

Application of the THEMIS Bus to New Missions

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ABSTRACT

It is recognized that small satellites can complement the services provided by existing larger satellites, providing cost effective solutions to military missions, communications systems, remote sensing applications, satellite rapid-response, science and technology demonstrator missions. However, today's small satellites are largely confined to low Earth orbit where they perform remote sensing missions, conduct science operations, and serve as technology test beds. Future small satellite missions will include interplanetary missions, space-weather mapping as well as space exploration and robotic probes.

INTRODUCTION

This paper presents an engineering approach for accomplishing innovative interplanetary and space-weather mapping missions utilizing constellations of small satellites. Specific applications explored will include science and exploration of the Moon and space-weather mapping. Insight is first provided into the Time History of Events and Macroscale Interactions during Substorms (THEMIS) spacecraft bus subsystem architectures which have characteristics that support these types of missions such as low mass, low power consumption, large delta-v capability, low magnetic signature and low surface charging characteristics. The re-use of the bus subsystem architectures allows for a rapid design cycle leveraging existing integration and testing capabilities that shorten the overall cycle time while providing excellent reliability. The following sections provide an overview of the THEMIS mission and a brief background on the THEMIS Bus subsystems. The paper will address adaptations of the THEMIS spacecraft bus to servicing other mission

applications in orbits that are different than the ones for which the bus was initially designed. In addition, this paper will address the utility such a mission could provide in answering scientific questions that have typically been the basis of much larger spacecraft.

THEMIS Mission Background

The THEMIS mission is a NASA Medium Class Explorer (MIDEX) Mission. The University of California Berkeley (UCB) has overall Mission responsibility and developed the instrument suite. UCB also manages the on-orbit operations of the five satellite constellation from their ground station at Berkeley as well as two other satellites. Swales Aerospace (now ATK Space) was the Prime Contractor for the THEMIS Probe Buses, the Probe Carrier, which is used to deploy the satellites from the spinning third stage, and the provider of the separation systems.

The THEMIS constellation was successfully launched in February 2007 off a Delta II rocket from Cape Canaveral Air Force Base (CCAFB). Figure 1 shows

the five Probes on the Probe Carrier awaiting fairing closure. In early June 2007, each of the five satellites completed their in-orbit checkout and instrument commissioning with only minor issues.

The THEMIS mission consists of a constellation of five satellites (probes) carrying identical suites of electric field, magnetic field, and particle instruments used to determine the cause of global reconfiguration and transport of explosive releases of solar wind energy into the Earth's magnetosphere. Each probe incorporates flight-proven instruments and subsystems reducing cost and risk while increasing system reliability. Every four days, the five probes line up along Earth's magnetosphere tail—providing an opportunity to measure substorm disturbances in concert with ground observatories dispersed throughout North America. The design mission life of the constellation is two years. The probes are deployed into highly elliptic orbits that extend from 1.2 earth radii (RE) at perigee out to 34 earth radii at apogee. These orbits require a robust design due to the high radiation environment, large delta-v requirements, and long eclipses, which are up to three hours in length.



Figure 1: THEMIS Constellation (Courtesy NASA)

Table 1 provides a summary of the THEMIS Mission and Bus subsystem characteristics. The subsequent sections of this paper provide some further background on the THEMIS requirements and subsystem design. The last section of the paper provides insight to future missions that can leverage the design and implementation of THEMIS Mission.

