# Cubesat-based infrared lunar astronomy: In search of water-ice signatures

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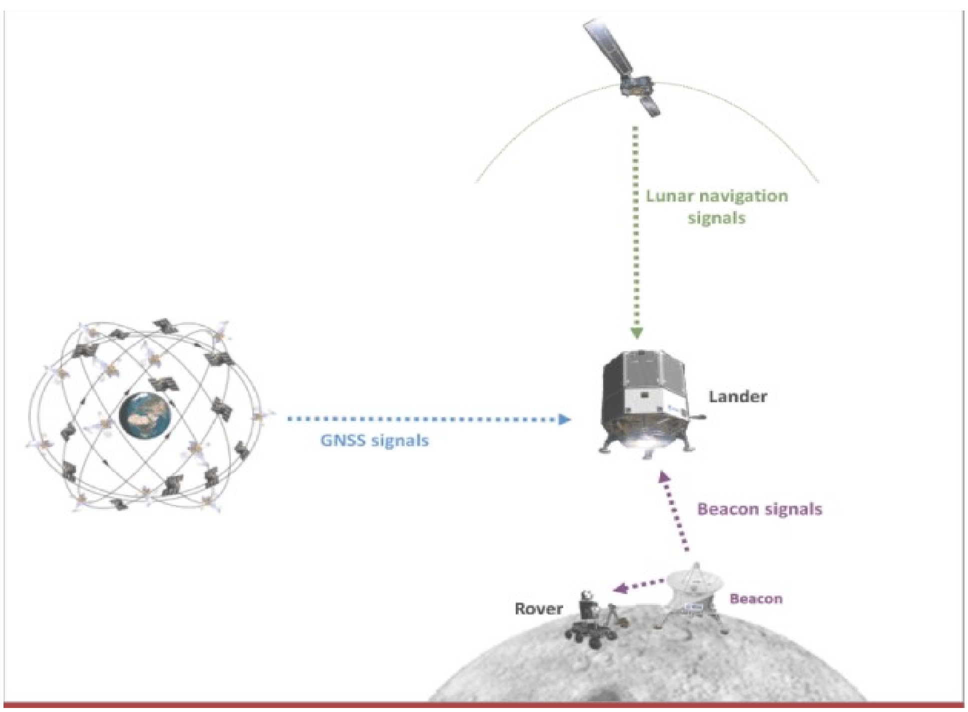
Abstract: The purpose of this paper is to explore the different water-ice signatures on the moon and the infrared technologies employed in their investigation by prospective cubesats intended Artemis payloads in the near future --- Lunar Flashlight, Lunar IceCube, and Lunar-H Mapper cubesat. Lunar orbit is one of the more thermally challenging environments in the solar system, with as much thermal flux coming from the surface as from the sun during lunar mid-day. Broadband (1 to 4 micron) InfraRed Compact, High- resolution Exploration Spectrometer, (BIRCHES)I,a miniaturized version of OVIRS (Osiris-Rex Visible InfraRed Spectrometer, will determine composition and distribution of volatiles in lunar regolith as a function of time of day for representative locations (up to 10% of the lunar surface) varying in latitude, regolith age and composition, and thus enable improved understanding of current dynamics of lunar volatile sources, sinks, and processes, with implications for evolutionary origin of volatiles. This paper was presented on March 02, 2022, at "Our Galactic Ecosystem: Opportunities and Diagnostics in the Infrared and Beyond" UCLA/ SOFIA Workshop (Lake Arrowhead, CA).
**Keywords**: water-ice volatiles, solar wind water, neutron spectroscopy, OASIS, SOFIA

## I. Introduction

Flying into the stratosphere at 38,000-45,000 feet puts SOFIA above 99 percent of Earth's infrared-blocking atmosphere, during which the10-hour overnight flights, allow astronomers at mid- and far-infrared wavelengths to gather data revealing chemical fingerprints of celestial molecules and atoms for the identification of complex molecules in space. On the other hand, **c**ubesat development and growing space mission applications are evolving signal a paradigm shift in interplanetary science. Positioned in a lunar orbit will provide not only imaging of the Moon's surface but communications with Lunar Reconnaisance Orbitor (LRO) for lunar-ground data transmission, as well as communications to lunar landers or rovers.



On the airless, lifeless Moon, the lunar regolith results from uniquely different processes—the continuous impact of large and small meteoroids and the steady bombardment of the lunar surface by charged atomic particles from the sun and the stars. Exposed rocks on the lunar surface are covered with impact craters whose diameters range from more than 1000 km to less than 1 μm. Superimposed on these mechanical processes are the effects of solar and cosmic particles that strike the lunar surface. At the very surface, dust particles form microcraters, and solar-wind atomic particles are trapped in the outer layers of regolith grains, while high-energy particles produce distinctive nuclear reactions to depths of several meters. The lunar regolith is the actual boundary layer between the solid Moon and the matter and energy that fill the solar system. Agglutinates are individual particles that are aggregates of smaller lunar soil particles (mineral grains, glasses, and even older agglutinates) bonded together by vesicular, flow-banded glass. Agglutinate particles are small (usually <1 mm) and contain minute droplets of Fe metal (much of which is very fine-grained, single domain Fe°), and troilite (FeS). They have probably formed by the melting and mixing produced by micrometeoritic bombardment of the lunar regolith. Some of the soil grains are melted, forming glass and liberating their implanted solar-wind H and He. The liberated H reacts with FeO in the glass, partly reducing it to metallic iron and producing some $H_2O$, which escapes from the glass [1].The vesicles are formed in the glass by the liberated solar-wind gases and possibly by the generated $H_2O$ as well. Analyses of infrared absorption spectra have identified water and hydroxyl (–OH) absorption bands at ∼3 μm within the lunar surface. Spatial distribution of the –OH signal suggests that water is formed by the interaction of the regolith-embedded solar wind with silicates and other oxides in the lunar basalt.

