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New estimates for the sublimation rate for ice on the Moon

Edgar L Andreas [*]

U.S. Army Cold Regions Research and Engineering Laboratory, 72 Lyme Road, Hanover, NH 03755-1290, USA

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Abstract

The strong hydrogen signal that the Lunar Prospector saw at the Moon's poles suggests that water ice may be present near the surface of the lunar regolith. A robotic mission to obtain in situ samples and to quantify the amount of this valuable resource must be designed carefully to avoid dissipating too much heat in the regolith during coring or drilling and, thus, causing the ice to sublimate before it is processed. Here I use new results for the saturation vapor pressure of water ice to extend previous estimates of its sublimation rate down to a temperature of 40 K, typical of the permanently shaded craters near the lunar poles where the water ice is presumed to be trapped. I find that, for temperatures below 70 K, the sublimation rate of an exposed ice surface is much less than one molecule of water vapor lost per square centimeter of surface per hour. But even if a small ice sample (∼4 ng) were heated to 150 K, it could exist for over two hours without sublimating a significant fraction of its mass. Hence, carefully designed sampling and sample handling should be able to preserve water ice obtained near the lunar poles for an accurate measurement of its in situ concentration.
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1. Introduction

The existence of water on the Moon has been debated for well over a hundred years (e.g., Coakley, 1885). There are at least three explanations for its origin (e.g., DesMarais et al., 1974; Arnold, 1979): The water could be primordial, existing since the Moon formed and now trapped in the regolith; it could be deposited when icy comets strike the Moon; or it could form when solar-wind protons interact with oxygen in the minerals near the Moon's surface.

When sunlit, for latitudes between 75° north and 75° south, the surface of the Moon and even depths down to a meter or more heat to temperatures at which water ice will sublimate and, thus, disappear quickly on a geological time scale (Watson et al., 1961; Hodges, 1973; Vasavada et al., 1999). Current theories therefore suggest that any near-surface water on the Moon will be trapped as ice deposits in permanently shaded craters near the lunar poles, where temperatures may be as low as 40 K (Watson et al., 1961; Arnold, 1979; Vasavada et al., 1999;

Carruba and Coradini, 1999). In fact, the neutron spectrometer on the Lunar Prospector showed the highest concentration of hydrogen to be within a few degrees of the lunar poles (Feldman et al., 2001). Though this hydrogen signal may not have resulted from water ice (e.g., Eshleman and Parks, 1999; Starukhina and Shkuratov, 2000; Campbell and Campbell, 2006), it still provides tantalizing motivation for mounting a robotic mission to the lunar poles to seek the source of the signal (Nozette et al., 2001).

Such robotic exploration could include drilling, coring, or other excavating that might dissipate heat in the regolith being sampled (cf. Taylor et al., 2006). The ice could thus conceivably be warmed enough to sublimate in the near-vacuum conditions on the surface of the Moon before its concentration is determined. To set bounds on the kind of processing that a regolith sample can endure without losing a significant fraction of its water ice, I make new estimates for the sublimation rate of ice at lunar temperatures. Earlier studies of ice on the Moon had likewise estimated its sublimation rate; but Watson et al. (1961) and Vasavada et al. (1999), for example, considered temperatures down only to 100 K. The shaded polar craters, however, have temperatures estimated to always be about 40 K (Arnold, 1979;

Table 1
Nomenclature and constants used in the manuscript

e_r	Saturation vapor pressure of a pure water ice surface with radius of curvature r [see Eq. (6)]
$e_{sat,i}$	Saturation vapor pressure over a planar surface of pure water ice [see Eqs. (2)–(4)]
L_v	Latent heat of sublimation of water ice
M_w	($= 18.015 \times 10^{-3}$ kg mol^{-1}) Molecular weight of water
m	Mass of a water ice sample [see Eq. (8)]
m_0	Initial mass of a water ice sample before any sublimation
r	Radius of curvature of a small water ice deposit
R	($= 8.31447$ J mol^{-1} K^{-1}) Universal gas constant
r_c	Radius of curvature at which the sublimation rate for an ice sample is e times the sublimation rate for a planar ice surface [see Eq. (12)]
r_0	Initial radius of a spherical water ice deposit
S_r	For a water ice sample, the sublimation rate at a surface with radius of curvature r [see Eq. (10)]
S_0	Sublimation rate for a planar surface of pure water ice [see Eq. (1)]
t	Time
T	Temperature in kelvins
α_m	Mass accommodation coefficient
ρ_i	Density of pure water ice [see Eq. (7)]
σ_i	($= 0.109$ J m^{-2}) Surface tension of a pure ice/vapor interface

Vasavada et al., 1999; Carruba and Coradini, 1999). I therefore update estimates of ice sublimation as a function of temperature using a recently developed formulation for the vapor pressure of water ice at low temperature. I also discuss how the sublimation rate will change if the ice is "dirty"—contaminated with other molecules—or if microscopic ice deposits have highly curved surfaces.