Table 1: THEMIS Mission Characteristics

Resource / Subsystem	Characteristic
Mass	Spacecraft Bus Dry Mass: 51 kg Instrument Mass: 26 kg Probe Dry Mass: 77 kg Propellant: 49 kg Probe Wet Mass: 126 kg Allowable Mass: 134 kg Margin: 8 kg (6.3%)
Power	Spacecraft Bus Power: 11 W Instrument Power: 15 W Heater Power (EOL for 3 hr eclipse): 11 W Probe Power: 37 W Available Power: 40.5 W Margin: 3.5 W (9.5%) Battery capacity (BOL): 12 AmpHr
Communication	S-band EIRP: 2.4 dBW Array of six Patch Antennas Two-way Doppler tracking Uplink command rate: 1 kbps Ten downlink rates Max rate: 1.024 Mbps
Command & Data Handling	CCSDS compatible command & telemetry formats Five days worth of engineering data storage Time (UTC) distribution
Attitude Control	Spin rate (Science): 16 ± 2 rpm Spin axis orientation: $< 1^\circ$ (knowledge), $< 3^\circ$ (control) Spin phase knowledge: $< 0.1^\circ$ Ground based attitude determination
Propulsion	Monopropellant Hydrazine System Number of thrusters: 4 (4.4N ea.) Total ΔV : 940 m/s Propellant: 49 kg
Launch Vehicle	Three-Stage Delta II, 7925-10 Mass to orbit capability: 829 kg
Orbit knowledge Accuracy	< 100 km
Formation Control	Not required other than drift compensation
Science Data Volume	Data Volume: ~ 400 Mbits per day Five days worth of storage
Radiation Environment	TID: 66 krad (2 years, 5mm Al, RDM of 2)
Reliability	Observatory Ps = 0.91 (2 years) Mission Ps = 0.94 (4 of 5 s/c required)
Ground Stations	UCB ground station and USN stations

THEMIS Orbits

As indicated above, one of the major drivers of the THEMIS mission are the multiple orbits that it must be designed for. This not only drives the radiation environment but also the thermal design due to the relatively long eclipses, which in turn drives the power subsystem dictating the power consumption and storage requirements. The multiple orbit design for this constellation required numerous assessments of the different spacecraft attitudes on the thermal subsystem. The multiple orbits also required extensive analysis of the orbit mechanics and required maneuvers which complicated the fuel budgeting for the mission. This was one of the primary reasons for implementing a re-pressurization system into the Propulsion subsystem as described by Holbrook, Rayburn, Miller & McCullough¹. Table 1 provides an overview of the final orbit characteristics that THEMIS is required to operate in order to map substorm activity in the magnetosphere.

Table 2: THEMIS Orbit Characteristics

Probe Designation #	Period (days)	Orbit Geometry		
		Perigee, Re	Apogee, Re	Inclination, Deg
1	4	1.6	34	3.9
2	2	1.2	19.9	9.8
3 & 4	1	1.6	11.6	7
5	0.8	1.3	13.1	12
Earth Radii (Re) = 6378 Km				

THEMIS Mission Instrument Suite

The THEMIS instrument suite is comprised of the Instrument Data Processing Unit (IDPU) which houses most of the electronics for the instruments on the THEMIS spacecraft: a Flux Gate Magnetometer (FGM), an Electrostatic Analyzer (ESA), an Electric Fields Instruments (EFI), Search Coil Magnetometer (SCM), and the Solid State Telescope (SST). In total there are eleven instruments in addition to the IDPU that are integrated onto each Probe. The entire instrument suite mass is approximately 26 kg and consumes 15.3 Watts orbit average power. All the instruments are designed to be magnetically clean and to minimize exposed insulators on their external surfaces (externally mounted on the Bus). Figure 2 provides an illustration of the instrument suite in the stowed configuration with outline of the probe bus structure. Additional information can be found on University of California, Berkeley's website located at <http://themis.ssl.berkeley.edu/instruments.html>.

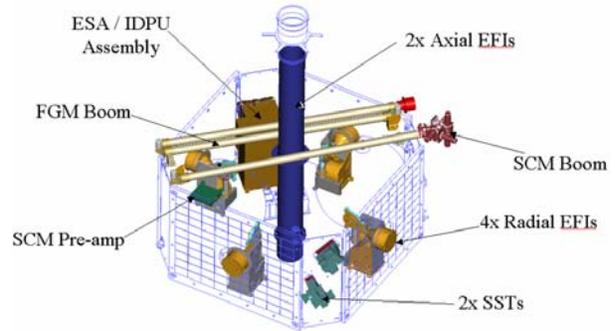


Figure 2: THEMIS Instrument Suite Stowed Configuration (Courtesy UCB)

Overview of the THEMIS Bus Subsystems

Figure 3 provides a view of the exterior and interior of the spacecraft bus with the instruments stowed. A simplified overview of the THEMIS Bus architecture is shown in Figure 4.

