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Laboratory experiments to investigate sublimation rates of water ice in nighttime lunar regolith

Marcus Piquette[a,*], Mihály Horányi[a], S. Alan Stern[b]

[a] Laboratory for Atmospheric and Space Physics, Boulder, CO 80303, USA
[b] Southwest Research Institute, Boulder, CO 80302, USA

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ABSTRACT

The existence of water ice on the lunar surface has been a long-standing topic with implications for both lunar science and in-situ resource utilization (ISRU). Cold traps on the lunar surface may have conditions necessary to retain water ice, but no laboratory experiments have been conducted to verify modeling results. We present an experiment testing the ability to thermally control bulk samples of lunar regolith simulant mixed with water ice under vacuum in an effort to constrain sublimation rates. The simulant used was JSC-1A lunar regolith simulant developed by NASA's Johnson Space Center. Samples with varying ratios of water ice and JSC-1A regolith simulant, totally about 1 kg, were placed under vacuum and cooled to 100 K to simulate conditions in lunar cold traps. The resulting sublimation of water ice over an approximately five-day period was measured by comparing the mass of the samples before and after the experimental run. Our results indicate that water ice in lunar cold traps is stable on timescales comparable to the lunar night, and should continue to be studied as possible resources for future utilization. This experiment also gauges the efficacy of the synthetic lunar atmosphere mission (SLAM) as a low-cost water resupply mission to lunar outposts.

1. Introduction

The lunar surface is made up of a regolith comprised of dust grains ranging in size from 10 nm–1 mm (Grün et al., 2011), whose thermal behavior is governed almost entirely by solar irradiance and internal heat flow (Arnold, 1979; Malla and Brown, 2015; Vasavada et al., 1999). Surface and sub-surface temperatures will therefore depend on both latitude and local time. At equatorial latitudes, surface temperatures will vary between 100 K and 380 K between night and day (Malla and Brown, 2015; Murray and Wildey, 1964; Vasavada et al., 2012), while sub-surface temperatures, below a thermal skin depth, stabilize near 250 K (Malla and Brown, 2015; Vasavada et al., 1999). Closer to the poles, near 85°, surface temperatures decrease dramatically with diurnal fluctuations between 100 K and 200 K and sub-surface temperatures stabilizing near 125 K, resulting in a near isothermal regolith during the night (Vasavada et al., 1999). Furthermore, permanently shadowed regions (PSRs) remain consistently cold throughout the lunar day with some regions reaching temperatures near 30 K (Arnold, 1979; Paige et al., 2010; Vasavada et al., 1999). The distribution of PSRs on the lunar surface is strongly correlated with latitude, with nearly 80% of PSRs existing within 20° from the lunar poles (Arnold, 1979; Bussey et al., 2003; Vasavada et al., 1999). The total area of PSRs has been estimated to be 7500 km^2 in the North and 6500 km^2 in the South, indicating that about a quarter of the total cratered surface within 20° of the poles is in permanent shadow (Bussey et al., 2003). Over the past couple decades, missions including Clementine, Lunar Prospector, ChangE-1, Chandrayaan-1, Lunar Reconnaissance Orbiter (LRO), and Lunar Crater Observation and Sensing Satellite (LCROSS) have made measurements of either the Hydrogen or the water content in the uppermost portions of PSRs to be 1–4% by weight (Meng et al., 2011; Mitrofanov et al., 2010). Understanding the thermal stability of ice in cold traps is crucial for interpreting the rate of capture and escape of water from cold traps.

The ability of cold traps to retain water ice and other volatiles is also important for its potential use for lunar ISRU. SLAM (Stern et al., 2012) is a concept originally intended to stimulate the lunar atmosphere, but has evolved into an efficient technique for supplying water to a human lunar outpost without the need for a soft landing. Using a launch vehicle with adequate surface targeting accuracy, a thermally protected payload of water ice on the order of 5000 kg could be sent on a minimum-energy Hohmann transfer orbit to impact the lunar night side or PSR near a human outpost where it can be stored and later harvested. The impact will bury

* Corresponding author.
E-mail address: marcus.piquette@colorado.edu (M. Piquette).

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water in the regolith at a depth and coverage that is dependent on the impactor speed, angle, and density (Melosh, 1989). Since surface and sub-surface temperatures decrease with latitude, water delivered to higher latitudes will be exposed to cooler regolith yielding less heating and loss. For this reason, the initial study presented here aims to re-create regolith properties present at higher latitudes or in PSRs where sub-surface temperature gradients are minimal or nearly isothermal.

In this paper we present the results of an experiment to explore volatile stability in lunar cold traps and assess the efficacy of both ISRU and SLAM. To the best of our understanding, this is the first time such an experiment has been conducted providing insight into the ability to cool and monitor bulk samples of regolith simulant in vacuum. In the next section of this paper we describe the sublimation behavior of water ice at low temperatures. The third section discusses interactions between water molecules and regolith grains. The fourth section describes the experimental procedure; and the fifth and sixth sections present results and the conclusions of the work.