2. Sublimation rate of ice

Estermann (1955; also Bohren and Albrecht, 1998, p. 187f.) derives the standard equation for the evaporation or sublimation rate from a planar surface of pure water or ice in a vacuum. The derivation relies on geometrical considerations, the ideal gas law, and the Maxwell–Boltzmann distribution for the speed of free gas molecules (e.g., Bohren and Albrecht, 1998, p. 60ff.). The resulting sublimation rate for water ice is

$$S_0 = e_{sat,i}(T) \left(\frac{M_w}{2\pi RT} \right)^{1/2}. \tag{1}$$

Here, S_0 is a mass flux; its units are kg m^{-2} s^{-1}. Subscript 0 denotes sublimation from a planar surface. Also, $e_{sat,i}(T)$ is the saturation vapor pressure (in pascals) for a planar ice surface at temperature T (in kelvins), M_w is the molecular weight of water, and R is the universal gas constant. Table 1 collects the definitions of the symbols used in Eq. (1) and elsewhere in the manuscript.

Equation (1) implicitly assumes that the so-called mass accommodation coefficient α_m (Hobbs, 1974, p. 441; Bohren and Albrecht, 1998, p. 187f.) is one (e.g., Bryson et al., 1974). That is, from a geometrical perspective, if the volatile surface is horizontal, all gas molecules striking the surface from above stick to it; the up-going flux of molecules thus results strictly from evaporation or sublimation—not from the reflection of down-going molecules. If α_m were not one, on the other hand, the actual sublimation rate would be $\alpha_m S_0$. Hence, Eq. (1) gives the maximum potential sublimation rate because $0 \leqslant \alpha_m \leqslant 1$.

3. Vapor pressure of ice

Using Eq. (1) to estimate the sublimation rate as a function of temperature is straightforward if we know the saturation vapor pressure of ice, $e_{sat,i}$, as a function of temperature. The availability of new data and a new expression for $e_{sat,i}$ from Murphy and Koop (2005) ultimately motivated this study.

Fig. 1 summarizes our current understanding of the saturation vapor pressure over a planar surface of pure water ice. It shows five sets of measurements or reference values for the saturation vapor pressure and three expressions for $e_{sat,i}$. In particular, the measurements from Bryson et al. (1974) extend down to almost 131 K.

At temperatures above 170 K, the five data sets are nearly indistinguishable and, thus, provide good constraints on the $e_{sat,i}$ functions here. At lower temperatures, the values from Hilsenrath et al. (1960) show some dispersion; and at even lower temperatures, the data from Bryson et al. (1974) tend to drift above the curve obtained by Murphy and Koop (2005).

Murphy and Koop (2005), however, speculate that, rather than observing hexagonal ice, as everybody else did, Bryson et al. (1974) may have been observing cubic or amorphous ice, which is known to be deposited from water vapor at the low range of the temperatures they studied (Hobbs, 1974, p. 44ff.). Had Bryson et al. allowed their samples time to anneal, the samples would have converted to hexagonal ice. Coincidentally, I infer that Vasavada et al. (1999) used the Bryson et al. data to make their estimates of sublimation rate on the Moon at 100 K. Consequently, with vapor pressure biased high, their sublimation rates will also be biased high.

The first function in Fig. 1 is from Buck (1981), who gives

$$e_{sat,i} = 6.1115 \exp\left[\frac{22.542(T - 273.15)}{273.48 + (T - 273.15)} \right] \tag{2}$$