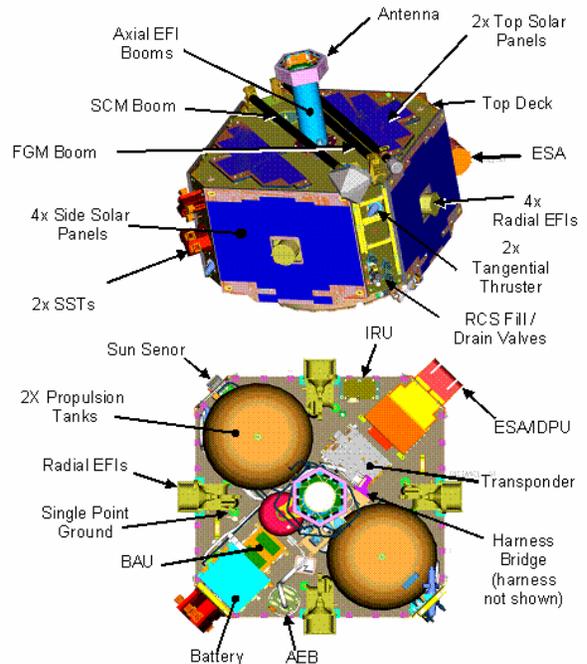


Figure 3: Spacecraft Exterior and Interior Views

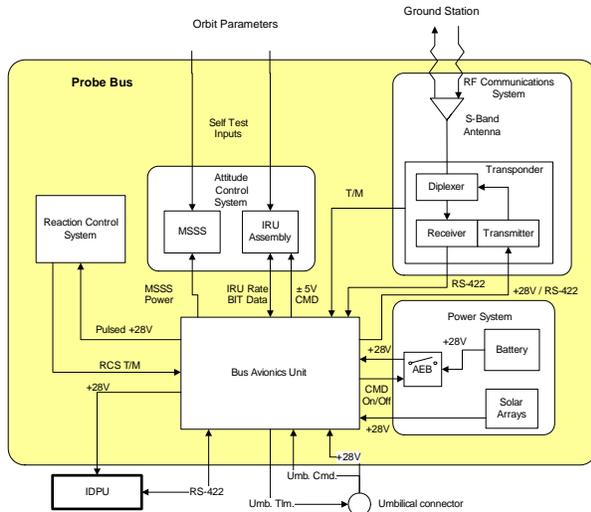


Figure 4: THEMIS Bus System Architecture

THEMIS Mission Driving Requirements

Bus Design – Volume Constraints

The THEMIS Probes have a high internal packing density as a result of the volume constraints imposed by Delta II launch vehicle fairing and the minimum clearance required between the Probes and Probe Carrier. The deployment of the Probes from the Probe Carrier, while attached to the third stage is facilitated through a marman band system that uses a common pyro system initiated from the third stage. The first Probe is released and three seconds later the four remaining Probes are released. The static clearances were originally set based on the preliminary deployment analysis of the Probes from the Probe Carrier. The deployment analysis was refined throughout the design and test lifecycle based on extensive separation system testing and the evolution of the mass properties. The validation analysis of the full-up deployment system included more than 1,000 cases that varied numerous parameters in order to assure that there was adequate clearance margin under all deployment scenarios². Figure 5 provides an illustration of the deployment model used in the verification analysis.

