

ON THE THEORY OF MIGRATION OF WATER ON THE MOON. Norbert Schorghofer, Institute for Astronomy, University of Hawaii, Honolulu, Hawaii, USA (norbert@hawaii.edu).

Do water molecules migrate? Watson, Murray, and Brown (WMB) [1] suggested that water molecules on the lunar surface move on ballistic trajectories until they reach one of the extremely cold permanently shaded areas near the lunar poles where they accumulate [2]. However, physiochemical considerations suggest that lunar rocks are so pristine and dry that H₂O molecules are strongly bound or even dissociated upon contact with the grain surface [3, 4]. Hence, there are two contrasting theories. One suggests that water molecules migrate quickly and efficiently on the lunar day side (WMB); the other suggests that they do not (Hodges-Cocks). Here, I investigate the migration process using a physical model of H₂O-regolith interaction that falls in between these two end-member models.

Quantification of adsorption residence time. For ice, the average molecular residence time only depends on temperature, but for adsorbed water it is also a function of the adsorbate layer thickness. Let θ denote the number of water molecules per area, and θ_m is one monolayer.

An important conceptual realization is that sublimation rate E , equilibrium vapor pressure p , and equilibrium vapor density n_v all encode the same information and are related to one another by simple physical formulas. The sublimation loss into vacuum is

$$E_0 = n_v \bar{v} / 4, \quad (1)$$

where \bar{v} is the mean thermal speed of a water molecule. The ideal gas law relates p with n_v , $p = n_v kT$.

Measurements of adsorption isotherms of lunar soil samples are reproduced in Fig. 1 [5]. If the isotherm is reversible, desorption rates can be calculated as a function of θ . Lacking any more detailed information about the temperature dependence of the isotherm, the desorption rates are scaled with the temperature dependence of the saturation vapor pressure of ice,

$$E(T, \theta) = E_0(T) p(\theta) / p_0 \quad (2)$$

where the ratio p/p_0 is shown in Fig. 1.

Model. A Monte-Carlo method for the migration of water molecules on the lunar surface is implemented (similar to Ref. [6]). The temperature model is a one-dimensional Crank-Nicholson solver for the heat conduction equation with a time step of 1 hour. Water molecules are launched in random direction with Maxwellian velocity components. The intersection with the surface is calculated with spherical trigonometry.

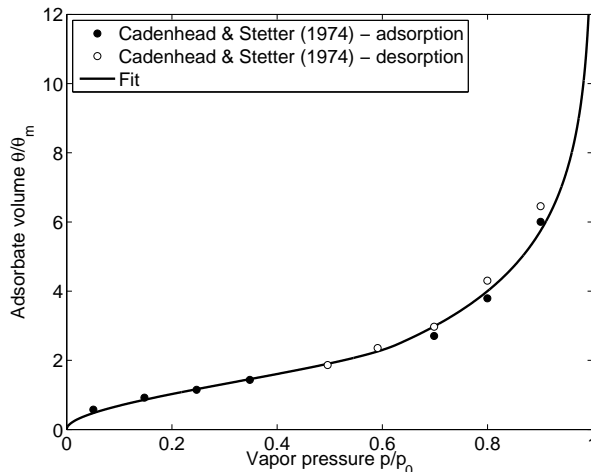


Figure 1: Measured adsorption isotherm of lunar sample 15565,3G at 15°C [5] with empirical fit.

An in-flight photodissociation destruction probability of 0.4% per hop is assumed [2] and H₂O molecules are also lost to cold traps. The residence time is calculated as a function of surface temperature and θ . An event-driven algorithm is used, where landing and launching events are processed in time-order. Since sorting is algorithmically fast, this is a computationally efficient method.

WMB versus Hodges-Cocks. Simulations are carried out with a one-time source of 18 kg of water, which still allows for rapid migration. For comparison, a global monolayer on a smooth surface corresponds to 11×10^6 kg of H₂O. Molecular residence times on the lunar dayside are still short compared to in-flight times, even when increased by many orders of magnitudes relative to ice. Hence, the WMB mechanism still works even when θ/θ_m is small. However, for the isotherm to be reversible at sub-monolayer coverage there needs to be surface diffusion on a grain-scale [7, 8].