for T in the range [193.15, 273.15 K]. The second function is from Wagner et al. (1994), who give
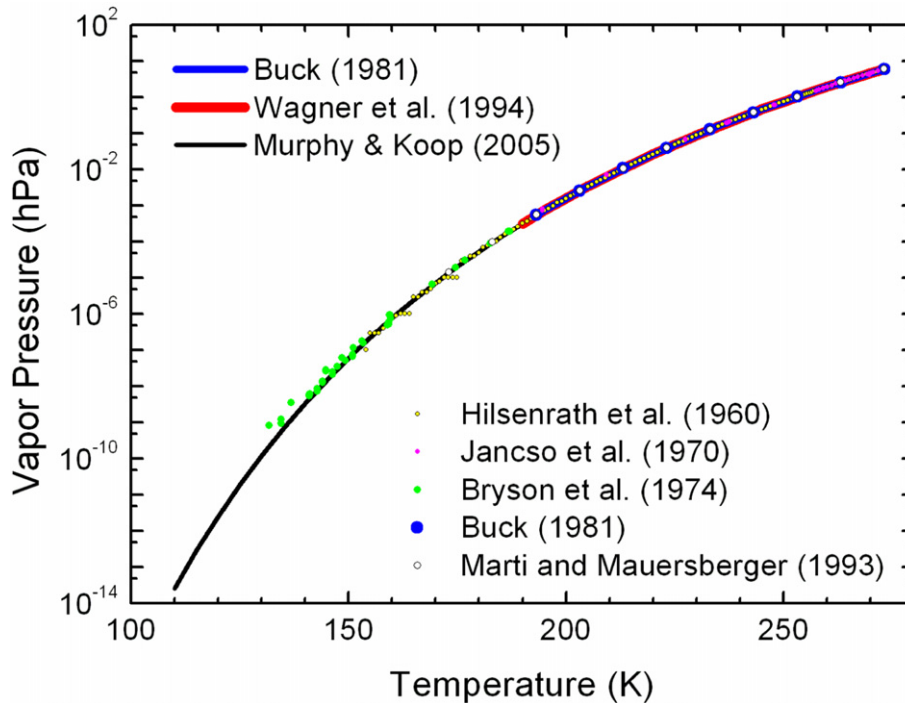
Fig. 1. Measurements or reference data for the saturation vapor pressure over a planar surface of pure water ice from Hilsenrath et al. (1960), Jancso et al. (1970), Bryson et al. (1974), Buck (1981), and Marti and Mauersberger (1993). The functional expressions for $e_{sat,i}$ are from Buck (1981), Wagner et al. (1994), and Murphy and Koop (2005) and are given in Eqs. (2)–(4). The Murphy and Koop curve is under the Buck and Wagner et al. curves in the region where they all overlap.

$$e_{sat,i} = 6.11657 \exp \left\{ -13.9281690 \left[1 - \left(\frac{T}{273.16} \right)^{-1.5} \right] \right.$$
$$\left. + 34.7078238 \left[1 - \left(\frac{T}{273.16} \right)^{-1.25} \right] \right\} \qquad (3)$$

for T in [190, 273.16 K]. Recent editions of the *Handbook of Chemistry and Physics* (Lide, 2001, p. 6-9), for example, base their tabulations for the vapor pressure of ice on Eq. (3). The final function in Fig. 1 is from Murphy and Koop (2005), who give

$$e_{sat,i} = 0.01 \exp \left(9.550426 - \frac{5723.265}{T} \right.$$
$$\left. + 3.53068 \ln T - 0.00728332 T \right) \qquad (4)$$

for T in [110, 273.15 K]. In each of these equations, $e_{sat,i}$ is in hPa, and T must be in kelvins.

Fig. 1 shows that, in the temperature range where these three equations overlap, they are indistinguishable on the scale of the plot. This agreement is not surprising. All expressions that I know for the saturation vapor pressure for a planar ice surface as a function of temperature derive from the Clausius–Clapeyron equation (e.g., Bohren and Albrecht, 1998, p. 192ff.). For an ice surface, this equation is

$$\frac{d \ln[e_{sat,i}(T)]}{dT} = \frac{M_w L_v(T)}{R T^2}, \qquad (5)$$

where $L_v(T)$ is the latent heat of sublimation of pure water ice as a function of temperature. As a result, most independently

derived expressions for $e_{sat,i}(T)$ are well constrained by the constants M_w and R and by evaluations of $L_v(T)$.

I will tend to focus on Murphy and Koop's (2005) new expression for $e_{sat,i}(T)$ because it extends to the lowest temperature and adequately represents the existing data down to 140 K. Although Murphy and Koop state that Eq. (4) is good for temperatures above 110 K, they obtained $L_v(T)$ for use in (5) by integrating data for the specific heat of ice at constant pressure that spanned 20–273 K. Therefore, because Murphy and Koop's $e_{sat,i}$ expression is well constrained by both thermodynamics and data, I have some justification for extrapolating it down to 40 K, which I do in the next section. But I also extrapolate both the Buck (1981) and Wagner et al. (1994) results down to 40 K to see if the three expressions provide any consensus as to the low-temperature sublimation rate of ice. Again, my justification for these extrapolations is that the Buck and Wagner et al. relations are also theoretically based and thus largely constrained by thermodynamics.

