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Research Paper

On Laboratory Simulation and the Effect of Small Temperature Oscillations About the Freezing Point and Ice Formation on the Evaporation Rate of Water on Mars

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ABSTRACT

We report measurements of the evaporation rate of water under Mars-like conditions (CO_2 atmosphere at 7 mbar and ~0°C) in which small temperature oscillations about the freezing point repeatedly formed and removed a thin layer of ice. We found that the average evaporation at 2.7 ± 0.5°C without an ice layer (corrected for the difference in gravity on Earth and on Mars) was 1.24 ± 0.12 mm/h, while at −2.1 ± 0.3°C with an ice layer the average evaporation rate was 0.84 ± 0.08 mm/h. These values are in good agreement with those calculated for the evaporation of liquid water and ice when it is assumed that evaporation only depends on diffusion and buoyancy. Our findings suggest that such differences in evaporation rates are entirely due to the temperature difference and that the ice layer has little effect on evaporation rate. We infer that the formation of thin layers of ice on pools of water on Mars does not significantly increase the stability of water on the surface of Mars. **Key Words: Water—Ice—Mars—Evaporation rate.** Astrobiology 6, xxx–xxx.

INTRODUCTION

THE DISCOVERY of an almost global distribution of subsurface ice (Boynton *et al*., 2002) and evidence for the flow of a liquid onto the surface of Mars (Malin and Edgett, 2000) has led to an increased level of interest in the stability of liquid water on Mars. We have constructed a laboratory facility for simulating surface conditions on Mars and recently reported our first results. We have reported measurements of the evaporation rate of water in a 7 mbar CO_2 atmosphere at 0°C (Sears and Moore, 2005) and reported the evaporation rate of brine at temperatures between 0°C and −26°C (Sears and Chittenden, 2005). In both cases, there was very good agreement between our experimentally determined values and those predicted by the model-dependent hypothesis of Ingersoll (1970). However, with surface conditions on Mars typically close to the triple point, at least at the Viking landing sites, it seems likely that liquid water on the surface of Mars may periodically be covered by an ice layer that would suppress the evaporation rate (*e.g.*, Clow, 1987). Here we report the first experimental attempt to experimentally investigate such an effect.

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EXPERIMENTAL PROCEDURES

F1

Our chamber, shown in Fig. 1, consists of an insulated (20-cm fiberglass) stainless steel tube 208 cm long and with an internal diameter of 61 cm, which can be pumped down to ~0.05 mbar and back-filled with dry CO_2. The pump is isolated from the chamber by a U-tube cold finger. A 1-ton hoist is used to remove the lid and insert experiments. The chamber is surrounded by 52 m of half-inch copper cooling coils, through which methanol–dry ice coolant is pumped.

Eight thermocouples are distributed throughout the apparatus, one of which is on the surface of the water, and pressure is constantly monitored with a Pirani gauge. A 7-W lamp could be momentarily turned on to view the water via a digital television camera. A 60-W heat lamp could also be momentarily turned on to warm the surface of the water.

For the present experiments, an Ainsworth top loading balance was installed on a platform, and a 100-ml beaker was placed on the balance. The beaker contained ~70 ml of distilled water and ice cubes, with copper gauze holding the ice below the surface. Our experiment involved cooling the chamber to the desired temperature, evacuating to about 0.07 mbar (to completely dry the chamber), filling to 1 atmosphere with dry gaseous CO_2 from a cylinder, opening the chamber and placing the beaker on the balance, adjusting the cameras and checking the thermocouples, and closing and evacuating to 7 mbar. During the last few minutes of the final evacuation, the beaker was monitored via television while pumping at a slow rate. The experiment was terminated in the event that boiling occurred. As soon as 7 mbar was reached, the logging of data began.