Utilizing available data sets on temperature-driven water formation and desorption from metal oxides (e.g., $SiO_2$, $TiO_2$, and $Al_2O_3$ with surface hydroxyl defects(-OH) and experimental data from a lunar mare regolith Apollo sample (10084), the 2.8 μm Optical signal on the Moon is modeled. Specifically, the presence and persistence of this band result from the balance of formation and loss mechanisms associated with solar wind production and thermal transformation of hydroxyls on and within the regolith. Though this mechanism forms gas-phase $H_2O$ on the sunlit side, photodissociation and photo dissociative adsorption lead to rehydroxylation and very limited exospheric water over a lunation.

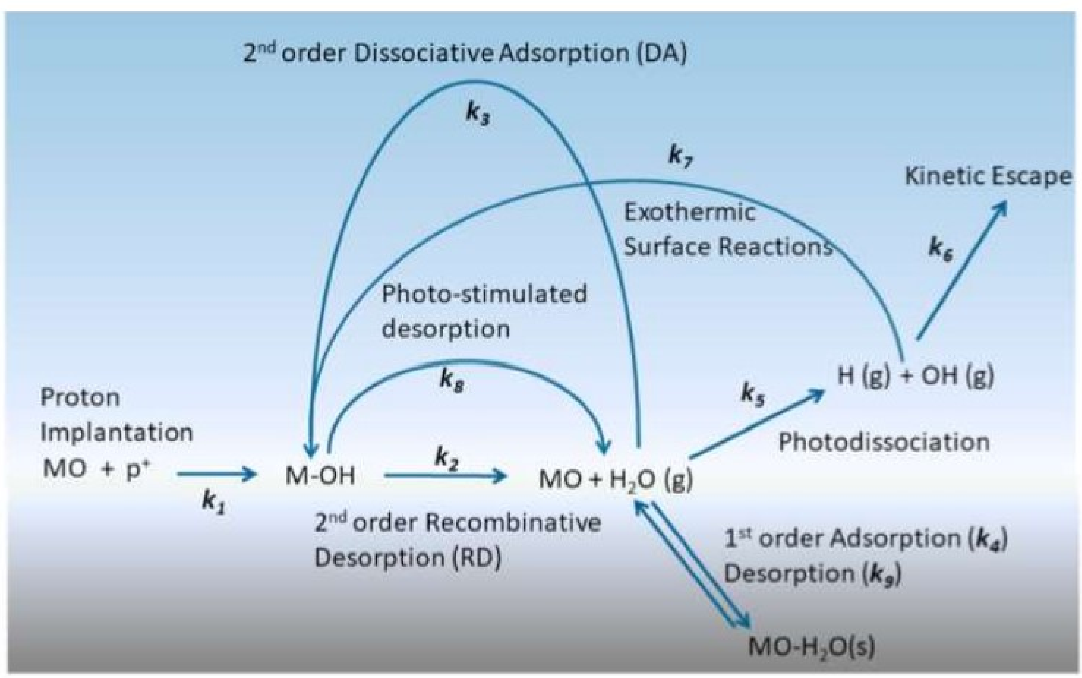



Figure. **Chemical Kinetics Model: Solar Wind-induced Water Cycle**

Remote infrared spectroscopic measurements of multiple missions have demonstrated abundance, location and transportation physics of lunar water ice lunar surface at a variety of latitudes—exospheric, surficial, and in permanently shadowed regions (PSR). The purpose of this paper is to explore the different infrared technologies employed in the prospective Lunar Flashlight, Lunar IceCube, and Lunar-H Mapper cubesat missions of NASA's Artemis Program.

Exposed to solar wind plasma, galactic cosmic rays, and secondary radiation due to the lack of a magnetosphere or a dense atmosphere, the moon undergoes intense space weathering of its regolith covered surface. When solar wind hits the surface, a fraction of it is reflected as protons [2] and as neutral hydrogen atoms [3]. Although it lacks a global magnetic field, the Moon possesses regions of local magnetization, referred as magnetic anomalies with magnetic field strengths of up to 100 nT where the solar wind is deflected at the surface [4]. Due to meteoroid bombardment, the original bedrock is covered by a fragmental layer of broken, melted debris from craters to form lunar regolith. Solar-wind atomic particles are trapped in the outer layers of regolith grains as high-energy particles produce distinctive nuclear reactions to depths of several meter [5]. Ionizing radiation on the Moon comes in the form of atomic particles from the solar wind, solar flares, and extrasolar high-energy cosmic rays. Each source contains a wide variety of atomic particles, mostly protons accompanied by an approximately "cosmic" distribution of heavier atoms. Solar-wind particles, with an average energy of 1 keV/amu, interact with the atoms in the target lunar grains [6] and become trapped [7]. The accumulation of solar-wind H enables subsequent chemical reduction of FeO in lunar materials involved in micrometeoroid impacts. Cosmic-ray protons and neutrons, sufficiently energetic (>1 GeV/amu) penetrate into lunar materials to depths of about 1 m producing nuclear reactions.

