THE LUNAR THERMAL ICE PUMP

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ABSTRACT

It has long been suggested that water ice can exist in extremely cold regions near the lunar poles, where sublimation loss is negligible. The geographic distribution of H-bearing regolith shows only a partial or ambiguous correlation with permanently shadowed areas, thus suggesting that another mechanism may contribute to locally enhancing water concentrations. We show that under suitable conditions, water molecules can be pumped down into the regolith by day-night temperature cycles, leading to an enrichment of H$_2$O in excess of the surface concentration. Ideal conditions for pumping are estimated and found to occur where mean surface temperature is below 105 K and the peak surface temperature is above 120 K. These conditions complement those of the classical cold traps that are roughly defined by peak temperatures lower than 120 K. On the present-day Moon, an estimated 0.8% of the global surface area experiences such temperature variations. Typically, pumping occurs on pole facing slopes in small areas, but within a few degrees of each pole the equator facing slopes are preferred. Although pumping of water molecules is expected over cumulatively large areas, the absolute yield of this pump is low; at best a few percent of the H$_2$O delivered to the surface could have accumulated in the near-surface layer in this way. The amount of ice increases with vapor diffusivity and is thus higher in regolith with large pore spaces.

Subject headings: Moon – molecular processes – diffusion

1. INTRODUCTION

Water ice is thought to be trapped in permanently shadowed craters in the polar regions of the Moon, where sublimation rates are negligibly low (Watson et al. 1961; Arnold 1979; Feldman et al. 1998). The degree to which the observed hydrogen abundance corresponds to the location of the cold traps remains uncertain (Feldman et al. 2001; Mitrofanov et al. 2010; Teodoro et al. 2014); any discorrelation suggests there is another physical mechanism to store water ice besides simple cold trapping. Here we study the “ice pump” mechanism in the context of the lunar polar regions.

Under suitable conditions, H$_2$O molecules can be “pumped down” into the regolith by day-night temperature cycles. The amplitude of surface temperature oscillations quickly decays with depth, and the strongly nonlinear dependence of molecular residence times on temperature leads to vertical drift processes, see Figure 1. The concept of an ice pump was first described in the context of Mars by Mellon & Jakosky (1993), where pumping can occur from a humid atmosphere into a porous subsurface. For an atmosphereless body, such as the Moon, volatile H$_2$O molecules on the surface are the source of the pump. If the surface concentration is high enough and the temperature amplitude is significant, pumping occurs.

Schorghofer & Taylor (2007) have studied two types of subsurface migration of H$_2$O in lunar environments. One is simple diffusion in a constant temperature environment. This process was found to produce only small amounts of subsurface H$_2$O, up to one monolayer. Beyond that there are no more concentration differences that could drive a flux. The same authors also discussed pumping from an ice cover, and they found that subsurface ice that accumulates in this way is quickly lost after the ice cover disappears. Siegler et al. (2011); Siegler (2012) argued that the ice pump effect may be a viable explanation for ice in the polar regions of the Moon and Mercury, but they did not consider the required H$_2$O density on the surface.

Here we quantitatively explore the pumping of water molecules to determine whether accumulation of macroscopic amounts of ice in the polar regions of the Moon is physically plausible with this mechanism.

2. PHYSICAL CONCEPT AND QUANTITATIVE DESCRIPTION

2.1. Physical concept

Migration of water molecules in the regolith of the Moon takes place in ultra-high vacuum conditions. At low temperature (<160K), migrating molecules spend most of their time residing on grain surfaces and, given their thermal speeds, only microseconds in-flight. The migration process can be thought of as a random walk, and it is thus described by a diffusion equation. Instantaneous vertical temperature gradients in the top layer of the lunar surface can be very large, and we consider the problem to be 1-dimensional.

For pure ice, the average molecular residence time only depends on temperature, but for adsorbed H$_2$O, this molecular residence time is also a function of the adsorbate layer thickness. Let $\theta$ denote the number of water
molecules per square area, and \( \theta_m \approx 10^{19} \text{m}^{-2} \) is monolayer coverage. The properties of pure ice are reached for \( \theta/\theta_m \gg 1 \).

