DARKNESS VISIBLE: INSTRUMENTATION AND THERMAL DESIGN TO ACCESS THE HIDDEN MOON

In poetic language, people often talk about "The Dark Side of the Moon," while their astronomical meaning is the "Far Side of the Moon." In this workshop, we are literally discussing the dark Moon – the entire Moon during the 14-day lunar night at the equator, and the regions of eternal darkness in polar craters that are rich in volatiles[1] which may be rich in volatiles for use as resources, and as a valuable record of the Moon's history. The dark Moon has been hidden for most of the history of spaceflight, as no human missions and few robotic missions have persisted through even one lunar night, and no missions whatsoever have landed in the permanently-shadowed regions. In this poster, we discuss "Night" mission concepts, previously developed by the authors with NASA funding, that remain directly relevant to NASA robotic and human science and exploration of the Moon - a long-lived (> 6 y) lunar geophysical network and a Discovery-class mission for the in-situ investigation of volatiles in the lunar polar cold traps. We also discuss Ball instrument and thermal technology enabling survival, situational awareness, and operations in the dark Moon, including low-light and thermal cameras, flash lidars, advanced multi-layer insulation (MLI), and phase-change material "hockey pucks" that can damp out thermal transients to help moving platforms scuttle through dark regions for 24 h or so on their way between illuminated area such as "the peaks of eternal light" near the lunar south pole, without expending precious stored electrical power for heat.

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"NIGHT" CONCEPTS

Two "Night" mission concepts were previously developed by the authors with NASA funding during the previous epoch of interest in a return to the Moon. They remain directly relevant to NASA robotic and human science and exploration.

INTERNATIONAL LUNAR NETWORK (ILN)

Lunar Geophysical Probe Features

- Long life and power (at least 6-7 years)
- Withstands diverse and harsh environments of the lunar surface
- Generic yet highly flexible probe that can easily be adapted for use with a variety of mission scenarios anywhere on the lunar surface.
- Probe deployment and regolith penetration options
- Mission enabled by an advanced radioisotope thermoelectric generator

Instruments

- Seismometer – drives requirement to survive for 6 year lunar tidal cycle
- Heat flow probe -- also requires many months to re-equilibrate after probe emplacement
- Magnetometer

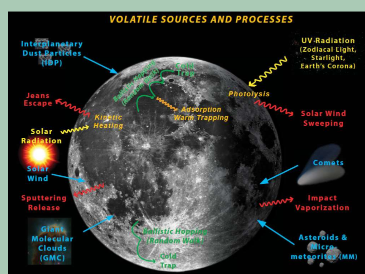
FINDINGS

- Energy density of Li-ion batteries is higher than that of phase change materials (Ulamec+ 2010) – it's just that electricity is a more costly form of energy than heat!
- 2 W load requires ~15 kg of Li-ion batteries + solar array mass to survive the night

EXOMOON

Exomoon Objectives

- Use a lunar permanently shadowed region (PSR) cold trap as a historical record of volatiles entering the inner solar system over the last 1-2 billion years
- Perform spatially distributed in-situ measurements of subsurface volatiles in a lunar polar cold trap
- Investigate volatile deposition, loss, and transport mechanisms over 1+ y



Exomoon: The Moon is a handy nearby collector of volatiles from around the Solar System and Beyond

THERMAL MITIGATION

Ball has a long heritage of solving challenging thermal problems in space, including the Spitzer Space Telescope and the combined optical, thermal, and mechanical elements of the JWST optics. Ball is pioneering advanced multi-layer insulation (MLI) and distributed phase-change material "pucks" which could be useful for surviving the lunar night and reduce the need for nuclear energy.

ADVANCED MLI

- High performance: 37 % lower heat leak per layer
- Robustness: bonded polymer spacers creates a very rugged structure
- Performance predictable
- Enables effective insulation of thermal oasis[3] using heat capacity of *modified* lunar regolith
- Will fly on Green Propellant Infusion Mission (GPIM)
- Improved cryogenic propellant storage in deep space and on the surface of the Moon

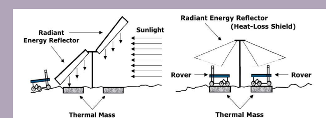
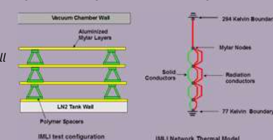


Figure from Balasubramaniam+[3]

The effective thermal storage capacity of the natural regolith is low because of the low thermal conductivity – only the top 10-20 cm experience diurnal change → requires enhanced heat transfer (nails, sintering, etc.), huddling near boulders, or filling water bottles

Ball Advanced Integrated MLI 20-layer blanket on left, conventional MLI 20-layer sample on right, shows inherently low layer density.