Infrared radiation is emitted by any object that has a temperature (ie radiates heat). So, basically all celestial objects emit some infrared. The wavelength at which an object radiates most intensely depends on its temperature. In general, as the temperature of an object cools, it shows up more prominently at farther infrared wavelengths. This means that some infrared wavelengths are better suited for studying certain objects than others. In these environments high-energy charged particles in space produce high-energy neutrons by their interaction with the spacecraft structural materials. With this objective in mind [8] developed was a phoswich detector for neutron spectrometry in a mixed field of neutrons and charged particles. In the detector, two organic scintillators of different light-output decay times were coupled, which could measure high-energy neutrons up to 130 MeV. The light decay time constants between the two scintillators discriminate pulses of the three different particle species – neutrons, gamma, and protons (n/γ/p). The Compton electron scattered by a gamma ray dissipates its energy only in the scintillator, and its signal displays a fast component of 3.7 ns. The neutron is detected via proton recoil that occurs in the scintillator has a slower decay time of 30 ns compared to the gamma-ray. The proton dissipates its energy in both scintillators, and its signal is much longer as it becomes the sum of the fast and slow components with a decay time of 225 ns for the slow component [9]. Broadband InfraRed Compact High Resolution Exploration Spectrometer (BIRCHES) provides cryocooling for broadband (1 to 4 micron) measurements, achieving sufficient signal-to-noise (>400) and spectral resolution (10 nm) through the use of a Linear Variable Filter to characterize and distinguish important volatiles (water, $H_2S$, $NH_3$, $CO_2$, $CH_4$, $OH^-$, organics) and mineral bands [10].

| Case | Lat | Time of Day hrs | Temp K | Total Signal/Reflectivity @ 3um photons/sec | | SNR | Band depth/PPM water | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 0.1 @ 1000 | 0.05 @ 500 | 0.01 @ 100 |
| 1 | 0 | +/-6.2 | 163 | 3254 | 2760 | 52 | 276 | 138 | 27 |
| 2 | 60 | 0 noon | 335 | 39045 | 26400 | 162 | 2640 | 1320 | 264 |
| 3 | 20 | +/-4.3 | 304 | 24279 | 20963 | 145 | 2096 | 1480 | 210 |
| 4 | 0 | 0 noon | 395 | 150777 | 52800 | 230 | 5280 | 2640 | 528 |

BIRCHES detect incoming radiation from light reflected off of the lunar surface, thermal emission from the lunar surface and thermal emission from detector surfaces. Absorption features was superimposed on the reflectance measurement. Radiometric plots, assuming 4 cm aperture and 6- degree field of view indicated that lunar surface emission does not become significant at temperatures within the instrument according to our thermal models until beyond the three-micron band. Emission from detector surfaces remains a minor component regardless of wavelength. In these models thermal emission may be removed as a function of wavelength. Moreover, for the three-micron band, adequate signal to noise ratio (SNR) permits absorption features even as long as water abundance is at the hundredths of a percent level or above (Clark, P., MacDowall, R., Farrell, W., Brambora, C., Hurford, T., Reuter, D., ... & Chapin, P. (2017). BIRCHES and Lunarcubes: Building the First Deep Space Cubesat Broadband IR Spectrometer).

The Lunar Flashlight (LF) will carry a novel instrument to quantify and map water ice harbored in the permanently shadowed craters of the lunar South Pole. The LF instrument, an active multi-band reflectometer which employs four high power diode lasers in the 1-2 µm infrared band, will measure the reflectance of the lunar surface near water ice absorption peaks[11].

Another novel instrument, the neutron spectrometer, remotely measures hydrogen abundance on lunar surface, and the existence of hydrogen abundance can be regarded as proof of the existence of water in a certain sense. The cosmic rays of the Milky Way interact with the surface of the moon to generate a stream of neutrons. After a series of elastic or inelastic collisions and other interactions with the nucleus of the planet's surface material, these neutrons will form a balanced energy spectrum on the planet's surface distribution. The energy spectrum usually has three ranges. Neutrons with energy greater than 0.5 MeV are collectively called fast neutrons, those greater than 0.5 eV and less than 0.5 MeV are collectively called superthermal neutrons, and those less than 0.5 eV are called thermal neutrons. Hydrogen atoms and neutrons have the same mass, so they have the unique ability to moderate neutrons. Among the three energy spectrum distributions, the hyperthermal neutrons are the most sensitive to the existence of hydrogen. If the hydrogen abundance in a certain area is high, the hyperthermal neutrons in that area will quickly lose energy and become thermal neutrons, so the neutron spectrometer can determine the hydrogen abundance in a certain area by measuring the decrease in the flux of superthermal neutrons (that is, the suppression of superthermal neutrons) and the increase in the flux of thermal neutrons degree. The superheated neutron flux is inversely proportional to the hydrogen content in the region. Scientists rely on this to determine the hydrogen abundance on the moon's surface, and then use the hydrogen abundance to vaguely judge the water ice content in the region.

## II. Methods and Results

A literature review of infrared findings of lunar characteristics was summarized to include challenges of their respective data collection. Inferences from the findings were elaborated, suggesting additional objectives for further investigation into lunar water-ice signatures. Infrared technologies being developed as payloads for prospective cubesat or rover deployment on the moon were described.

**Infrared Absorption Spectroscopy.**

Spectroscopic techniques are mandatory in experiments oriented toward astrophysical applications providing information on astrophysical objects obtained from remote observations with satellites and telescopes. Infrared spectroscopy is adequate to follow the vibrational modes absorptions in molecules, radicals and solids, and is used to identify and monitor physical and chemical evolution of interstellar ice mantles. The mantles often occur in interstellar regions opaque to probing by ultraviolet or visible (UV-vis) radiations [12].