Diurnal asymmetry: It has been suggested that there is increased O-H absorption band depth near both terminators of the Moon [9]. Figure 2 shows the model distribution of H₂O molecules with a continuous source. Here it is assumed water molecules originate at the hottest regions, where H₂O may be generated by recombination of OH [10, 11], but the specific supply mechanism is not crucial for the considerations here. There is an enhanced concentration of water molecules near the morning terminator. Molecules exposed by sunrise leave the surface, and many of them quickly hop back

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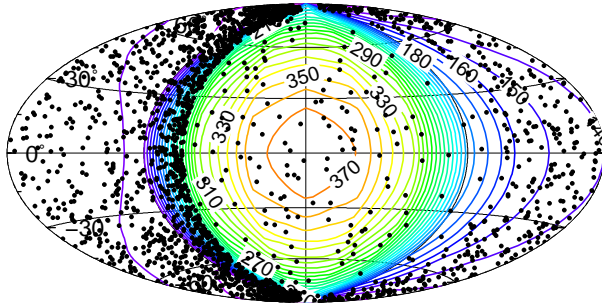


Figure 2: Steady-state distribution of water molecules on a global map (equal-area Hammer projection). There is an enhanced concentration of water molecules near the morning terminator, but not at the evening terminator. Colored contours are surface temperature with noon at the center. The morning terminator is to the left of the center.

to the night side, thus enhancing the concentration near the morning terminator. No such phenomenon occurs at sunset. Hence, diurnal variation in H_2O coverage is expected to lead to high concentration of H_2O on one terminator and low concentration at the other. This suggests that the increased absorption band depth on both terminators [9] is unrelated to the presence of surficial H_2O .

The Lunar Ice Pump: It has long been suggested that water ice can exist in extremely cold regions near the lunar poles [1, 2], but measurements of the geographic distribution of H-bearing regolith show only a partial relationship with permanently shaded areas, thus suggesting there may be another mechanism that leads to locally enhanced water concentration.

Under suitable conditions, water molecules can be “pumped down” into the regolith by day-night temperature cycles, leading to an enrichment in H_2O concentration in excess of the surface concentration. Surface temperature oscillations quickly decay in amplitude with depth, with an e -folding depth on the order of 1cm. The strongly nonlinear dependence of molecular residence times on temperature leads to vertical drift processes [12]. For ice accumulation the long-term average of this flux is relevant.

The concept of an ice pump is illustrated in Figure 3 and described in the figure caption. For an atmosphereless body, such as the Moon, the presence of volatile H_2O molecules on the surface are the source of the pump. If the concentration is high enough, pumping occurs. While pumping is expected in polar regions, the absolute strength of this pump is found to be too small everywhere to produce macroscopic amounts of subsurface ice.

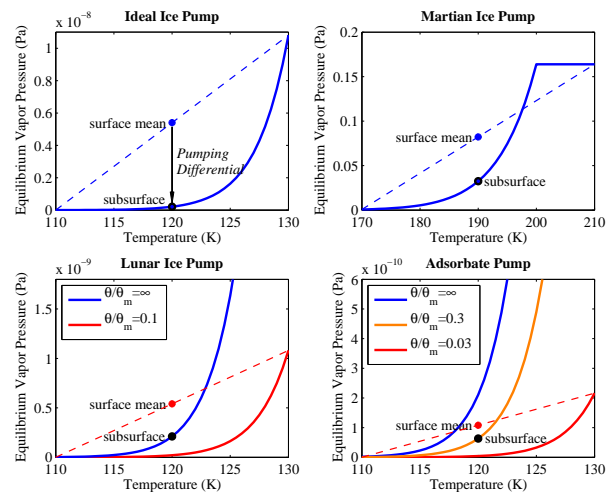


Figure 3: Illustration of the physical concept of ice pumps when the surface temperature alternates between cold and warm. a) An ideal ice pump works in the presence of an ice cover, where the vapor pressure on the surface equals the equilibrium vapor pressure of ice. b) For a humid atmosphere, such as on Mars, the air is saturated at night and the humidity is limited by the frost point at day. If the frost point temperature is sufficiently high, pumping results [13]. c) On the Moon, the surface has adsorbed water molecules with a lower vapor pressure than ice, a situation that can also give rise to a pumping differential. d) If the density of water molecules on the surface is too low to balance the vapor pressure of subsurface ice, the subsurface still has more adsorbed water molecules than the surface. Properties of pure ice are approached for $\theta/\theta_m \gg 1$.

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