The sublimation rate into vacuum \( E \), saturation vapor pressure \( p \), saturation vapor density \( n_v \), and residence time \( \tau \) are related to one another by simple physical formulas. The sublimation loss into vacuum is \( E = n_v \bar{v}/4 \), where \( \bar{v} \) is the mean thermal speed of a water molecule. \( E \), for ice or adsorbate, is related to \( n_v \) by the ideal gas law, \( p = n_v k_B T \), where \( k_B \) is the Boltzmann constant. At low temperature, nearly all water molecules that touch the surface stick to it (Haynes et al. 1992).

The concept of an ice pump is illustrated in Figures 1 and 2. The simplest case involves pumping from an ice cover (Fig. 2a). Crucial for the pumping mechanism is the damping of the temperature amplitude with depth. Since the vapor pressure at the ice is the saturation pressure, which has a convex shaped temperature dependence, larger temperature amplitudes implies a larger vapor pressure, thus creating a gradient in vapor pressures that preferentially moves molecules downward. An ice pump is thought to work on Mars (Mellon & Jakosky 1993; Schorghofer & Aharonson 2007), where the humid atmosphere acts as a water source (Fig. 2b). If the humidity is sufficiently high, the time-averaged vapor pressure on the surface exceeds the vapor pressure of ice at depth leading to pumping. This process stabilizes Mars’ extensive near-surface ice reservoirs. For an atmosphereless body, such as the Moon, the concentration of volatile \( \text{H}_2\text{O} \) molecules on the surface are the source of the pump. If the concentration is high enough such that the temperature amplitude effect compensates for the reduced saturation pressure of the adsorbate compared to solid ice, pumping occurs (Fig. 2c).

A weaker form of the lunar ice pump occurs when it does not produce ice but only adsorbate (Fig. 2d). In the absence of a geothermal gradient and when in equilibrium, subsurface \( \text{H}_2\text{O} \) concentrations always exceed surface \( \text{H}_2\text{O} \) concentrations.

### 2.2. Quantification of adsorption residence time

Measurements of adsorption isotherms on lunar soil samples by Cadenhead & Stetter (1974) provide quantitative information about the sublimation rate of water molecules adsorbed on the grain surface; they are reproduced in Figure 3 and approximated by an empirical fit. For a reversible isotherm, desorption rates can be calculated as a function of \( \theta \). Combined with the temperature dependent saturation vapor pressure of ice, this provides the residence time as a function of \( T \) and \( \theta \),

\[
E(T, \theta) = E_{\text{ice}}(T) f(\theta/\theta_m) \quad (1)
\]

The function \( f \) is shown in Figure 3. Factorization of the dependence on \( T \) and \( \theta/\theta_m \) is used due the lack of a more detailed quantification of adsorption behavior.

At temperatures below about 145K, ice is known to form in an amorphous rather than crystalline state. We use the saturation vapor pressure of Sack & Baragiola (1993).

### 2.3. Surface balance

The surface \( \text{H}_2\text{O} \) balance is determined by supply rate \( s \), space weathering \( w \), and sublimation loss to space \( E \).

These quantities have units of number of water molecules per area and time, but can be more intuitively expressed in units of ice layer thickness per time. For example, many of our model calculations will assume a supply rate of 1 m/Ga.

Space weathering occurs due to solar sputtering, deflected into the Moon’s permanently shadowed regions by Earth’s magnetotail, and due to Lyman-\( \alpha \) radiation from the interstellar medium (Arnold 1979). A rate of \( w_{\infty} = 1 \text{ m/Ga} \) is appropriate for a thick ice layer (Lanzerotti et al. 1981; Morgan & Shemansky 1991), and is scaled with \( 1 - \exp(-\theta/\theta_m) \), such that for small \( \theta \), \( w \) becomes proportional to \( \theta/\theta_m \). Net loss into the subsurface is comparatively small and will be neglected. The model equation for the surface mass balance is

\[
\frac{d\theta}{dt} = s - \left(1 - e^{-\theta/\theta_m}\right) w_{\infty} - E(T, \theta) \quad (2)
\]

For small concentrations and low temperature, the steady-state solution is set by a balance between supply and weathering, \( \theta/\theta_m = s/w_{\infty} \). Even when weathering exceeds the supply, the surface concentration of water molecules does not vanish, because destructive ions or photons will often not interact with the sparse water molecules.