OASIS science is targeting submillimeter and far-infrared transitions of H2O and its isotopologues, as well as deuterated molecular hydrogen (HD) and other molecular species from 660 to 80 µm, which are inaccessible to ground-based telescopes due to the opacity of Earth's atmosphere. OASIS will have >20x the collecting area and ~5x the angular resolution of Herschel, and it complements the shorter wavelength capabilities of the James Webb Space Telescope. With its large collecting area and suite of terahertz heterodyne receivers, OASIS will have the sensitivity to follow the water trail from galaxies to oceans, as well as directly measure gas mass in a wide variety of astrophysical objects from observations of the ground-state HD line.

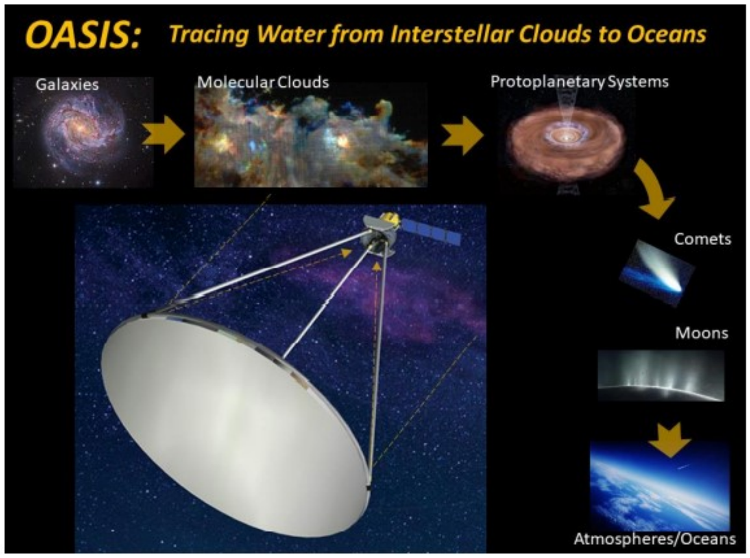



Figure 1. OASIS Concept. The science objectives of OASIS are met by utilizing a 17-meter inflatable aperture and cryogenic, terahertz receivers operating in a Sun-Earth L1 Halo Orbit. From this vantage point, the unparalleled sensitivity of OASIS will, for the first time, allow us to follow the water trail from galaxies to oceans.

The first evidence for water ice on the Moon came from observations of neutrons from the Lunar Prospector orbiter, where neutron flux spectra were interpreted as providing evidence for hydrogen in the form of water ice at the lunar poles. Direct evidence for hydration on the lunar surface was detected by the Moon Mineralogy Mapper (M3) on the Chandrayaan-1 orbiter, by the EPOXI mission during a lunar flyby, and by Cassini/VIMS during its lunar flyby en route to Saturn. These 3-mm observations showed a mixture of adsorbed water and OH in the lunar regolith. Next, a plume of water and water ice was detected by the LCROSS investigation following the impact of a Centaur rocket near the lunar South Pole.

## Water-ice lunar signature 1.

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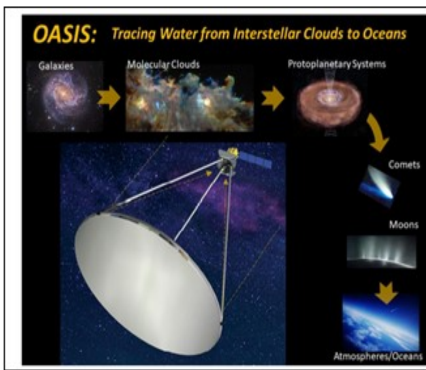


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Observations conducted from SOFIA detected $H_2O$ in the regolith at 6 microns at high lunar latitudes. Water generated from meteoroid impacts was expected to form a $H_2O$ exosphere. The Neutral Mass Spectrometer on the Lunar Atmosphere and Dust Environment Explorer (LADEE) detected exospheric $H_2O$ liberated by meteoroid impacts. The density and spatial variation of the lunar exosphere was unknown. The unique vantage point of OASIS at the L1 Lagrange point permitted high spatial resolution observations of $H_2O$ and OH in the exosphere of the

Moon, including the polar regions. OASIS targeted the 1.670 THz transition of $H_2O$ and the 1.838 THz line of OH. These observations helped determine whether sublimation of water ice contributes to the exosphere or, in contrast, whether the exosphere is present only following meteoroid impacts [13].

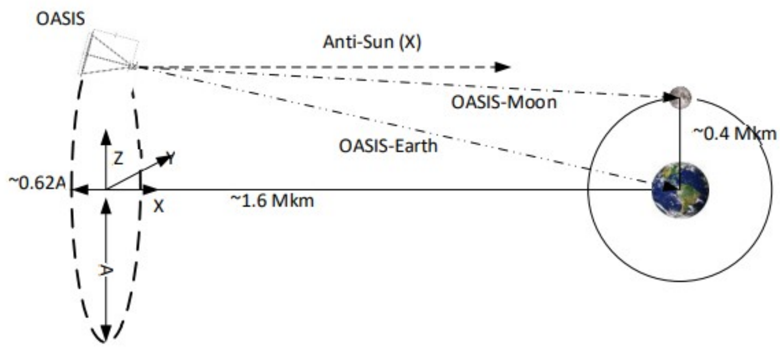


Figure. Sketch of the geometry of OASIS's Sun-Earth L1 halo orbit. (Note: drawing is not to scale)[14]