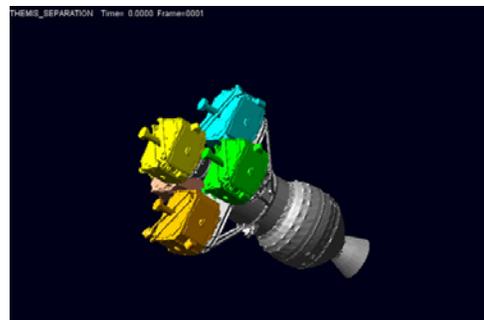


Figure 5: Deployment Model

Bus Design – Mass and Power Constraints

As with most small satellite designs, mass and power are a premium resource that need to be managed with great diligence. The mass of the probe bus was not dictated by the launch vehicle throw weight since there was ample mass margin for the Probe Carrier Assembly (five probes and probe carrier) on the Delta II. The mass requirements were driven by the individual delta-v requirements (> 900 meters/sec) for the largest apogee orbit. Mass was managed aggressively by UCB and ATK Space throughout the design cycle, which resulted in minimal mass growth. In fact, the total mass growth on the mission from the Phase A study through final weighing, excluding the delta-v enhancements, was less than 15% for the Bus and Instruments combined. A discussion of the challenges posed to the structural design is provided in Eppler³. Table 3 provides the summary of the masses for the bus subsystems prior to shipment to UCB for instrument integration and mission testing.

Table 3: Bus Dry Masses

Bus Subsystem/Hardware	Mature Mass (kg)	% of Total
Prime Structure (excludes arrays)	11.03	21.47%
Secondary Structure and Miscellaneous Hardware	2.62	5.10%
Separation Ring	2.00	3.89%
Propulsion	12.20	23.75%
ACS Sensors (IRU Assembly & Sun Sensor)	0.61	1.19%
Auxiliary Electronics	0.53	1.03%
Bus Avionics Unit (BAU)	3.02	5.88%
S-Band Antenna Assembly	0.65	1.26%
S-Band Transponder	2.58	5.02%
Battery Assembly	3.27	6.36%
Bus Harness	3.24	6.31%
Solar Panels (8 per Bus)	6.53	12.70%
Thermal	2.17	4.23%
Bus Spin Balance Masses	0.94	1.82%
Total Mass (kg)	51.40	100.00%

As discussed earlier, the probe bus power limitations were highly constrained, primarily attributed to the relatively long eclipses for the 24 hour orbit. This resulted in a highly constrained power budget that was managed aggressively by both UCB and ATK Space. A number of power consumption techniques were used to lower consumption on the Bus side. The Bus Avionics Unit (BAU), which houses the Bus flight computer, communication subsystem interface, and the power control electronics incorporated the following power saving techniques⁴:

- Maximized the use of low power devices (3.3v supply) wherever possible
- Matched processor speed to FSW throughput requirements
- Powered down EEPROM devices when not being used
- Utilized high efficiency switching power supply design
- No opto-isolation to save power, increase reliability

These power consumption optimization techniques were major enablers for the THEMIS mission. The totally passive Bus Thermal design was also optimized to reduce the power load of heaters during eclipses. The Thermal subsystem is one area where the program realized power consumption growth predominately due to heater power requirements. Regardless, both ATK Space and UCB managed power extremely effectively throughout the design cycle.

Thermal Requirements and Design

The THEMIS requirements posed many challenges for the Thermal Control System (TCS). One of these challenges was minimizing heater power consumption during 180 minute shadows using passive techniques. Because of the small size Probe, the body mounted solar arrays were limited in area and hence limited the power available for heating components, such as the hydrazine Reaction Control System.

To minimize heater power consumption during 3-hour long eclipses and off-nominal attitudes, the THEMIS TCS design utilized high efficiency MLI blankets, customized ULTEM isolators, and high absorptivity to emissivity ratio coatings (Vapor Deposited Gold). These passive design aspects allowed for a worst case cold orbit average heater power of 11 Watts while maintaining temperature limits in the worst case hot orbit.

Magnetic cleanliness and surface charging requirements also created challenges for the TCS in that it limited the pool of thermal control materials from which to choose from. And to meet these requirements, unique methods and procedures had to be implemented as mentioned in the following sections.

Figure 6 demonstrates the thermal design.