4. Results

Using Eqs. (2)–(4) for $e_{sat,i}$ in Eq. (1), I can make three distinct estimates for the sublimation rate of water ice for temperatures typical of shaded craters near the lunar poles. Fig. 2 shows the results of those calculations. The left axis gives the sublimation rate down to 40 K as a mass flux; units here are micrograms of ice lost per square centimeter of exposed ice per hour. The right axis in Fig. 2 gives the sublimation rate in terms of water vapor molecules escaping from the ice per square centimeter of its exposed surface per hour.
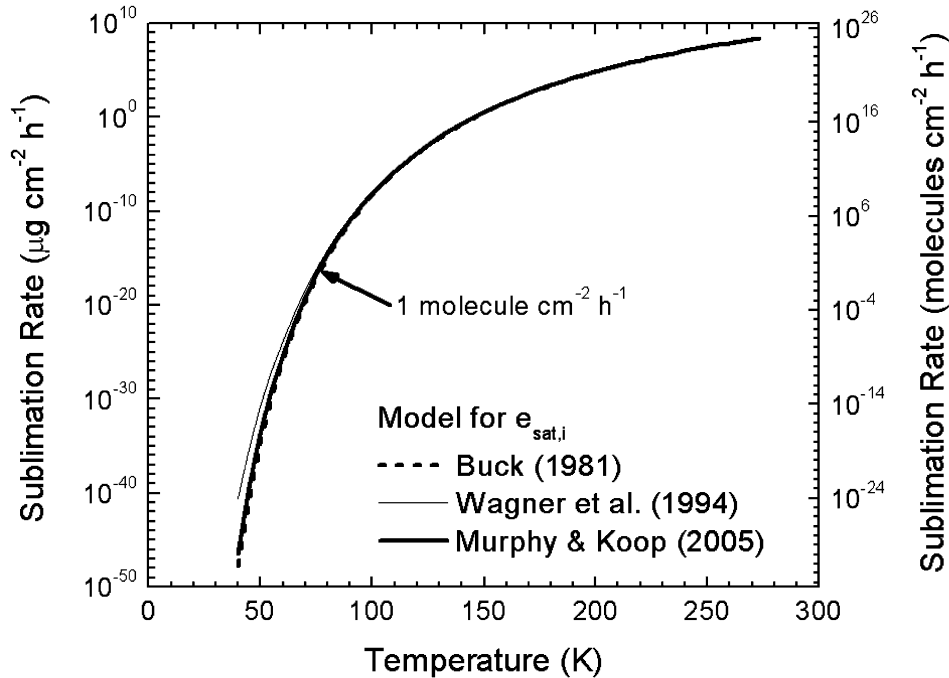
Fig. 2. The sublimation rate for a planar surface of pure ice calculated using the expressions from Buck (1981), Wagner et al. (1994), and Murphy and Koop (2005) for $e_{sat,i}$ in Eq. (1). The left axis gives the sublimation rate as a mass flux; its units are $\mu g\, cm^{-2}\, h^{-1}$. The right axis gives the sublimation rate as the number of molecules of water vapor leaving a square centimeter of the ice surface per hour. The arrow shows where the sublimation rate is only 1 molecule $cm^{-2}\, h^{-1}$.

For temperatures down to about 80 K, the three estimates of sublimation rate in Fig. 2 are indistinguishable on the scale of this plot. Notice, to make estimates at 80 K, I extrapolated both the Buck (1981) and Wagner et al. (1994) expressions downward over 100 K. The consistency among the three estimates at this point is good evidence that the functional forms used in Eqs. (2)–(4) are well guided by theory and data.

Below 80 K, estimates for sublimation rate based on Buck's (1981) and Murphy and Koop's (2005) expressions for the saturation vapor pressure are still quite close despite the large temperature range over which I have extrapolated them. The sublimation rate based on Wagner et al. (1994) is about seven orders of magnitude above these other two at 40 K. Nevertheless, by this point, I predict the sublimation rate to be so small that even such seemingly large discrepancies are negligible for estimating the mass loss for water ice during sampling of the lunar regolith.

The right axis in Fig. 2 tries to put this assessment in perspective. It shows that, at about 70 K, the sublimation rate is *one molecule* of water vapor per square centimeter per hour for all three curves. And the sublimation rate decreases by 25–30 orders of magnitude as the temperature decreases from 70 to 40 K. Hence, if a robotic or human explorer were to drill or excavate a regolith sample that is originally near 40 K, essentially no water ice will be lost if the sample is not heated by more than, say, 100 K and if the ice concentration can be measured within an hour of freeing the sample. Fig. 2 also allows evaluating other sampling and handling scenarios. Section 6 further quantifies this assessment.

5. Other effects on sublimation rate

5.1. Contamination

Ice deposits on the Moon might be "dirty"—for example, mixed with regolith dust, carbon dioxide, or some other contaminant (Nozette et al., 2001). Any such contaminants will lower the saturation vapor pressure of the ice and, consequently, slow its sublimation rate. A simple thought experiment demonstrates this effect. If ice is mixed with other molecules, some of these molecules must be at the surface of the sample and have, thus, displaced ice molecules here. The vapor pressure of the ice must consequently be less than for a pure sample by a fraction reflecting the surface area of the ice and the surface area of the contaminants on the sublimating surface.

This lowering of the vapor pressure in a contaminated sample is essentially Raoult's law if the ice and the contaminant are miscible (Bohren, 1987, p. 22f.; Bohren and Albrecht, 1998, p. 230ff.). If the ice and the contaminant are not miscible—for example, if the contaminant is regolith dust—we can still estimate the lowering of the vapor pressure by using geometry to evaluate what fraction of the exposed surface is dust.

