BI-SAT OBSERVATIONS OF THE LUNAR ATMOSPHERE ABOVE SWIRLS (BOLAS): TETHERED SMALLSAT INVESTIGATION OF HYDRATION AND SPACE WEATHERING PROCESSES AT THE MOON.

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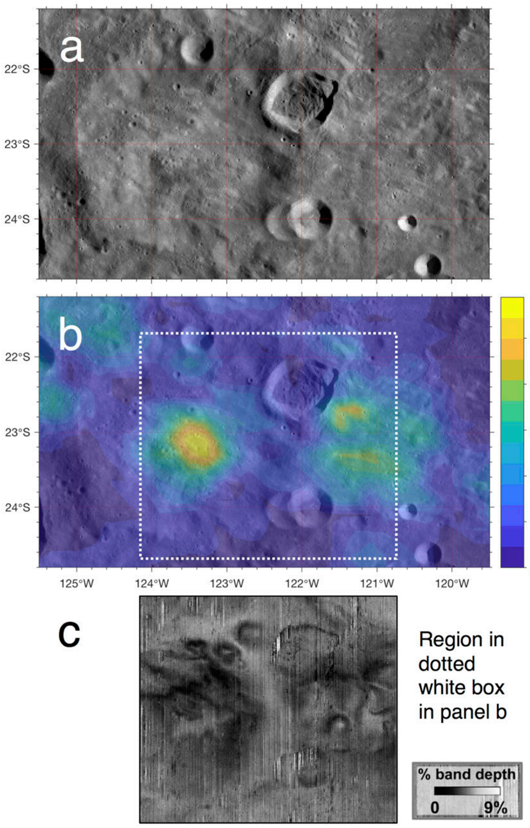
Introduction: Space weathering and hydration/hydroxylation of the lunar surface are fundamental processes for the Moon and other inner Solar System airless bodies [1, 2]. A thorough characterization of these processes is vital to our understanding of the evolution and origins of airless bodies, especially the production and transport of volatiles [3, 4]. At the Moon, space weathering of the surface regolith appears to be driven by the implantation of solar wind protons and meteoroid impacts, causing surfaces to darken, redden, and lose spectral features that could be used to constrain their mineral composition [1]. Recent spectral observations of hydroxyl absorption bands on the Moon indicate that solar wind protons react with oxygen-bearing minerals in the regolith to form OH, and possibly water [2]. In both cases, hydrogen from solar wind protons play a critical role, but the sources, sinks and pathways in the "lunar hydrogen cycle" remain poorly characterized.

Bright albedo "swirl" patterns on the lunar surface likely hold the key to our understanding of the lunar hydrogen cycle (Fig. 1a). Swirls are collocated with magnetic anomalies [5] (Fig. 1b) that appear to be able to shield the surface from solar wind protons and prevent darkening from space weathering [6], and hydroxylation [2] (Fig. 1c). Exactly how magnetic anomalies modify the flux and energy of the solar wind protons reaching the surface, and how this varies under different conditions, is not well understood. The critical interactions between the solar wind and magnetic anomaly occur at very low altitudes, which requires in situ measurments below 20 km, if not much lower [7].

The Bi-sat Observations of the Lunar Atmosphere above Swirls (BOLAS) is a Planetary Science Deep Space SmallSat Study (PSDS3) concept for a mission capable of making the repeated low altitudes measurements required in order to understand vital aspects of the lunar hydrogen cycle and space weathering.

Science Objectives: The BOLAS mission will investigate the lunar hydrogen cycle by determining:

i. the mechanisms and dynamics of lunar hydrogen implantation, and their dependence on surface composition, regolith properties, local topography, plasma conditions, time-of-day, and crustal magnetic fields;
ii. how this relates to the formation of lunar swirls, space weathering and the evolution of airless bodies.



Region in dotted white box in panel b

Fig. 1: The primary target for the BOLAS mission will be the Gerasimovich magnetic anomaly on the far side of the Moon [5], which exhibits extensive swirl patterns [11] (panel a), is predicted to have magnetic field strengths at the surface of several 100s of nT [12] (panel b), and observations of the 2.8 μm OH absorption feature reveal a relative absence of hydroxyl associated with the bright swirl features [2] (panel c).

Science Orbits: Most of the prominent swirls and storng crustal fields are within 30° of the equator, and the need to investigate diurnal changes, requires BOLAS to have a low inclination orbit. To make the necessary in situ measurements, BOLAS has to maintain an orbit that reaches low altitudes (~10 km). At such low altitudes, orbit lifetime is dictated by gravitational perturbation from lunar "mascons" – e.g., a 50 km circular orbit would only survive about 10 weeks – and propulsive orbit maintenance maneuvers require prohibitive fuel mass, especially for SmallSats. In order to capture the long term variations, such as those driven by annual meteoroid streams, it is desirable for a mission duration of one year, but a minimum of one month should capture the diurnal effects.