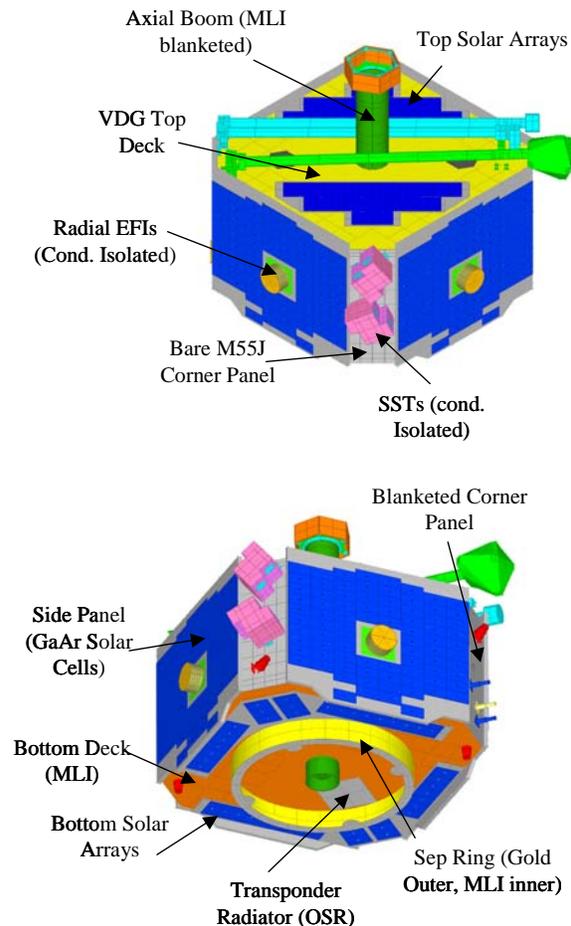


Figure 6: THEMIS Thermal Design

Magnetic Cleanliness Requirements

The magnetic requirements were a mission essential requirement and had a major impact on the THEMIS bus design, integration, and test program. The THEMIS team had to assure and verify, early in the design cycle, the magnetic cleanliness of the subsystems and components to ensure DC and AC magnetic experiments can reliably observe the magnetic field. The magnetic requirements for the THEMIS mission were driven by the two magnetometer instruments aboard each of the spacecraft: Search Coil

Magnetometer (SCM) on a 1 meter deployable boom and a Fluxgate Magnetometer (FGM) on a 2 meter deployable boom. The requirement for static DC magnetic field generated by the spacecraft components and subsystems was not to exceed 5nT at 2 meters from the spacecraft corresponding to location of the deployed FGM. The spacecraft DC stability requirement was less than 0.1nT over a 12 hour period. These requirements demanded a rigorous magnetic deperm program throughout the integration and test program as well as an integrated design effort by the design teams to minimize local magnetic fields produced by the bus components. In process part magnetic testing was performed prior to bus level integration. The data was stored in the THEMIS magnetics directory developed by UCB. A Magnetics Control Board was held during the course of the design and integration phase and consisted of the Mission Systems Engineer, the Principal Investigator, and the Spacecraft Systems Engineers. In addition, the minimization of stray electric fields were implemented by the design of probe wiring magnetic cancellation techniques such as twisted leads, shielded wires, and current loop cancellation paths. Bus components, which were directly effected by the requirements in regards to wiring methodology, were the BAU, Harness, Battery, Solar Arrays, Heaters, and Thermostats. Magnetic field measurements were taken during the entire integration effort: at the component level prior to integration, subsystem level, bus level, and ultimately at the integrated spacecraft level. UCB test verified the magnetic requirements at JPL during the environmental test program and the fully configured satellites had measured values well below these requirements.