Ices in interstellar environments are traced almost exclusively by their molecular vibrational transitions in the near- to far-infrared. Most ice features are detected as pure absorption bands against infrared continuum point sources. Studies of the spatial variations of the ice properties are therefore relatively rare, yet very powerful. They often rely on the presence of many point sources (usually infrared-bright giants) behind clouds [15]. Ice mapping is however also possible if the background emission is extended by scattering from dust in any disk, envelope, or outflow cone [16]. New instruments on platforms such as the Stratospheric Observatory for Infrared Astronomy (SOFIA) and the Space Infrared Telescope for Cosmology and Astrophysics (SPICA) are needed to give access to the ice lattice modes (> 25 µm), which are particularly powerful tracers of the ice composition and thermal history. As they appear in emission, the ices may be mapped. The good understanding of the main ice bands allows them to be used as tools in the characterization of new sources that will be found with new infrared facilities [17] [18].

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**OASIS embraces an overarching science theme of "following water from galaxies, through protostellar systems, to oceans." This theme requires space-borne observations of galaxies, molecular clouds, protoplanetary disks, and solar system objects. From its Sun-Earth L1 halo orbit.**

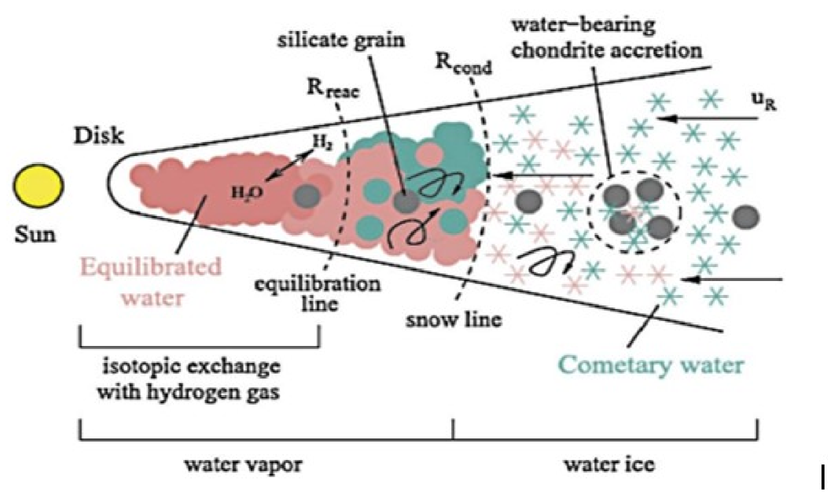


Figure 2. Illustration of the formation of a D/H gradient with heliocentric distanceOASIS will permit probing conditions across this gradient. Vertical mixing of ice grains to the photosphere of the disk where photodesorption and photochemistry produces atomic oxygen. This atomic oxygen is then transported downwards again where chemistry reforms it into H2O and HDO on ice grain surfaces but with much reduced deuterium fractionation (see for example becomes very important. The key process is mixing of ice grains to the surface of the disk.

**Stratospheric Observatory for Infrared Astronomy (SOFIA)**

From the discovery of water on the sunlit surface of the Moon to the detection of the first molecule to form in the infant universe, SOFIA explores a vast astronomical parameter space and reveals water on the sunlit surface of the Moon that complements NASA's multi-mission investigations of the mineral content and history of volatiles on planetary surfaces. Studying lunar water remotely with SOFIA is critical for future NASA missions of Volatiles Investigating Polar Exploration Rover (VIPER) mobile robot and the Artemis program returning humans to the Moon by 2025. Directly related to the SOFIA studies are several CubeSats planned for launched with Artemis 1 — Lunar IceCube, Lunar Flashlight, and LunaH-Map — that will help investigate the possible presence of lunar water-ice.

**Infrared Telescopic Scientific Findings and Challenges**

A literature review of infrared findings of lunar characteristics was summarized to include challenges of their respective data collection. Inferences from the findings were elaborated, suggesting additional objectives for further investigation into lunar water-ice signatures. Infrared technologies being developed as payloads for prospective cubesat or rover deployment on the moon were described.