The ordinary differential equation (2) involves terms that change at different time scales and is solved numer-
Fig. 2.—Illustration of the physical concept of ice pumps when the surface temperature alternates between cold and warm. 

2.4. Pumping condition and pumping strength

The vertical flux of molecules is given by differences in sublimation rates between two grain surfaces, \( J = E \) (lower grain) – \( E \) (upper grain), and thus \( J(z) = -\ell dE/dz \), where \( \ell \) is the typical vertical height of the pore space. The gradient in \( E \) is due to gradients in \( T \) and \( \theta \). For ice accumulation only the long-term average of this flux is relevant. Swapping the time average with \( E \) as expected if the redistribution of at most a few monolayers of \( \text{H}_2\text{O} \). This is justified post facto; if the pumping is so slow that the time averaging is not justified, the amount of \( \text{H}_2\text{O} \) is uninterestingly small. For periodic temperature cycles, and that is all we will consider, the time average in eq. (4) can be taken over one period.

Equation (5) provides a simple criterion for \( \text{H}_2\text{O} \) accumulation in the subsurface. If \( \Delta E > 0 \), then downward pumping exceeds the upward loss. If \( \Delta E < 0 \), the pumping is too weak and any buried ice will be lost.

The sign of \( \Delta E \) reveals whether an ice pump is operating, but the pumping might still be too slow to lead to a significant buildup of ice in the subsurface. The inward flux can be estimated by Eq. (5), where \( \Delta z \) corresponds roughly to the diurnal thermal skin depth. The rate of pumping, \( \langle J \rangle \), is smaller than the pumping differential \( \Delta E \) by a factor of \( \ell/\Delta z \ll 1 \).
Local mass conservation for the H₂O density ρ, ∂ρ/∂t + ∂J/∂z = 0, combined with Eq. (3) leads to

$$\frac{\Delta \rho}{\Delta z} \approx \ell \frac{\Delta E}{(\Delta z)^2}$$

For these order of magnitude estimates, the porosity of the regolith is neglected.

For dust thermal conductivity $k = 0.01$ Wm⁻¹K⁻¹ (Langseth et al. 1976), heat capacity $c = 300$ J kg⁻¹K⁻¹ (appropriate for low temperature, Winter & Saari (1969)), and soil density $\rho_s = 700$ kg m⁻³, the diurnal skin depth is 0.2 m. If, also for dust, $\ell = 100$ µm, then $\ell/\Delta z \approx 5 \times 10^{-4}$. If, on the other hand, the regolith consists of much larger particles and void spaces, $\ell = 1$ cm, the thermal conductivity may be 0.1 Wm⁻¹K⁻¹, $\rho_s = 1100$ kg m⁻³, and the resulting skin depth 0.5 m. For these much coarser grains, $\ell/\Delta z \approx 0.02$.

2.5. Results

Supply rates to the cold traps are badly constrained observationally. However, if supply rates were very large ($\gg 10$ m/Ga), massive ice deposits would be expected in the cold traps, which is not observed. Alternatively, if supply rates were very small ($\ll 0.01$ m/Ga), even all of the supply would not provide macroscopic concentrations of H₂O to the top decimeter of the surface. Hence, interesting supply rates are on the order of 1 m/Ga, which is comparable to the weathering rate.