Conditions for the experiment were adjusted to hold the sample a few degrees below freezing,

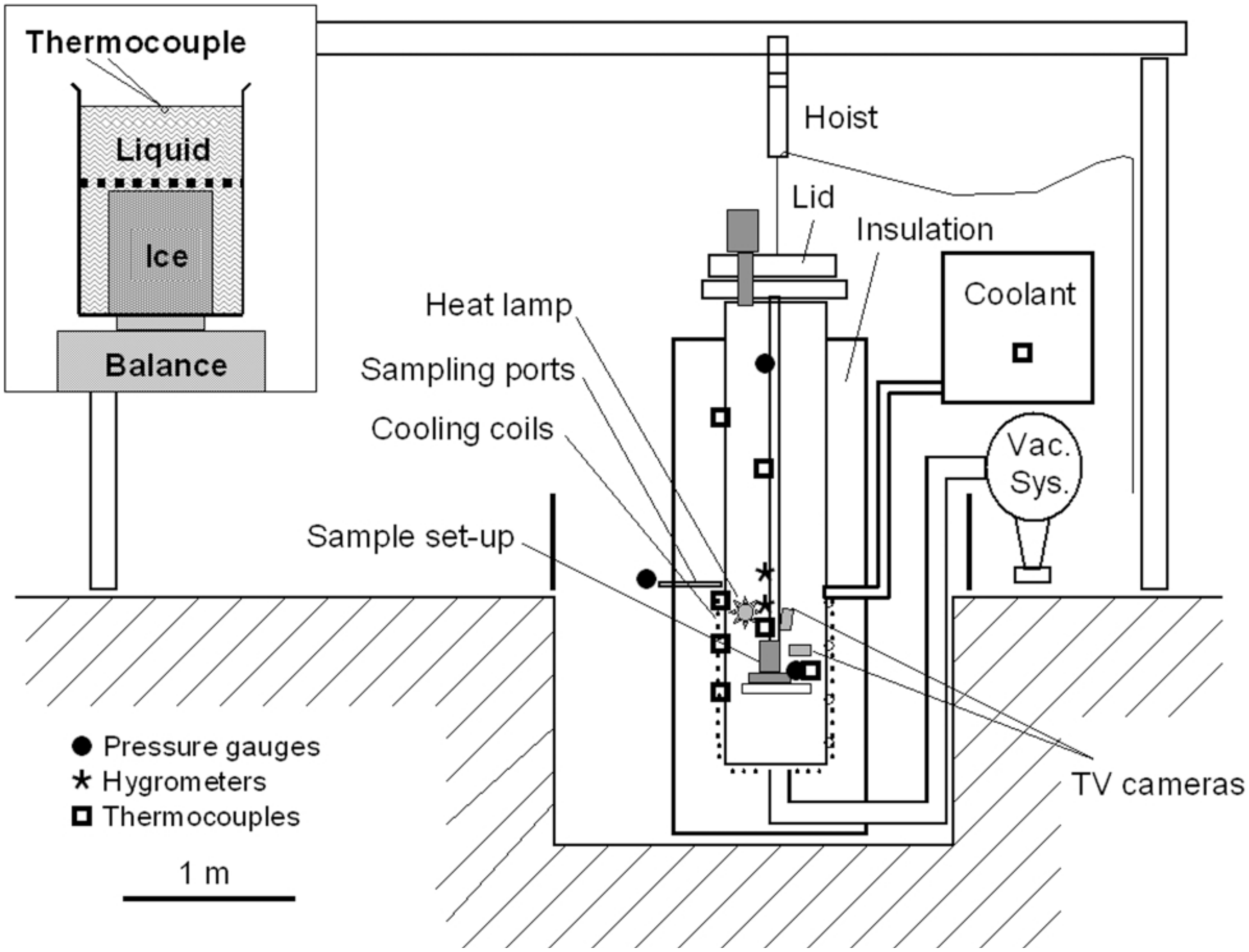

FIG. 1. Schematic diagram of the apparatus used for the present work. (**Inset**) Sample-balance set-up.

F2

while the surface of the water could be illuminated by the heat lamp to bring the temperature to just above freezing (Fig. 2). This method of temperature cycling was performed every 20 min during the course of the experiment.

A thin ice layer was observed to form across the water—fingers of ice radiating out from a point on the circumference until 80% or more of the surface was covered—when the heat lamp was turned off. This ice layer would immediately shrink to less than about 25% of the surface as soon as the lamp was turned on. The details of the appearance and disappearance of the ice were remarkably reproducible.