Schematic of Ball Advanced MLI



PHASE-CHANGE MATERIALS

- "Pucks" can smooth out temperature changes for ~24 h excursions from illuminated to shadowed areas during the lunar day.
- Pucks can add heat capacity to components to reduce thermal shock at sunrise/sunset
- Pucks can locally stabilize temperature on system extremities without a complex thermal distribution system from an intense point source of heat (RHU).
- Example material: Phase Change Energy Solutions (phasechange.com) markets products with melting points of -20 C and -40 C– typical cold operating and survival temperatures of electronics -- and a heat of fusion of 230 kJ/kg.

Example "hockey puck" application in a flight system

SEEING IN THE DARK

Ball has a 30+ year history of building thermal, low-light, and active illumination instrumentation for Earth and space science, spacecraft rendezvous operations, and national defense applications.

LOW-LIGHT AND HIGH DYNAMIC RANGE

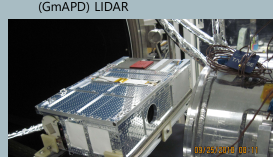
Using patented Enhanced Automatic Gain Control (E-AGC) and Anti-Blooming (ABT-21) image enhancement technologies, Ball's RS-170 cameras provide high-resolution visible and near-infrared images under lighting conditions from daylight to overcast night.

THERMAL

CIRiS (Compact Infrared Radiometer in Space) is a Ball radiometric infrared imager designed for a 6U CubeSat spacecraft which uses uncooled bolometers for a low power (<10 W), low mass (<2 kg), and sensitive (<50 mK NEDT at 30 fps) instrument

- Carbon nanotube technology to provides stable, highly-accurate, rugged, and compact radiometric calibration
- Passed TVAC, will be launched to LEO in 2019
- Flexible design allows swap of blackbody and deep-space viewing ports for landed operations

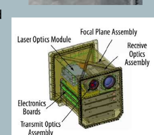
CIRiS is integrated in its 6U spacecraft and is currently under test in a thermal vacuum chamber. CIRiS text & images by D. Osterman (PI)/R. Schindhelm (BATC)



LIDAR

The Ball Vision Navigation Sensor (VNS) is a fully self-contained flash LIDAR system with a modular design that could be configured to land in a PSR or navigate into shadow or at night

- Demonstrated for landing and terrain relative navigation with helicopter flights over a simulated lunar terrain
- Ball algorithms calculated hazards and safe landing zones
- 256 x 256 pixel detector read at 30 Hz.
- Range 1 m to 5 km
- Orbital TRL 9 from STS-134 STORRM, Orion EFT-1, STP-H5 Raven
- For further advances, Ball is developing Geiger-mode avalanche photodiode (GmAPD) LIDAR



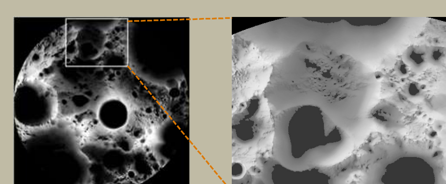
SHADOW AND NIGHT

Ball has demonstrated a variety of enhanced spacecraft and instrument capabilities in the lab and in flight to advance autonomy and control for spaceflight hardware, such as surface navigation in polar regions or shadow excursions elsewhere.

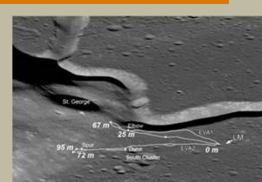
THE POLAR TWILIGHT

Left:100 m/pix LRO image WAC_POLE_ILL_TWI_SOUTH_100M showing the lighting conditions within 2 degrees of the south pole of the Moon[6].

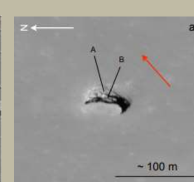
Right: Histogram-equalization scaled zoom showing twilight regions in upper center of right image (white box).



DARKNESS IS EVERYWHERE



Apollo 15 traverses near Hadley Rille. On the airless Moon, light and temperature drop suddenly when entering shadows.



Marius Hills skylight (303.3°E, 14.1°N) discovered by SELENE[5] and verified by GRAIL[4] and LRO[7]. NAC image M137929856R shown in [7]. Red arrow is sun azimuth. Note overhang.

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