| **Infrared Telescopic Scientific Findings** | ***Infrared Telescopic Challenges*** |
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| Remotely sensed infrared spectra come from the very top of the lunar regolith; in fact, from depths of no more 1 mm. Heat flow measurements were made with sensors that were emplaced in the regolith. | *At the resolution of these methods (>1 km2), the lunar surface appears totally covered with regolith.* |
| Agglutinates contain an appreciable amount of metallic Fe° in their glass, which has formed by the reduction of Fe-silicates in the soils. Because agglutinates are continuously produced by micrometeoroid bombardment at the surface of the regolith, the agglutinate abundance in a soil increases with time and is directly proportional to its cumulative exposure age Diagnostic absorption bands are present in the visible and infrared spectra of lunar rocks | *Both the Fe° metal and the glass in the lunar soil obscure and modify infrared and X-ray fluorescence signals from the other soil phases, thereby complicating the mapping of the lunar surface, especially with orbital and Earth-based remote sensing. These bands are subdued in the reflectance spectra from the regolith because of the regolith's high content of dark, absorbing agglutinates* |
| Remote infrared spectroscopic measurements have recently re-opened the possibility that water is present on the surface of the Moon. Analyses of infrared absorption spectra obtained by three independent space instruments have identified water and hydroxyl (–OH) absorption bands at ~3 µm within the lunar surface. | *Findings not consistent with experimental results in lab. Bi-directional infrared reflection absorption spectra do not show any discernable enhancement of infrared absorption in the 3 µm spectral region following 1 or 100 keV proton irradiation at fluences between $10^{16}$ and $10^{18}$ ions $cm^{-2}$. Post-irradiation spectra characterized a decrease in the residual O–H band within both anorthite and ilmenite. Similarly, secondary ion mass spectrometry showed a decrease rather than an increase of the water group ions following proton bombardment of ilmenite.* |
| Upper limit for the production of surficial –OH on the lunar surface by solar wind irradiation to be 0.5% (absorption depth). Reported band depths (3–14%) of lunar OH/water cannot result from solar protons. | *Absence of significant formation of either –OH or $H_2O$ is ascribed to the preferential depletion of oxygen by sputtering during proton irradiation, which is confirmed by post-irradiation surface analysis using X-ray photoelectron spectroscopy measurements. Results provided no evidence to support the formation of $H_2O$ in the lunar regolith via implantation of solar wind protons as a mechanism responsible for the significant O–H absorption in recent spacecraft data.* |
| Mature materials such as rock and regolith were found along the Yutu-2 rover's route. Te regolith was more mature than the surrounding rocks. Moreover, Diviner IR radiometer was only able discern lunar surface temperature brightness(Tbr) profiles vs microwave's penetrative assays of Tbr correlated to dielectric constants for FeO and $TiO_2$ lunar regolith content.. | *Space weathering introduces changes to visible and near-infrared reflectance spectra because the moon is an airless body, its surface is altered through irradiation by solar wind and galactic cosmic rays, a process that reduces the strength of mineralogical absorption bands, including the mafic minerals pyroxene and olivine.* |


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NASA's Lunar Crater Observation and Sensing Satellite (LCROSS), the Lunar Reconnaissance Orbiter (LRO) and India's Chandrayaan-1 lunar orbiters and other missions discovered in 2009 both water ($H_2O$) and hydroxyl (—$OH^-$) deposits at high latitudes on the lunar surface, indicating the presence of trace amounts of adsorbed or bound water are present [19].

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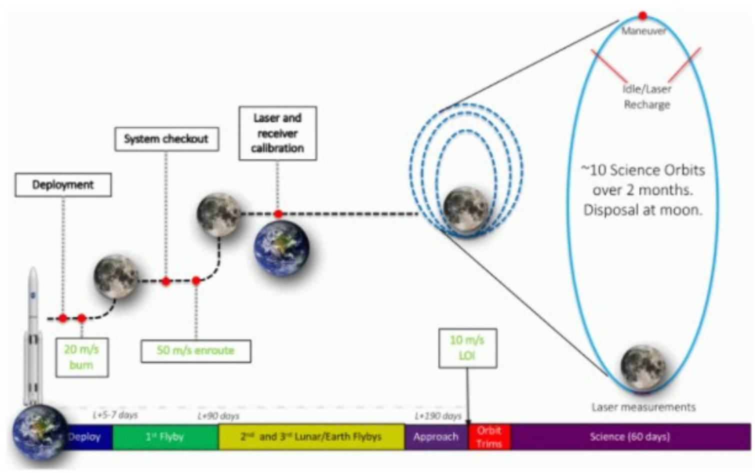
One hypothesis, based on the spatial distribution of the –OH signal, is that water is formed by the interaction of the solar wind with silicates and other oxides in the lunar basalt. To test this hypothesis, a series of laboratory simulations examined the effect of proton irradiation on two minerals: anorthite and ilmenite. Bi-directional infrared reflection absorption spectra did not show any discernable enhancement of infrared absorption in the 3 μm spectral region following 1 or 100 keV proton irradiation at fluences between $10^{16}$ and $10^{18}$ ions $cm^{-2}$. In fact, the post-irradiation spectra characterized a decrease in the residual O–H band within both minerals. Similarly, secondary ion mass spectrometry showed a decrease rather than an increase of the water group ions following proton bombardment of ilmenite. The absence of significant formation of either –OH or $H_2O$ was ascribed to the preferential depletion of oxygen by sputtering during proton irradiation, which was confirmed by post-irradiation surface analysis using X-ray photoelectron spectroscopy measurements. No evidence supported the formation of $H_2O$ in the lunar regolith via implantation of solar wind protons as a mechanism responsible for the significant O–H absorption in recent spacecraft data [20].

**Lunar Flashlight,** a 6U cubesat, will use near-infrared lasers to shine light into shaded polar regions near the south pole to detect volatiles on the moon. Meanwhile, an onboard reflectometer carried by the briefcase-sized orbiter will gauge surface reflection and composition. A ground data system will plan the instrument observations and process the data. The goal of Lunar Flashlight is to determine the presence or absence of exposed water ice and its physical state, and map its concentration at the 1-2 kilometer scale within the permanently shadowed regions of the lunar south pole. The mission will be one of the first CubeSat to reach the Moon, and the first mission to use lasers to look for water ice [21]. Any polar volatile data collected by Lunar Flashlight could then ensure the most appropriate landing sites for a more expensive rover to perform *in situ* measurements and chemical analyses [22]. The spacecraft will maneuver to its lunar polar orbit and use its near infrared lasers to shine light into the shaded polar regions, while the on-board spectrometer measures surface reflection and composition.



Mission profile and timeline for Lunar Flashlight. Image via Cohen et al./ IEEE.