We have carried out model calculations for the surface H₂O concentration, Eq. (2), with $s = 1$ m/Ga and $w_\infty = 1$ m/Ga. The temperature varies sinusoidally with time for half a solar day, which mimics daytime, and it is constant for the other half of the solar day, which mimics nighttime. We verified this rectified sinusoid shape describes the data well by examining the Diviner-derived diurnal temperature oscillations in cold regions. Differences between the measured temperatures and this model curve are generally smaller than the scatter in the data due to local slope and geography. The minimum temperature is $T_m$; the amplitude $T_a$ is the difference between the maximum and minimum temperature; the peak temperature is $T_m + T_a$, and the mean temperature is $T_m + T_a/\pi$.

Figure 4 shows the pumping differential as a function of mean and peak temperature. This phase diagram can be divided into three nearly complementary regions. At peak temperatures of $\lesssim 120$ K there is very weak pumping, and this parameter region nearly coincides with the temperature conditions for classical coldtrapping. At peak temperatures of $\gtrsim 120$ K and mean temperatures lower than $\sim 105$ K, significant pumping occurs. When the mean temperature is above $\sim 110$ K, neither pumping nor coldtrapping occurs. At the mean temperature boundary of $\sim 110$ K, the vapor pressure of the buried ice approximately balances the supply rate.

Figure 4 also demonstrates that the maximum pumping differential, $\Delta E$, is of the same order of magnitude as the supply rate, $s$. At high temperature, every supplied water molecule is volatile during some part of the diurnal cycle, and hence contributes to upward or downward sublimation loss.

Figure 5 shows an example of the variation in surface temperature and in H₂O surface concentration, $\theta$, over one diurnal cycle. At night, water molecules accumulate and most are lost as the surface warms up. For temperature conditions with significant pumping, we find the time-averaged coverage to be on the order of a tenth of a monolayer. At low temperature, $\theta$ is almost constant with time and is set by an equilibrium between weathering and sublimation. We have carried out the same model calculations for supply rates from 0.1 m/Ga to 10 m/Ga, and weathering rates from 0.1 m/Ga to 10 m/Ga, and find that the optimal temperature range is about the same as in Fig. 4. And the maximum pumping differential relative to the supply rate is almost 1, as it is for Fig. 4.

The volumetric concentration of pumped H₂O can be estimated with Eq. (6). For dust and with 1 m of supply, the density is of the order of 2 kg m⁻³. If, on the other hand $\delta = 0.6$ m and $\ell = 1$ cm, the density is 40 kg m⁻³.
This corresponds to a few percent of the mass (40/1100 ≈ 4%). Hence, under favorable conditions no more than a few mass percent of the supplied H$_2$O can be expected to accumulate.

2.6. Discussion

Pumping is an inefficient process due to the rapid loss of surface molecules to space relative to their downwards diffusion. The pumping differential is smaller than the sublimation loss to space, which is smaller than the supply rate,

\[
\Delta E \leq \langle E \rangle \leq s
\]

Combining eqs. (7) and (6) yields

\[
\rho \Delta z \leq \frac{\ell}{\Delta z} s \Delta t
\]

In other words, the column-integrated subsurface ice density, \( \rho \Delta z \), is smaller than the time-integrated supply of water, \( s \Delta t \), by at least a factor of \( \ell/\Delta z \). This demonstrates how inefficient the pumping effect is on an atmosphereless surface, due to the factor \( \ell/\Delta z \). For every molecular hop from the surface downward there is probabilistically one hop upward and thus one molecule lost.

Impact gardening stirs the regolith. The turnover depth increases with time and is estimated to be 10 cm over 1 Ga (Gault et al. 1974). For coarse grains, the skin depth is \( \sim 0.5 \) m, and thus the stirring is not expected to be a major effect.

The surface to volume ratio of lunar soil particles is much larger than for smooth spherical particles, a situation not captured by our one-dimensional model. This would dilute supply and weathering rates, each by about the same factor, and hence is not expected to change our conclusions drastically.

3. APPLICATION TO THE MOON

Accurate measurements of the Moon’s surface temperatures are available globally from the Lunar Diviner instrument (Paige et al. 2010). Temperatures were derived from sorting the bolometric temperatures into spatial and temporal bins, at 16 bins per degree in latitude and longitude, and 12 bins of local time over the diurnal cycle, for the mission duration available at the time of analysis, from July 2007 to September 2012. From these data, the minimum and maximum temperatures (the difference between which is the oscillation amplitude) are estimated according to the 10th and 90th percentile points of the distribution, chosen for robustness to rare outlying temperature measurements. The results are mapped in Figure 6, and are insensitive to the choice of extrema points.