Because we know neither the size of lunar water ice deposits nor the composition or concentration of possible contaminants, I see little value in speculating here how much such contaminants might lower the sublimation rate of ice. Suffice it to say that any contamination lowers the already miniscule sublimation rate of ice near the lunar poles.

5.2. Surface curvature

If ice on the Moon does not occur in massive blocks deposited by comets—and no good evidence exists that it does (e.g., Stacy et al., 1997; Campbell and Campbell, 2006)—it still may occur in small quantities attached to regolith grains. In this case, the curvature of the ice surface could affect its sublimation rate. The Kelvin equation describes this effect (Pruppacher and Klett, 1997, p. 170; Bohren and Albrecht, 1998, p. 240ff.),

$$\frac{e_r}{e_{\text{sat,i}}} = \exp\left(\frac{2 M_{\text{w}} \sigma_{\text{i}}}{\rho_{\text{i}} r R T}\right). \tag{6}$$

Here, $e_{\text{sat,i}}$ is again the saturation vapor pressure of a pure, planar water ice surface, as calculated with Eqs. (2)–(4); e_r is the vapor pressure of a curved ice surface with radius of curvature r; σ_{i} is the surface tension of a pure ice/vapor interface; and ρ_{i} is the density of the water ice. Two situations are possible. If the ice coats a regolith grain and thus has a convex surface, r is positive and the vapor pressure is increased. If the ice joins two grains or otherwise has a concave surface, r is negative and the vapor pressure is reduced.

Fig. 3 shows some examples of how surface curvature could affect the vapor pressure of microscopic ice deposits on regolith grains that have the size found in lunar samples (Heiken et al., 1993, p. 318). I obtained these values from Eq. (6) by using Hobbs' (1974, p. 440) value for the surface tension, 0.109 J m^{-2}, and Pruppacher and Klett's (1997, p. 79f.) equation for the density of pure ice as a function of temperature,

$$\rho_{\text{i}} = 916.7 - 0.175(T - 273.15) \\ - 5.0 \times 10^{-4}(T - 273.15)^2. \tag{7}$$

Here, ρ_{i} is in kg m^{-3} and T is in kelvins. Equation (7) agrees to within about 1% with Hobbs' (1974, p. 348) tabulated values for the density of ice for all temperatures between 13 and 273.15 K.

Because $e_r/e_{\text{sat,i}}$ is close to one, Fig. 3 plots $e_r/e_{\text{sat,i}} - 1$. Therefore, in the figure, where $e_r/e_{\text{sat,i}} - 1$ is positive, the vapor pressure over a curved surface is higher than it would be over a planar surface. Where $e_r/e_{\text{sat,i}} - 1$ is negative, as it is for a
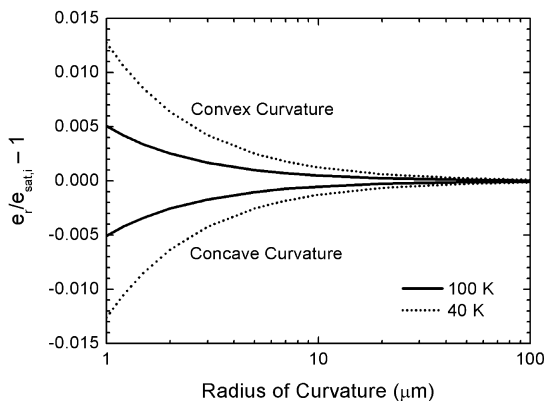
concave surface, the vapor pressure is lower than over a planar surface.

According to Fig. 3, concave curvature lowers the vapor pressure by less than 2% for the smallest ice deposits we would likely find in the shaded lunar craters. Convex curvature, on the other hand, raises the vapor pressure for these smallest deposits by less than 2%. Consequently, sublimation rates will either decrease or increase accordingly. The magnitude of these curvature effects decreases rapidly with increasing radius of curvature, however; it is practically zero for radii of 100 μm and larger.

6. Mass loss during sublimation

No evidence has appeared to suggest that water ice at the lunar poles occurs in massive deposits. In fact, the relevant evidence discounts the possibility of massive deposits (Stacy et al., 1997; Margot et al., 1999; Campbell et al., 2003; Campbell and Campbell, 2006). Therefore, I suspect that any lunar ice deposits are very small. Furthermore, any robotic sampler of water ice must work with very small samples simply because of mission weight limitations. Consequently, in estimating how sublimation will alter measurements of water ice concentration in samples obtained robotically, I can assume, in general, that such samples are small.