Surface Charging Requirements

Due to the need to measure the ambient electric fields, as well as charged particle fluxes, the electrical potential of all external surfaces was a major influence on the spacecraft design. The primary driver was the length of the axial booms, since they were the closest electric field instruments to the spacecraft body. A detailed analysis was performed by UCB to develop the surface charging requirements, which limited the voltage potential between any two points to 1 volt, with a 0.1V goal (in an 8 nA/m² flux). This, in turn, resulted in a derived requirement that all exposed insulator area be limited to no more than 1 cm² on the external surface of the spacecraft. These requirements posed a significant challenge to the program since they dictated the surface resistivity of all the external coatings, including the thermal blankets, thermal coatings, radiators, composite structures, solar arrays and antenna. All of the thermal blankets required a germanium black kapton outer layer with multiple

ground wires. All tapes were electrically conductive and grounded using conductive adhesives or folded ground tabs. The composite structure was also grounded with conductive adhesives and ground wires. The solar array design required ITO coated coverglasses that had to be connected to ground. No solar array wires or RTV were left exposed. The transponder radiator mounted to the bottom deck required ITO covered Optical Solar Reflectors (OSRs) incorporating metalized edges and conductive epoxy for grounding. The S-Band antenna was affected since the stacked patch design had an external dielectric that had to be covered with a conductive ITO coating. These design changes resulted in various degrees of impact in both performance and validation activities. External surface resistance measurements had to be performed throughout the integration effort to assure the requirements were being met, and in several cases led to design or process changes. In the end, not only were the requirements met, but the design goal of 0.1V potential was also met leading to a robust surface charging design that will enable the Electrical Field Instruments to meet all science measurement objectives.

System Safety Requirements

Throughout the design, integration, and test of the THEMIS spacecraft, system safety requirements were implemented where each hazardous or potentially mission catastrophic element, such as inadvertent thruster firing, was provided a two-fault tolerant design. Many of the inhibits were two-fault tolerant, both electrically and mechanically. Inhibit enable switches were applied in the Bus Avionics Unit and the RF Subsystem. A health and safety monitoring function is provided by the flight software, which monitors telemetry points, memory addresses or I/O ports, and initiates predetermined responses upon detection of a constraint violation.

ADAPTATIONS OF THE THEMIS PROBE BUS TO OTHER POTENTIAL MISSIONS

The THEMIS Probe Bus is adaptable to other instrument suites and missions environments. The packaging of the bus subsystems and the mechanical subsystem allow for additional mass attachment points. Additional adaptability features are described below.

The THEMIS bus provides the necessary housekeeping and performance to interchange instruments suites or payloads through the Bus Avionics Unit interface. The THEMIS Bus contains built-in limit monitoring and detection that is tailored to the requirements of the

THEMIS mission. These limits can be reprogrammed through the BAU Electrically Erasable Programmable Read-Only Memory (EEPROM) and FSW interface to provide the limits applicable to the next mission. Relative Time Sequence (RTS) can be uploaded into the BAU EEPROM in conjunction with a specific limit monitor to provide safe, autonomous fault detection and correction.

The passive thermal design allows the spacecraft to survive in a wide range of thermal environments including LEO, GEO, and HEO orbits. The thermal design also minimizes heater power consumption during 3 hour shadows and off-nominal attitudes (0 to 180 degrees).

The THEMIS constellation design demonstrates how multiple, essentially identical, satellites can be managed by using a simple ID structure embedded in the Bus Avionics Unit. This sense of identical satellites with their own ID leads to the ability of communicating with multiple spacecraft in succession given that all THEMIS spacecraft are tuned to the same S-band uplink and downlink frequencies. The spacecraft configuration management provides ground based position knowledge for multiple spacecraft.

Such scientific applications utilizing the THEMIS Bus could include heliospheric applications enhancing the knowledge and science of the solar wind and its interaction with the Earth-Moon system, shocks, and interplanetary disturbances such as coronal mass ejections.

Space Weather

The constellation of five THEMIS probes are ideally suited to provide data on space weather since they can provide identical electric, magnetic, and particle measurements at different points in space, throughout the whole magnetosphere (reference Figure 7). If multiple launches of THEMIS spacecraft were performed it would be possible, with the proper orbits, to create a real-time map of all field and particle flows at tens of points within and outside the magnetosphere, which could be used to feed real-time models of the solar wind and the terrestrial magnetic field. The THEMIS spacecraft are uniquely suited to this purpose. They are relatively inexpensive to re-build, can be launched five at a time, have enough on-board fuel to allow them to be placed in orbits throughout the magnetosphere, and are simple to maintain and operate.