Lunar Flashlight will beam its lasers into some of these craters where the ice is either known or suspected to exist. It will do this for at least two months, and will be able to map out where deposits are with great accuracy.
The spacecraft's four-laser reflectometer uses near-infrared wavelengths in the laser beams, which are absorbed by water ice. Bare rock simply reflects back to the spacecraft. If there were a lot of absorption in a crater, that would be evidence for widespread ice deposits. Those findings will then be compared with those from other orbiters that have previously found ice on the moon. Comparisons with great data already obtained from other moon-orbiting missions will show correlations in signatures of water ice or not, thereby a global view of surface ice distribution.

| SPECTRAL REGION | WAVELENGTH RANGE (microns) | TEMPERATURE RANGE (degrees Kelvin) | WHAT WE SEE |
|---|---|---|---|
| Near-Infrared | (0.7-1) to 5 | 740 to (3,000-5,200) | Cooler red stars<br>Red giants<br>Dust is transparent |
| Mid-Infrared | 5 to (25-40) | (92.5-140) to 740 | Planets, comets and asteroids<br>Dust warmed by starlight<br>Protoplanetary disks |
| Far-Infrared | (25-40) to (200-350) | (10.6-18.5) to (92.5-140) | Emission from cold dust<br>Central regions of galaxies<br>Very cold molecular clouds |

**Lunar IceCube**

The primary science goal of the Lunar IceCube mission is to investigate the distribution of water as a function of time of day, latitude, and regolith composition in the context of lunar mineralogy. While Chandrayaan M3 provided a 'snapshot' mosaic of the lunar nearside, indicating surface coating of OH/H2O near the poles, Lunar IceCube will provide coverage of the same swaths as a function of latitude at several times of day. Lunar Ice Cube will extend evidence for diurnal variation in OH absorption provided by Deep Impact and other C-, H-, O-, and S-bearing volatiles provided by LCROSS through geospatial linkage. Lunar IceCube will include the Broadband InfraRed Compact High Resolution Exploration Spectrometer (BIRCHES) needed to distinguish forms of water, including ice. Working together as the first "ad hoc" constellation of interplanetary CubeSats exploring the Moon, Lunar IceCube, Lunar Flashlight and LunaH-Map have the potential to lend significant insight into the location, depth, cyclic nature and transport mechanisms of water on the Moon. The 13 secondary payloads to be deployed on Artemis 1, including Lunar IceCube, will usher in a new era of solar system exploration with small satellite platforms.

The broadband measurements from BIRCHES encompass the three micron region and sufficient spectral resolution to discriminate OH from $H_2O$. The Lunar Ice Cube nearly polar, highly elliptical lunar orbit allows repeated coverage of selected locations, with a range of physical and geochemical properties, at two or more times of day to allow determination of variation in water-related abundances as a function of time of day. In this way, Lunar Ice Cube will achieve its primary goal: to measure the water components (weak physi-adsorbed OH, strong chemi-adsorbed OH, molecular water, ice) as a function of lunation, solar zenith angle, slope, and surface properties as a means of addressing the NASA HEOMD Strategic Knowledge Gap of understanding the distribution and transportation of water on the Moon

IceCube will prospect for lunar volatiles and water during its six months in lunar orbit. While the NASA Jet Propulsion Laboratory's Lunar Flashlight will locate ice deposits in the moon's permanently shadowed craters, IceCube's BIRCHES will investigate the distribution of water and other volatiles as a function of time of day, latitude, and regolith age and composition. Its study is not confined to the shadowed areas.

| Mission | Finding | IceCube |
|---|---|---|
| Cassini VIMS, Deep Impact | Surface water detection, variable hydration, with noonpeak absorption | Water & other volatiles, fully characterize<br>3 µm region as function of several times of<br>day for same swaths over range of latitudes<br>w/ context of regolith mineralogy and<br>maturity, radiation and particle exposure,<br>for correlation w/ previous data. |
| Chandrayaan M3 | $H_2O$ and OH (<3 µm) in mineralogical context nearside snapshot at one lunation | |
| LCROSS | Ice, other volatile presence and profile from impact in polar crater | |
| LP, LRO, LEND, LAMP,<br>DVNR, LOLA, LROC, LADEE | H+ in first meter (LP, LEND) & at surface (LAMP) inferred as ice<br>abundance via correlation with temperature (DIVINER), PSR and<br>PFS (LROC, LOLA), H exosphere (LADEE) | |

**Table A: Lunar IceCube versus previous missions**

## Lunar Polar Hydrogen Mapper

LunaH-Map mission will map the distribution of hydrogen around the lunar South Pole using a miniature neutron spectrometer. The mission builds upon a decade of lunar science, which has revealed both regional and more localized enrichments of water ice near the lunar poles (i.e., permanently shadowed regions). The spatial extent of these regions is often below the resolution of previous neutron instruments that have flown on lunar missions. The neutron leakage spectrum from planetary surfaces is primarily sensitive to hydrogen abundance in the top meter of regolith, however, for neutron spectrometers with omnidirectional sensitivity, the spatial resolution is limited by the spacecraft orbital altitude above the surface. A low altitude measurement from a distance on the same scale of the PSRs could spatially isolate and constrain the hydrogen enrichments both within and around within those regions. A small spacecraft mission is ideally suited to acquire the low-altitude measurements required to localize hydrogen enrichments using neutron spectroscopy at the lunar South Pole.