I want to estimate how the mass of a pure water ice sample, $m(t)$, decreases as a function of time (t) because of sublimation when the ice is raised to temperature T. This problem has no general solution, however, because each estimate will depend on the geometry of the sample—in particular, on the ratio of the area of exposed surface to the total volume. As the geometrically simplest example, I consider a spherical ice deposit with initial radius r_0 and, thus, initial mass $m_0 = 4\pi \rho_{\text{i}} r_0^3 / 3$. As the radius of this sample changes because of sublimation, the mass at any later time is

$$m(t) = \frac{4}{3}\pi \rho_{\text{i}} r(t)^3, \tag{8}$$

where $r(t)$ is the radius as a function of time.

Essentially by definition, the change in radius of this ice sphere with time at constant temperature is related to the sublimation rate,

$$\frac{dr}{dt} = -\frac{S_r}{\rho_{\text{i}}}. \tag{9}$$

Here, though, because I acknowledge that the sample may be small, S_r must include curvature effects; hence, from Eqs. (1) and (6),

$$S_r = e_{\text{sat,i}}(T)\left(\frac{M_{\text{w}}}{2\pi R T}\right)^{1/2} \exp\left(\frac{2 M_{\text{w}} \sigma_{\text{i}}}{\rho_{\text{i}} r R T}\right) \\ = S_0 \exp\left(\frac{2 M_{\text{w}} \sigma_{\text{i}}}{\rho_{\text{i}} r R T}\right). \tag{10}$$

Consequently, from Eqs. (9) and (10), we can find the time evolution of the radius:

$$\int_{r_0}^{r(t)} \exp(-r_{\text{c}}/r)\, dr = -\frac{S_0}{\rho_{\text{i}}} \int_0^t dt, \tag{11}$$

Fig. 3. The saturation vapor pressure over a curved ice surface (e_r) compared to the saturation vapor pressure over a planar ice surface ($e_{\text{sat,i}}$) for two lunar temperatures.

where

$$r_c \equiv \frac{2M_w\sigma_i}{\rho_i RT} \qquad (12)$$

is the radius at which curvature effects increase the sublimation rate by 2.7 times (i.e., where $S_r = e^1 S_0$).

The largest value of r_c occurs at the lowest temperature—40 K in our case—where $r_c = 1.3 \times 10^{-8}$ m. For ice deposits of 1-µm radius or larger, I can thus approximate the exponential in Eq. (11) as a Taylor series and need to keep only the first two terms. Then, Eq. (11) integrates to

$$r(t) - r_0 - r_c \ln\left[\frac{r(t)}{r_0}\right] = -\frac{S_0 t}{\rho_i}. \qquad (13)$$

Because we want to prevent an ice deposit from losing appreciable mass—say no more than 10%—from the time it is obtained until it is tested, $r(t)/r_0$ must always be at least 0.95. Therefore, I can also expand the logarithm in Eq. (13) as a Taylor series around r_0 and, again, need to keep only the first two terms to finally obtain

$$r(t) = r_0 - \left(\frac{r_0}{r_0 - r_c}\right)\frac{S_0 t}{\rho_i}. \qquad (14)$$

Consequently, the fraction of mass remaining at time t in a spherical ice deposit of initial radius r_0 after the deposit is raised to temperature T is

$$\frac{m(t)}{m_0} = \left[1 - \frac{S_0 t}{\rho_i(r_0 - r_c)}\right]^3. \qquad (15)$$

Because Eq. (15) depends inversely on r_0, the fractional mass loss becomes more severe as the original size of the ice deposit decreases. Fig. 4 therefore shows $m(t)/m_0$ for two small, spherical ice deposits: one with an initial radius of 100 µm, for which curvature effects are negligible (see Fig. 3); and the other with $r_0 = 1$ µm, for which both the small size and the curvature effects combine to speed sublimation.

The time in Fig. 4 ranges from 1 to 10^{14} s, where 10^{14} s is over three million years. Thus, if a small, spherical lunar

water ice deposit, originally at 40 K, is not heated to more than 70 K, sublimation losses during robotic sampling would be insignificant. If a 100-µm-radius ice deposit were heated to 170 K during processing, however, it would lose 10% of its original mass in about an hour. If the original sample is only 1 µm in radius and were heated to 170 K, it would sublimate 10% of is mass in only 32 s.

As I mentioned, the results shown in Fig. 4 are just examples of the estimates possible with the information I have presented. In general, though, Fig. 4 suggests that robots or humans who collect in situ samples of regolith near the lunar poles to test for the presence of water ice will not lose much of the water through sublimation if the excavating and testing are done quickly and the sample is not heated above, say, 150 K. The largest ice deposit depicted in Fig. 4 has an initial radius of 100 µm. Because larger spheres have smaller surface-to-volume ratios, they would lose relatively less mass for the same temperature and exposure time as shown for these 100-µm deposits. Consequently, if ice deposits are more massive or if the sampling can accommodate larger samples, the handling restrictions are less severe than those I describe.