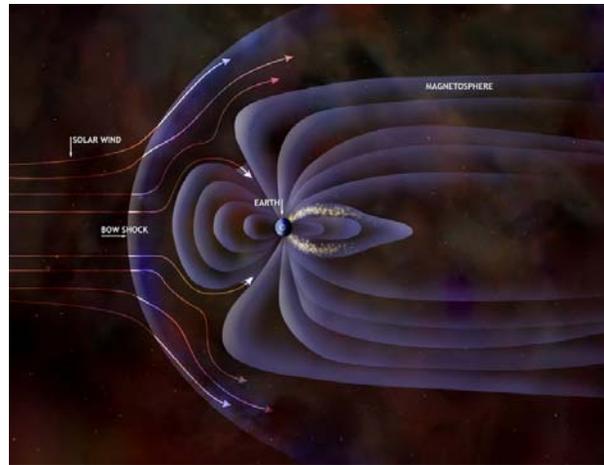


Figure 7: The Earth's Magnetosphere
(Courtesy NASA)

Instead of always approaching the study of space weather and plasma dynamics with one-of-a-kind spacecraft and instruments (Wind, Polar, Cluster, etc.), more data for science could be gathered if successful tools (THEMIS Probes) were re-used to gather data at more locations in space and time, instead of efforts being expended in engineering new tools.

Spin stabilized, high delta-V capability THEMIS-derived spacecraft can provide a generic platform for space weather studies at Earth and upstream. Directly upstream from Earth's bowshock, about 30Re apogee, the probes can provide short-timescale advance warning of solar wind disturbances (10 min) but with high-fidelity. The probes can detect interplanetary shocks, determine structure, orientation, and geo-effectiveness, assuming that earlier warning systems from Solar-Surface (e.g., STEREO imaging, ~1 day) and L1 monitors (ACE, ~2hrs) are present to provide preliminary detection of threatening structures. With their high delta-V capability, THEMIS probes can utilize a lunar gravity assist and propel themselves to the L1 point, performing advance warning in addition to ACE and other assets, in particular in determining interplanetary shock orientation and scale-size. Through a second lunar swing-by it is possible to reach interplanetary trajectories and insert into orbits that monitor the solar wind near Earth's distance but at different longitudes. This permits correlation studies at various distances, as is done currently by STEREO. While STEREO's differential drift is optimized towards imaging, exploring correlations at multiple scale sizes together or in addition to STEREO is also important for in situ measurements of the interplanetary medium.

LUNAR SCIENCE INVESTIGATIONS

The inherent deep-space capability of the THEMIS spacecraft make them ideal candidates for a small, low-cost lunar orbiter mission designed to study the interaction and weathering of the lunar surface in the variable solar wind. Additional payloads optimized as technology demonstrations relevant to both scientific and human exploration objectives can easily be accommodated.

The interaction of the moon with the space environment constitutes a set of high-priority observations that are not addressed by other current or planned missions, and are of importance to both basic lunar science and the Vision for Space Exploration (VSE). Figure 8 shows the Moon immersed in the space environment, consisting of incoming solar plasma and illumination, solar energetic particles (SEPs) from solar coronal mass ejections (CMEs), terrestrial plasma in the Earth's geomagnetic tail, and meteoric influx. The lunar surface responds to these influences in a multitude of ways. Solar wind and energetic particles associated with CMEs can cause the ejection of neutrals and ions from the lunar surface, which then populate the lunar exosphere and ionosphere. One important process is ion sputtering; once generated, these "pickup" ions are