The solution to this problem has two parts: (i) employ two vertically-aligned tethered SmallSats in a gravity gradient formation where the array center-of-mass is in a stable lunar orbit [8], (ii) adopt a highly stable "frozen orbit" for the tethered array's center-of-mass, such that no station-keeping is required (similar to Lunar Reconnaissance Orbiter's extended mission).

A elliptical frozen orbit with a 30° inclination was discovered with periapsis altitudes ranging from 14.5 to 59.7 km (accounting for terrain height above the mean lunar radius) close to Gerasimovich – one of the Moon's strongest crustal field regions [5]. By using a 25 km long tether, the lower altitude SmallSat (BOLAS-L) has a closest approach to the Moon of about 2 km at periapsis and about 11.8 km above the Gerasimovich region. This orbit, stable in excess of one year, provides the spatial and temporal coverage required to address the science objectives, especially at Gerasimovich.

Science Payload: This consists of the following in situ detectors that leverage both ongoing development of miniaturized instrumentation and substantial flight heritage [8]: (i) ion spectrometers for measuring protons incident and reflected from the Moon and/or crustal fields; (ii) energetic neutral atom (ENA) imager to detect neutralized solar wind protons backscattered from the Moon (may also include an electron-detection mode); (iii) mini-magnetometer to measure ambient magnetic fields; (iv) plasma wave system (PWS) for measuring electron concentrations, but can also detect electric fields and dust impacts (interplanetary and exospheric). An ENA imager will only be placed on BOLAS-L since neutrals will not be effected by ambient electric and magnetic fields. As illustrated in Fig. 2, these crucial new measurements at high and low altitudes will enable the determination of the solar wind driver and lunar environmental response, respectively; especially important at magnetic anomalies.

Mission Architecture: The two BOLAS SmallSats will be very similar, each with a volume of ~0.04 m^3, the main difference being an ENA imager aboard BOLAS-L and the tether system [9] on the high altitude spacecraft (BOLAS-H). The architecture leverages experience and development from Lunar IceCube where possible. Each BOLAS SmallSat can operate independently with its own power system, propulsion (two Busek BIT-3 RF ion engines each), communication (Iris X-band transponder) and attitude control system (ACS). BOLAS is designed to launch attached to an EELV secondary payload adapter (ESPA) ring by means of a lightband, which will also facilitate deployment.

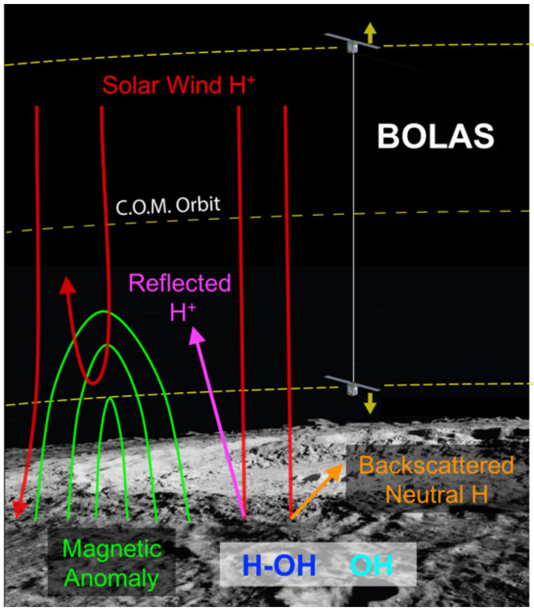


Fig. 2: The lunar hydrogen cycle processes to be investigated by the BOLAS tethered SmallSat mission.

Prior to the science orbit, the BOLAS SmallSats will be connected together by a lightband which will provide a small impulse when they separate and the tether is deployed. The tether itself will be made of the thinnest (125µm) commercially available high tenacity yarn, which will have a break load far in excess of the tension between the BOLAS SmallSats. The 25 km long tether will be braided into a Hoytether structure to provide multiple redundant load bearing paths to enable significantly greater survivability against any single strand being cut by a meteoroid or exospheric dust impact. The longest space tether to date was 20 km and deployed on the Small Expendable Deployer System (SEDS) I mission, while the Tether Physics and Survivability Experiment (TiPS) had a 4 km tether that survived a decade [10]. Both SEDS I and TiPS flew in Low Earth Orbit, whereas BOLAS would be the first planetary mission to employ the benefits of a tether system.

References: [1] Hapke (2001) JGR, 106, E5. [2] Kramer et al. (2011) *JGR*, 116, E00G18. [3] 2014 NASA Science Plan. [4] Crider &Vondrak (2000) JGR, 105, 26. [5] Blewett et al. (2011) JGR, 116, E02002. [6] Bamford et al. (2012) *ApJ*, 830, 146. [7] Fatemi et al. (2015) JGR, 120, 4719. [8] Collier (2016) *Acta Astron.*, 128, 464. [9] Hoyt et al. (2007) AIAA, SCC07-VII-8. [10] Carroll (1993) AIAA 93-4764. [11] LRO/WAC mosaic. [12] Tsunakawa et al. (2015) JGR, 120, 1160.