7. Conclusions

By surveying available data for the saturation vapor pressure of ice and on invoking a new expression for the vapor pressure as a function of temperature, I have made the first estimates for the sublimation rate of water ice in a vacuum down to 40 K. My estimates thus extend to temperatures 60 K lower than previous estimates by Watson et al. (1961) and Vasavada et al. (1999) and predict sublimation rates at 40 K that are 33–39 orders of magnitude smaller than their lowest predicted rates.

The explicit application for this research is for developing sampling and handling methods for expeditions to the lunar poles to make in situ measurements of water ice concentration in the regolith. The results I have developed, however, would apply equally well for exploring Mars or Mercury (e.g., Vasavada et al., 1999; Campbell and Campbell, 2006;
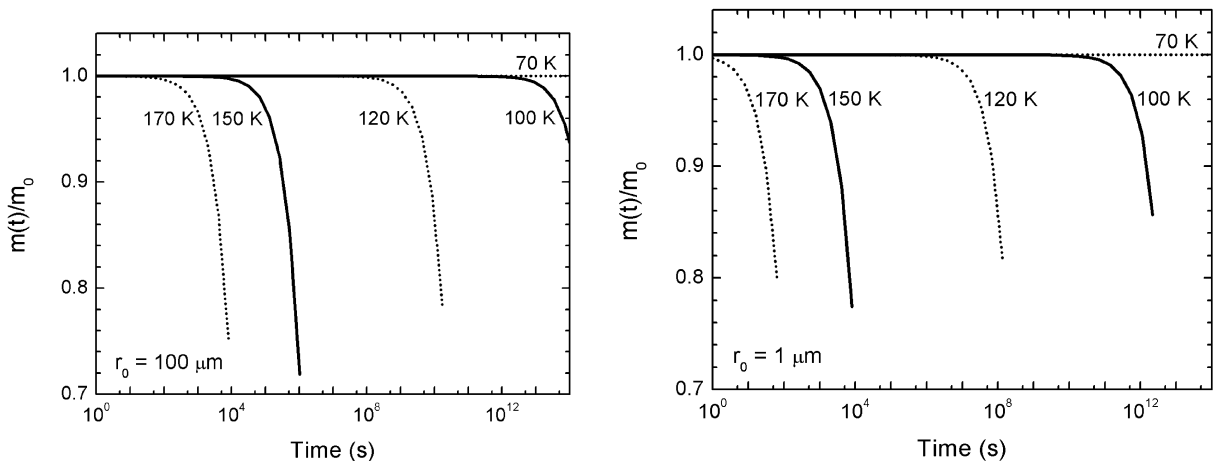

Fig. 4. The fraction of initial mass (m_0) remaining after time t when spherical samples of pure water ice with initial radii (r_0) of 100 µm and 1 µm (initial masses of 3.9 ng and 3.9 fg, respectively) are exposed at the indicated temperature. The estimates are based on Eq. (15) with sublimation rates computed using Murphy and Koop's (2005) expression for $e_{sat,i}$, Eq. (4).

Taylor et al., 2006) and for work in evacuated, low-temperature test chambers on Earth. In a nutshell, the sublimation rate for an ice sample collected at the lunar poles, where temperature is predicted to be 40–70 K, is so slow that only by careless heating or handling would the sample lose a significant fraction of its ice in the hour after it was freed from the regolith.

Contaminants in the ice sample decrease this sublimation rate. The surface curvature of microscopic ice deposits also affects their sublimation rate. For a deposit with a radius of curvature of 1 μm, concave curvature lowers the sublimation rate by less that 2%; convex curvature raises it by less than 2%. Larger deposits experience smaller effects.

On combining these new estimates of sublimation loss and curvature effects, I predict that a spherical lunar ice deposit of initial radius 1 μm would lose 10% of its initial mass in only 32 s if it were heated to 170 K. A 100-μm-radius deposit, however, would require about an hour to lose 10% of its mass by sublimation if it were heated to 170 K. Larger samples suffer even smaller rates of fractional mass loss. Retaining lunar ice samples near their original temperature of 40 K, on the other hand, would preserve the ice against sublimation for many millennia.

Acknowledgments

References

Arnold, J.R., 1979. Ice in the lunar polar regions. J. Geophys. Res. 84, 5659–5668.

Bohren, C.F., 1987. Clouds in a Glass of Beer: Simple Experiments in Atmospheric Physics. Wiley, New York.

Bohren, C.F., Albrecht, B.A., 1998. Atmospheric Thermodynamics. Oxford Univ. Press, New York.

Bryson III, C.E., Cazcarra, V., Levenson, L.L., 1974. Sublimation rates and vapor pressures of H_2O, CO_2, N_2O, and Xe. J. Chem. Eng. Data 19, 107–110.

Buck, A.L., 1981. New equations for computing vapor pressure and enhancement factor. J. Appl. Meteor. 20, 1527–1532.

Campbell, B.A., Campbell, D.B., 2006. Regolith properties in the south polar region of the Moon from 70-cm radar polarimetry. Icarus 180, 1–7.