swept up by the solar wind electric field, where they can be detected by orbiting spacecraft. In addition to particle sputtering, the lunar surface responds to plasma and UV illumination electrically, becoming either positively or negatively charged. One consequence of lunar surface charging is the possibility for surface dust to become lofted in a dynamic process that may best be described as a lunar dust storm. The study of these processes is in some sense a description of lunar weather – in which the lunar surface responds dynamically to changes in ambient plasma and solar conditions. The study of these aspects of the lunar environment has both intrinsic science value as well as relevance to the VSE. Much is unknown regarding the distribution, composition, and temporal variability of the lunar exosphere, due to contamination effects generated during the Apollo missions and the intrinsic difficulties in performing remote observations. Once studied in detail, the exosphere may reveal details of the composition of the lunar surface, and of dynamic processes both external and internal to the Moon that influence it. While we have some observational evidence for dust fountains and "streamers" from Apollo astronaut observations, the properties and prevalence of lofted dust, as well as the candidate physical mechanisms for generating it are completely unexplored. The presence of dust, UV, and energetic particle radiation also has biological consequences.

These science objectives can easily be accomplished with a payload mass of 25 kg or less, and would include ion and electron electrostatic analyzers, electric and magnetic field instrumentation, an ion mass spectrometer, and a dust detector. Additional payloads examining the radiation environment at the moon would also be desirable, including energetic proton detectors for solar energetic particle events, and radiation monitors using both solid-state and biological samples to assess the environment from the perspective of future manned missions.

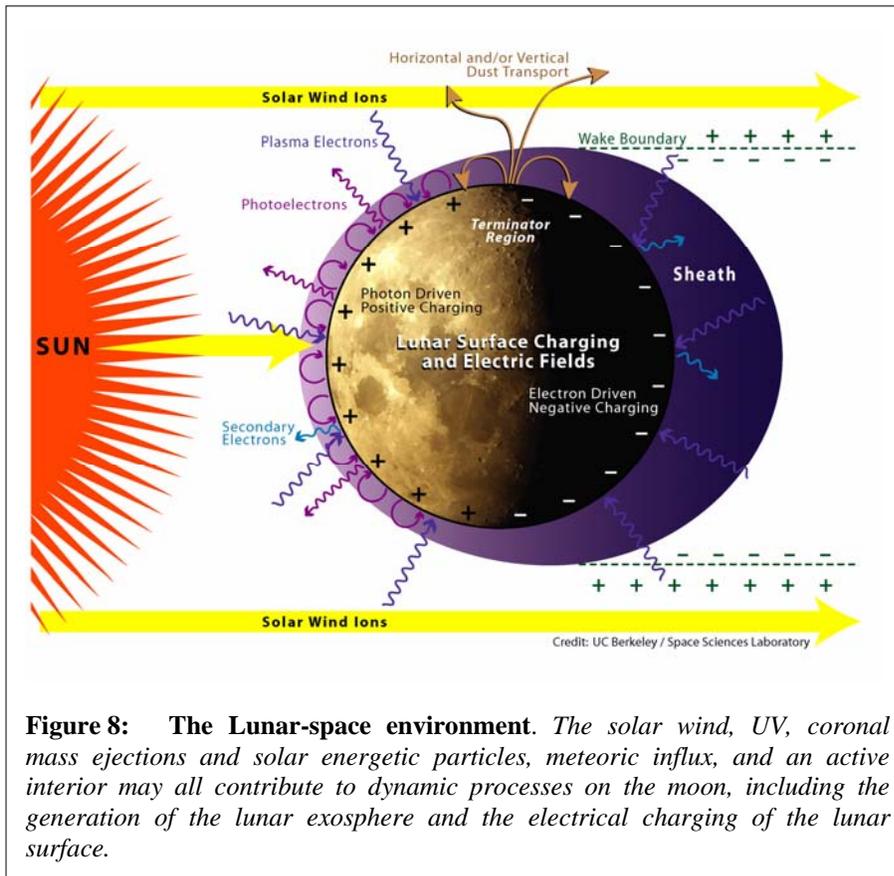


Figure 8: The Lunar-space environment. The solar wind, UV, coronal mass ejections and solar energetic particles, meteoric influx, and an active interior may all contribute to dynamic processes on the moon, including the generation of the lunar exosphere and the electrical charging of the lunar surface.

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