2. Sublimation of water ice at low temperatures

An understanding of the behavior of water ice in vacuum is important for unraveling volatile history and evolution on airless bodies. Past experiments have explored the physical structure and sublimation characteristics of sub-micron layers of water ice (Hudson and Donn, 1991) as well as the affects on sublimation from inorganic and organic impurities (Zhang and Paige, 2009). In general however, under vacuum, water ice sublimates at a rate that depends on both the vaporization pressure and the temperature. For planar ice in a vacuum, the sublimation rate in $[\frac{kg}{m^2 s}]$ is given by (Andreas, 2007) to be:

$$S = p_{sat}(T)\sqrt{\frac{M_w}{2\pi RT}}, \quad (1)$$

where M_W is the molecular weight measured in $[\frac{kg}{m^2 s}]$, R is the gas constant in units of $[\frac{J}{K\ mol}]$, T is the temperature [K], and $p_{sat}(T)$ is the vapor pressure in [Pascal] also given by Andreas (2007) to be:

$$p_{sat}(T) = exp\left[9.550426 - \frac{5723.265}{T} + 3.53068 \ln T - 0.00728332T\right]. \quad (2)$$

For a temperature of 100 K, the calculated sublimation rate of water ice converts to $S = 2 \times 10^{-17} \frac{kg}{m^2\ s}$, or $\sim 2 \times 10^{-11} \frac{kg}{m^2}$ per lunar night. For non-planar ice the sublimation rate can change by a few percent depending on its curvature (Andreas, 2007). The characteristics of the ice grains used in our experiment described below are not planar; but to first order the calculation above serves as an indication that very little water is expected to sublimate at such low temperatures.

3. Interactions between water and the regolith

Initially proposed by Watson et al. (1961), see also Arnold (1979), cold traps on the lunar surface are predicted to capture volatiles transported along the surface. Water molecules in the lunar environment are predominantly in the vapor phase and travel, bouncing ballistically along the surface, until re-adsorbed into the regolith, destroyed via photoionization, photo-dissociation, solar wind ionization, or captured in a cold trap (i.e., in a PSR or in the nighttime regolith) (Hodges, 2002). If adsorbed by the regolith, water vapor may be liberated via solar wind sputtering or meteoritic bombardment, the thermal environment is generally not enough to eject the chemically bonded water (Hibbitts et al., 2011; Hodges, 2002).

Using a method called temperature programmed desorption (TPD), studies have explored the temperature relation of ad/desorption properties of both JSC-1A regolith simulant and lunar return samples, revealing extended adsorption profiles extending from 180–400 K (Hibbitts et al., 2011; Poston et al., 2015). In the experiment presented here, samples were mixed near 270 K resulting in a portion of the water being adsorbed on the regolith. However, the amount of water adsorbed is negligible compared to the total mass of the water mixed in the sample.

Water buried in the regolith, from impacts or internal transport (Schorghofer and Taylor, 2007), will undergo a random walk process in order to make it to the surface and escape. This process creates a diffusive barrier that will act to slow sublimation and prolong the lifetime of water and other volatiles (Hibbitts et al., 2011; Schorghofer and Taylor, 2007). Even small layers of regolith, of the order of 10 mm, can reduce the rate of sublimation by a factor of 10 (Chevrier et al., 2007). The sublimation of water ice will therefore be dominant near the top of the sample where water molecules can escape.

4. Experimental apparatus and materials

In order to obtain the desired ambient and internal conditions on the sample, our experiment utilized a variety of vacuum and cryogenic equipment. The experiment consisted of four main components: (1) the vacuum system including chambers, pumps, and gauges; (2) the cooling system, including the liquid nitrogen feed and controller; (3) the sample containment and monitoring system, including the experimental container, thermistors, cover, and internal cooling rig; and (4) the sample including the mixture of water ice snow and JSC-1A simulant. Fig. 1A depicts the overall set-up for this experiment with the major components labeled.

The experimental chamber consisted of two vacuum chambers, a four-way cross with 8-inch flanges, and a tube with 6-inch flanges. Mounted to the four-way cross was a window for viewing the sample, an electric feed through flange for the thermistors, an ionization gauge used to monitor pressure, and the vacuum pump system. The vacuum pumps used were a TriScroll dry roughing pump and a Pfeiffer turbo pump capable of pumping to sub-μTorr pressures. The tube housed the sample container and facilitated the cooling system.

Liquid nitrogen was fed through the bottom of the tube chamber. It followed a stainless steal pipe into the experimental chamber and into a copper block. The liquid nitrogen exited the experimental chamber via a stainless steal return pipe and filled a reservoir exterior the chamber. Levels of liquid nitrogen in the return reservoir were controlled with a Teragon LC2 liquid nitrogen controller that ensured liquid nitrogen was in continuous contact with the copper block throughout the experiment.

The required depth of the experimental sample depends on the properties of the lunar regolith. The depth at which a thermal wave penetrates into the regolith is determined by the specific heat and thermal conductivity of the regolith, which are dependent on both temperature and compression (Keihm and Langseth, 1973; Sakatani et al., 2016). In-situ measurements of lunar regolith revealed a thermal conductivity on the order of $1 \times 10^{-2} \frac{W}{m\ K}$ (Keihm and Langseth, 1973). Laboratory experiments on lunar returned samples indicated a specific heat at 100° K to be 210 $\frac{J}{kgK}$ (Hemingway et al., 1973). Assuming a bulk density of $1500 \frac{kg}{m^3}$, and a time scale of about five days, we find an e-folding thermal skin depth of approximately 10 cm. This implies that in order to properly model sublimation within the regolith, the experimental