Campbell, B.A., Campbell, D.B., Chandler, J.F., Hine, A.A., Nolan, M.C., Perillat, P.J., 2003. Radar imaging of the lunar poles. Nature 426, 137–138.

Carruba, V., Coradini, A., 1999. Lunar cold traps: Effects of double shielding. Icarus 142, 402–413.

Coakley, G.W., 1885. The disappearance of the water and atmosphere of the Moon. Papers Am. Astron. Soc. 1, 1–8.

DesMarais, D.J., Hayes, J.M., Meinschein, W.G., 1974. The distribution in lunar soil of hydrogen released by pyrolysis. Geochim. Cosmochim. Acta (Suppl.) 5, 1811–1822.

Eshleman, V.R., Parks, G.A., 1999. No ice on the Moon? Science 285, 531.

Estermann, I., 1955. Gases at low densities. In: Rossini, F.D. (Ed.), Thermodynamics and Physics of Matter. Princeton Univ. Press, Princeton, NJ, pp. 736–776.

Feldman, W.C., Maurice, S., Lawrence, D.J., Little, R.C., Lawson, S.L., Gasnault, O., Wiens, R.C., Barraclough, B.L., Elphic, R.C., Prettyman, T.H., Steinberg, J.T., Binder, A.B., 2001. Evidence for water ice near the lunar poles. J. Geophys. Res. 106, 23231–23251.

Heiken, G.H., Vaniman, D.T., French, B.M., 1993. Lunar Sourcebook: A User's Guide to the Moon. Cambridge Univ. Press, Cambridge, UK.

Hilsenrath, J., Beckett, C.W., Benedict, W.S., Fano, L., Hoge, H.J., Masi, J.F., Nuttall, R.L., Touloukian, Y.S., Woolley, H.W., 1960. Tables of Thermodynamic Transport Properties of Air, Argon, Carbon Dioxide, Carbon Monoxide, Hydrogen, Nitrogen, Oxygen, and Steam. Pergamon Press, Oxford, UK.

Hobbs, P.V., 1974. Ice Physics. Clarendon Press, Oxford, UK.

Hodges Jr., R.R., 1973. Helium and hydrogen in the lunar atmosphere. J. Geophys. Res. 78, 8055–8064.

Jancso, G., Pupezin, J., Van Hook, W.A., 1970. The vapor pressure of ice between $+10^{-2}$ and $-10^{+2°}$. J. Phys. Chem. 74, 2984–2989.

Lide, D.R. (Ed.), 2001. CRC Handbook of Chemistry and Physics, 82nd ed. CRC Press, Boca Raton, FL.

Margot, J.L., Campbell, D.B., Jurgens, R.F., Slade, M.A., 1999. Topography of lunar poles from radar interferometry: A survey of cold trap locations. Science 284, 1658–1660.

Marti, J., Mauersberger, K., 1993. A survey and new measurements of ice vapor pressure at temperatures between 170 and 250 K. Geophys. Res. Lett. 20, 363–366.

Murphy, D.M., Koop, T., 2005. Review of the vapour pressures of ice and supercooled water for atmospheric applications. Quart. J. R. Meteor. Soc. 131, 1539–1565.

Nozette, S., Spudis, P.D., Robinson, M.S., Bussey, D.B.J., Lichtenberg, C., Bonner, R., 2001. Integration of lunar polar remote-sensing data sets: Evidence for ice at the lunar south pole. J. Geophys. Res. 106, 23253–23266.

Pruppacher, H.R., Klett, J.D., 1997. Microphysics of Clouds and Precipitation, second ed. Kluwer, Dordrecht.

Stacy, N.J.S., Campbell, D.B., Ford, P.G., 1997. Arecibo radar mapping of the lunar poles: A search for ice deposits. Science 276, 1527–1530.

Starukhina, L.V., Shkuratov, Y.G., 2000. The lunar poles: Water ice or chemically trapped hydrogen? Icarus 147, 585–587.

Taylor, P.A., Baibakov, K., Brown, S., Hecht, M.H., Hudson, T.L., Li, P.-Y., Lange, C.F., Prieto, L., Savelyev, S., 2006. On the sublimation of ice particles on the surface of Mars; with applications to the 2007/8 Phoenix Scout mission. Icarus 181, 375–387.

Vasavada, A.R., Paige, D.A., Wood, S.E., 1999. Near-surface temperatures on Mercury and the Moon and the stability of polar ice deposits. Icarus 141, 179–193.

Wagner, W., Saul, A., Pruss, A., 1994. International equations for the pressure along the melting and along the sublimation curve of ordinary water substance. J. Phys. Chem. Ref. Data 23, 515–527.

Watson, K., Murray, B.C., Brown, H., 1961. The behavior of volatiles on the lunar surface. J. Geophys. Res. 66, 3033–3045.