## Measuring $H_2$ Abundance on Lunar Surface to Infer $H_2$O Presence

## Inversing water ice from neutron data (Neutron Spectrometer)

- The cosmic rays of the Milky Way interact with the surface of the moon to generate a stream of neutrons.
- After a series of elastic or inelastic collisions with the nucleus of lunar surface agglutinates, neutrons form a balanced energy spectrum on the lunar surface distribution.
- Hydrogen atoms and neutrons have the same mass, so the superthermal neutrons are the most sensitive to the existence of hydrogen. If the hydrogen abundance in a certain area is high, the hyperthermal / fast neutrons (0.5eV< Energy <0.5 MeV) loses energy and becomes thermal neutrons (< 0.5eV). So,
- Neutron spectrometer determines $H_2$ Abundance by measuring the decrease in the flux of superthermal neutrons and the increase in the flux of thermal neutrons.
- The superheated neutron flux is inversely proportional to the hydrogen content in the region. Scientists rely on this to determine the hydrogen abundance on the moon's surface, and then use the hydrogen abundance to vaguely judge the water ice content in the region.

**The Lunar Compact Infrared Imaging System**

The Lunar Compact Infrared Imaging System (L-CIRiS) is a multispectral imaging radiometer designed for mineralogical and thermophysical measurements on the lunar surface. From its mounting location on the deck of a lunar lander, L-CIRiS will scan the landscape in four spectral bands, generating images of surface temperature and spectral emissivity. Emissivity images will be further processed to generate high spatial resolution (< 1 cm) maps of silicate mineral composition. Data from L-CIRiS will provide the first-ever view of compositional variations of lunar minerals on the Moon's surface at spatial scales down to < 1 cm. The results will shed light on phenomena contributing to crustal evolution, including large- and small-scale impact events, volcanism, and space weathering. [23].

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| Band | Wavelength Range (um) | Primary function |
|---|---|---|
| 1 | 7.7 to 8.1 | Mineralogy |
| 2 | 8.0 to 8.4 | Mineralogy |
| 3 | 8.3 to 8.9 | Mineralogy |
| 4 | 7.5 to 13.5 | Temperature imaging |

Table 1. L-CIRiS spectral bands

NASA's Commercial Lunar Payload Services (CLPS) initiative allows rapid acquisition of lunar delivery services from American companies for payloads that advance capabilities for science, exploration or commercial development of the Moon [24].

| Cubesats for Lunar Delivery | Cubesat Mission | Cubesat Proposed Operation |
|---|---|---|
| Lunar Polar Hydrogen Mapper (LunaH-Map) | To produce a high-resolution map of the Moon's bulk water deposits, unveiling new details about the spatial and depth distribution of potential ice previously identified during a variety of missions. | The Miniature Neutron Spectrometer (Mini-NS) uses a set of CLYC scintillators to detect neutrons and has a gadolinium shield to provide sensitivity primarily to neutrons above 0.5 eV. |
| Lunar InfraRed Imaging (LunIR) | To collect data about the lunar surface: --material composition<br>--thermal signatures<br>-- presence of water.<br>LunIR's infrared sensor will map the Moon during both day and night and can collect data at much higher temperatures than similar sensors per innovative micro-cryocooler technology (t0 -234 degrees F).. | Minerals such as pyroxene, plagioclase, olivine, and ilmenite, in different sizes and shapes, constitute most of the lunar surface rocks. They have distinctive spectral characteristics in the Visible and Near-infrared (VIS/NIR) wavebands. |
| Lunar IceCube | To prospect, locate, and estimate amount and composition of water ice deposits on the Moon | BIRCHES, Broadband InfraRed Compact, High-resolution Exploration Spectrometer to characterize and distinguish important volatiles (water, H2S, NH3, CO2, CH4, OH, organics) and mineral bands, BIRCHES has the high spectral resolution (5nm) and wavelength range (1 to 4µm) needed to distinguish phase states of water. |
| Lunar Flashlight | To explore, locate, and estimate size and composition of water ice deposits on the Moon | To carry an active multi-band reflectometer to measure the reflectance of the lunar surface from orbit near water ice absorption peaks. |
| OMOTENASHI (Outstanding MOon exploration TEchnologies demonstrated by NAno Semi-Hard Impactor) | Small spacecraft and semi-hard lander of the 6U cubesat format that will demonstrate low-cost technology to land and explore the lunar surface. | |

| | | |
|---|---|---|
| Lunar Compact Infrared Imaging System (L-CIRiS) | Includes a radiometer determining the thermal stability of volatiles based on temperature measurements. | To determine the presence and abundance of water ice and other volatiles on lunar surface and subsurface. |

## III. Conclusion

Lunar soil consists of glass-containing agglutinates formed from micrometeorite bombardment of regolith when heated, liberates hydrogen and helium that reacts with the FeO in the glass to produce water. Alternatively, spectral analysis identifies water and hydroxyl (–OH) absorption bands at ~3 μm within the lunar surface, suggesting solar wind-carried water that reacts with metallic particles embedded in lunar regolith. Major telescopic infrared programs, OASIS and SOFIA, have successfully imaged water on lunar surface. However, with Artemis programs nearing longer-termed lunar exploratory missions, low lunar orbital cubesats in communication with rovers/ landers will facilitate guiding, pointing, and tracking needed in operations. A literature review of infrared findings of lunar characteristics was summarized to include challenges of their respective data collection. Inferences from the findings were elaborated, suggesting additional objectives for further investigation into lunar water-ice signatures. Infrared technologies being developed as payloads for prospective cubesat or rover deployment on the moon were described.

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