SUBSURFACE MIGRATION OF H2O AT LUNAR COLD TRAPS. Norbert Schorghofer and G. Jeffrey Taylor. Institute for Astronomy and NASA Astrobiology Institute, 2680 Woodlawn Drive, Honolulu, HI 96822, USA (norb1@ifa.hawaii.edu), Hawaii Institute of Geophysics & Planetology and NASA Astrobiology Institute, University of Hawaii, 1680 East-West Road, Honolulu, HI 96822 (gtaylor@higp.hawaii.edu).

Introduction: Water molecules delivered to the Moon transiently move along ballistic trajectories and can get trapped at permanently shaded areas near the lunar poles, where sublimation rates are so low that ice would survive over billions of years [1, 2], unless it is destroyed by photodissociation, solar wind, or other mechanisms [2, 3, 4]. Transport and deposition of water molecules has been studied previously [2, 5]. To transport and trapping, we add subsurface migration caused by molecular diffusion in the porous regolith, taking a different approach than that used by [6]. Ground ice would be better protected from destruction. We have not yet considered transport and deposition of water by large comet impacts, only by continuous delivery to the lunar surface.

Physics of Vapor Migration: The saturation vapor pressure $P_s$ is defined by an equilibrium between particles that hit the surface and stick to the surface and the number of molecules that escape from a solid ice surface. The rate of incident particles from a saturated atmosphere is $[7, 1]$

$$E_{\text{max}} = P_v/\sqrt{2\pi k T \mu},$$

with $k$ the Boltzmann constant, $T$ temperature, and $\mu$ the mass of an H2O molecule. This is a maximum condensation rate, because not all incident molecules stick to the surface. When vapor is in equilibrium with ice

$$E_{\text{conden.}} = \alpha E_{\text{max}} = E_{\text{evap.}},$$

where $\alpha$ is the condensation coefficient. The mean residence time $\tau$ of a molecule is thus $\tau = \theta/E_{\text{evap.}}$, where $\theta$ is the number of molecules per area $\theta = (\rho/\mu)^{2/3}$ and $\rho$ the density of solid ice. Figure 1 shows the residence time of water molecules as a function of temperature. This physical model provides finite residence times at all temperatures and can describe the migration of H2O molecules within cold areas. (The binding energy of molecules adsorbed to the regolith or on amorphous ice will differ from that in crystalline ice.) A fraction $(1 - \alpha)$ of incident molecules are reflected from the surface. The coefficient $\alpha$ in the temperature range 40–120K is in the range 1–0.7 [8].

Subsurface Migration: H2O molecules on the surface can migrate into the porous, loose regolith by random jumps. Our model uses discrete jumps of $l = 75\mu$m, which represent a typical grain size diameter or pore space size. At every time step of length $\Delta t$, there is a probability $\Delta t/\tau$ for the molecule to leave the surface. Once released we assume molecules move with equal probability upward or downward. Any molecule that moves upward from the surface is assumed lost.

Model calculations are carried out with a continuous supply of water molecules to the surface. Figure 2a shows the amount of ice in the ground as a function of time. Only a fraction of the water supplied accumulates in the subsurface, most is lost from the surface, but the amount of ice steadily increases with time. Figure 2b shows the mass distribution with depth $z$.

Continuum Description. The random migration of molecules can also be described by a continuous mass density $\rho(z, t)$ that obeys the diffusion equation $\partial \rho/\partial t = D \partial^2 \rho/\partial z^2$ with a diffusion coefficient $D = l^2/\tau$. On the surface,
molecules are incident at rate \( s \) and lost at rate \( \sigma(t)/\tau \), where \( \sigma \) is surface density, \( \partial \sigma/\partial t = s - \sigma(t)/\tau \). Hence, \( \sigma(t) = \tau s (1 - e^{-t/\tau}) \). After a transitional period, \( \sigma \) approaches a constant value \( \tau s \). The solution to the diffusion equation with boundary condition \( \rho(0, \tau) = \tau s/\ell \) is obtained with standard mathematical methods as

\[
\rho(z, t) = \frac{\tau s}{\ell} \left( 1 - \text{Erf}(z/\sqrt{4Dt}) \right) \quad \text{for} \quad t \gg \tau \tag{2}
\]

The total ice mass is

\[
m(t) = \int_{0}^{\infty} \rho(z, t) dz = \frac{\tau s}{\ell} \sqrt{4Dt/\pi} = 2s \sqrt{\frac{\ell \tau}{\pi}}. \tag{3}
\]

It is proportional to the supply rate \( s \), increases with the square root of time \( t \), and decreases with temperature via the residence time \( \tau \). For comparison, the total amount of water supplied is \( st \). The mean depth of the ice is

\[
\langle z \rangle = \frac{\int_{0}^{\infty} z \rho(z, t) dz}{m(t)} = \sqrt{\pi Dt/4} = \frac{\ell}{2} \sqrt{\frac{\pi t}{\tau}}. \tag{4}
\]

The colder, the shallower is the ice (Figure 3). At very cold temperatures \( t \ll \tau \), molecules rarely migrate at all, and the mass is estimated as \( m(t) = st(1 + \alpha)/2 \) instead of eq. (3).

Figure 3: Mean depth \( \langle z \rangle \) of migrating ice from eq. (4) compared to the gardening depth [9]. Meteoroid impacts lead to turnover and burial of regolith. This does not necessarily destroy the ice and may in fact protect it [2].

**Destruction:** Ice is lost not only by sublimation, but also by UV-radiation from the sun or the local interstellar medium [4, 3] and by sputtering from solar wind directly or from the tail of Earth's magnetosphere. Destruction rates of exposed surface ice may exceed accumulation rates [3]. Radiation destroys molecules on their way to the coldtraps and on the surface of the coldtraps, before they can migrate downwards. The existence of a condensation coefficient \( \kappa \) may be crucial, because some molecules that land on cold areas will jump to protected pores without spending time on the surface. If all surface molecules are destroyed at every time step, the fraction of remaining ice is \( (1 - \alpha)/2 \) times \( m(t) \), in agreement with our model calculations.

**Mass Balance:** Figure 4 summarizes the various results for the amount of retained ice relative to the amount supplied, \( m/st \). The solid green line shows the amount retained without destruction of surface molecules. For example, if \( 10^{14} \) kg of ice are supplied over 1 Ga, at 100K an estimated \( 10^{11} \) kg are in the form of ground ice and the remainder is assumed lost. The green dash line is for rapid destruction of surface molecules. For comparison, the solid black line is for negligible migration into the regolith. Without migration, all molecules would be lost by surface destruction.

Subsurface migration has two important effects on the total mass of accumulated ice. 1) At temperatures above \( \sim 80K \), most of the ice accumulated over a billion years may be in the subsurface rather than on the surface, even without burial. 2) Immediate reflection of a small portion of H2O molecules from a cold surface into deeper hiding places may save it from destruction.

**Conclusions:** Our calculations indicate that water molecules can travel into the regolith before they are destroyed. Lower temperatures favor retention of water, but higher temperatures lead to deeper burial. The deeper burial leads to preservation during impact gardening; this suggests that areas receiving substantial reflected sunlight could contain enough water to be useful for scientific studies and resource utilization. We are currently trying to reproduce the migration phenomenon in the laboratory.

**References**