For a pair of temperatures describing the cycle at a given location on the Moon, the pumping differential \( \Delta E \) is interpolated from a table computed according to Eq. (4). The results are mapped in Figure 7. Positive pumping differential extends the distribution of regions expected to harbor ice relative to the traditional permanently shadowed cold traps. Within a few degree of each pole, equator facing slopes have a stronger positive pumping differential, because at this latitude these slopes are cold and their aspect still allows larger temperature oscillations than over flat ground. At other latitudes, pole facing slopes have stronger positive pumping differential, because at these latitudes the sun rises high enough over the horizon such that there are temperature oscillations, but the poleward slope aspect maintains these surfaces relatively cold (See Figure 8). The classical, permanently shadowed cold traps have a positive pumping differential, but the strength of the pump is weak because the oscillations are small.

Zonally averaged area histograms summarize the conditions on the Moon where pumping is active, as a function of latitude (Figure 9). The theoretical criteria predict there are areas with peak temperature higher than 50 K where pumping occurs (solid lines), but substantial
Fig. 7. — Polar maps of the pumping differential ($\Delta E$), color coded and plotted only where positive, overlaid on a shaded relief topographic grid illuminated from the equatorial direction. The maps are stereographically projected from 78° latitude to each pole. Pumping defined by $\Delta E > 0.5$ (dashed lines) is limited to areas with peak temperature $> 120$ K and oscillation amplitude $> 70$ K. At the spatial resolution of the maps ($\sim 2$ km), the total area where any pumping occurs is $0.20 \times 10^6$ km$^2$ in the South and $0.21 \times 10^6$ km$^2$ in the North. The sum of these two amounts to 1.1% of the global surface area. The pump is substantial ($\Delta E > 0.5$) over an area of $0.14 \times 10^6$ km$^2$ (0.4%) in the South and $0.16 \times 10^6$ km$^2$ (0.4%) in the North.

4. CONCLUSIONS AND DISCUSSION

We conclude from our analysis that pumping is conceptually and quantitatively plausible in many polar areas, but the amount of ice that accumulates will only be a small fraction of what is delivered to the surface. An uncertainty in assessing the role of an ice pump is the concentration and mobility of volatile water molecules on the surface. Additional observational constraints on the distribution of water are not needed to further assess the role of an ice pump on Moon. More specifically, we draw the following conclusions:

(i) Strong pumping occurs for mean surface temperatures lower than 105 K and peak surface temperature higher than 120 K. Figure 4 shows the optimal temperature range applicable for a wide range of supply rates. Classical coldtrapping and strong pumping are nearly complementary. Areas of strong pumping exhibit variations in surface water concentration over one thermal cycle (one month).

(ii) The ice pump is inefficient on bodies without atmosphere. With a supply of 1 m of ice, at most a few percent of H$_2$O accumulate in the top half meter of the surface. More generally, at most a few percent of the H$_2$O delivered to the surface could have accumulated in the near-surface layer.

(iii) A rocky surface layer with large pore spaces is required for fast diffusion; dust is an inefficient medium for pumping.

(iv) Conditions for strong pumping are present over 0.8% of the global surface area of the Moon, about 0.4% in each lunar polar region (Figure 7). The total area where any positive pumping can be expected is estimated as 1.1%.

(v) Typically pumping occurs on pole facing slopes in polar areas, but within a few degrees of each pole the equator facing slopes are preferred (Figure 8).
It is noteworthy that an ice pump could also act on asteroidal surfaces, if the asteroid has a steady supply of water molecules. On Mercury, the occurrence of ice is well correlated with the location of the cold traps and the concentration of ice appears to be much higher than on the Moon. An alternative mechanism to cold trapping, such as the ice pump, is hence unnecessary although may still act on Mercury.

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