTube". The Fall 2007 AGU new results press conference was well attended and was well covered by the print media. It resulted in numerous interviews broadcast by BBC, CBC, and NPR, including a feature on the NPR program Earth & Sky. Two presentations at the Maryland Science Center, (in 2007 and 2008) and at the Smithsonian brought the excitement of science to the general public. PBS's Newshour presented a special report on our E/PO efforts to engage Alaskan students and is preparing a follow-up program. The NOVA channel repeatedly aired a THEMIS story on magnetic storms (Figure 9.1) while popular science magazines have captured THEMIS discoveries and extended the message of NASA's successes to the public. Astronomy Magazine rated the THEMIS discoveries one of the top 10 stories in 2008 (Figure 9.2).

These results bespeak of an public affairs team that is well positioned to carry the ARTEMIS message of innovation and discovery to the public, to inspire the nation and motivate the next generation of scientists and engineers.

Figure 9.2 *Left: Jim Lehrer show on THEMIS Ground Magnetometers observing space currents in the classroom. Right: THEMIS discoveries were amongst the top 10 stories in Astronomy magazine in 2008.*

10. References

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