We report the customary meteorology precipitation units for our evaporation rates (mm/h). However, such units can be converted to units of flux (g/cm^2·h) by dividing by 10 to convert mm to cm and multiplying by the density of water (1 g/cm^3).

RESULTS

F3

Figure 3A shows the loss of mass during the experiment. Over a period of about 100 min, about 9 g of water were lost by evaporation. The mass loss with time was not perfectly linear, but the evaporation rate changed monotonically from about 1.17 mm/h to 0.94 mm/h. This is consistent with a suppression of the evaporation rate by the buildup of ~20% (by volume) water vapor in the atmosphere of the chamber (Fig. 3B). This effect was observed when the water vapor was not removed.

More significantly, superimposed on the long-term evaporation rate change trend were temperature changes associated with turning the heat lamp on and off, which resulted in oscillations of the surface temperature between 3°C and −2°C and the disappearance and re-formation, respectively, of an ice layer (Fig. 3C). By plotting a line through segments of the data that correspond to the main intervals of any one cycle, it was possible to determine the evaporation rate for each interval. The data points measured during each interval are listed in Table 1 and shown as solid symbols in Fig. 2. The data points shown as open symbols in Fig. 2 represent time points when the system was in transition. The average evaporation rate determined with the lamp off when the

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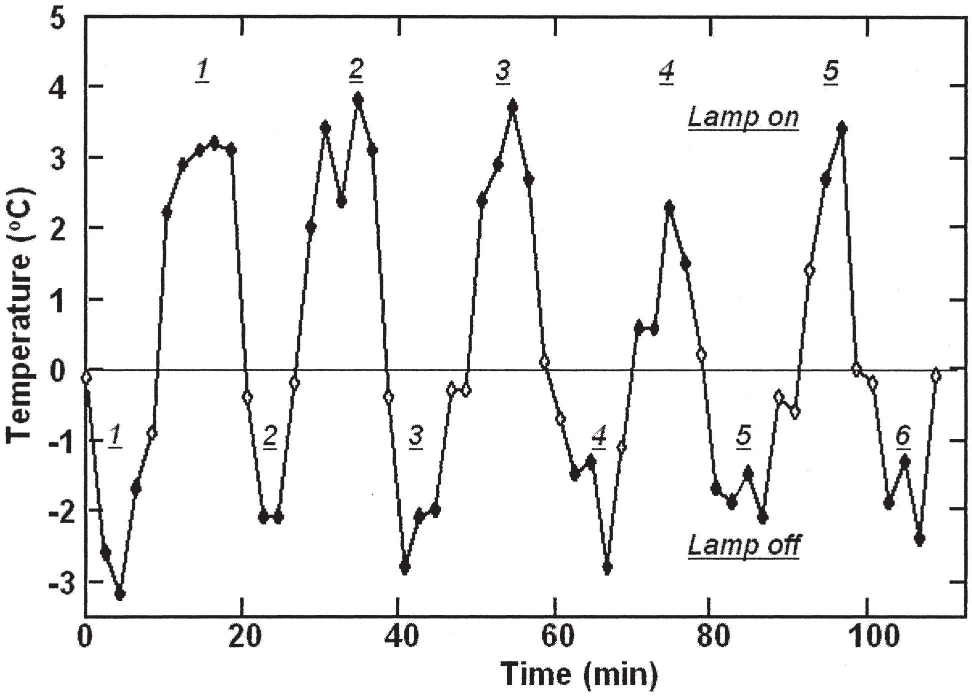

FIG. 2. Temperature of the surface of the water throughout the duration of the experiment. The periods of time when the temperature of the water surface was 2–3°C above freezing alternated with periods when the temperature was 2–3°C below freezing because of the heating effect of a lamp turned on/off to cycle the temperature. Throughout the experiment, the atmosphere and the walls of the chamber were maintained close to 0°C. The numbers refer to the lamp on/off intervals as indicated in Table 1. Data for solid symbols were used in calculating temperatures and evaporation rates.

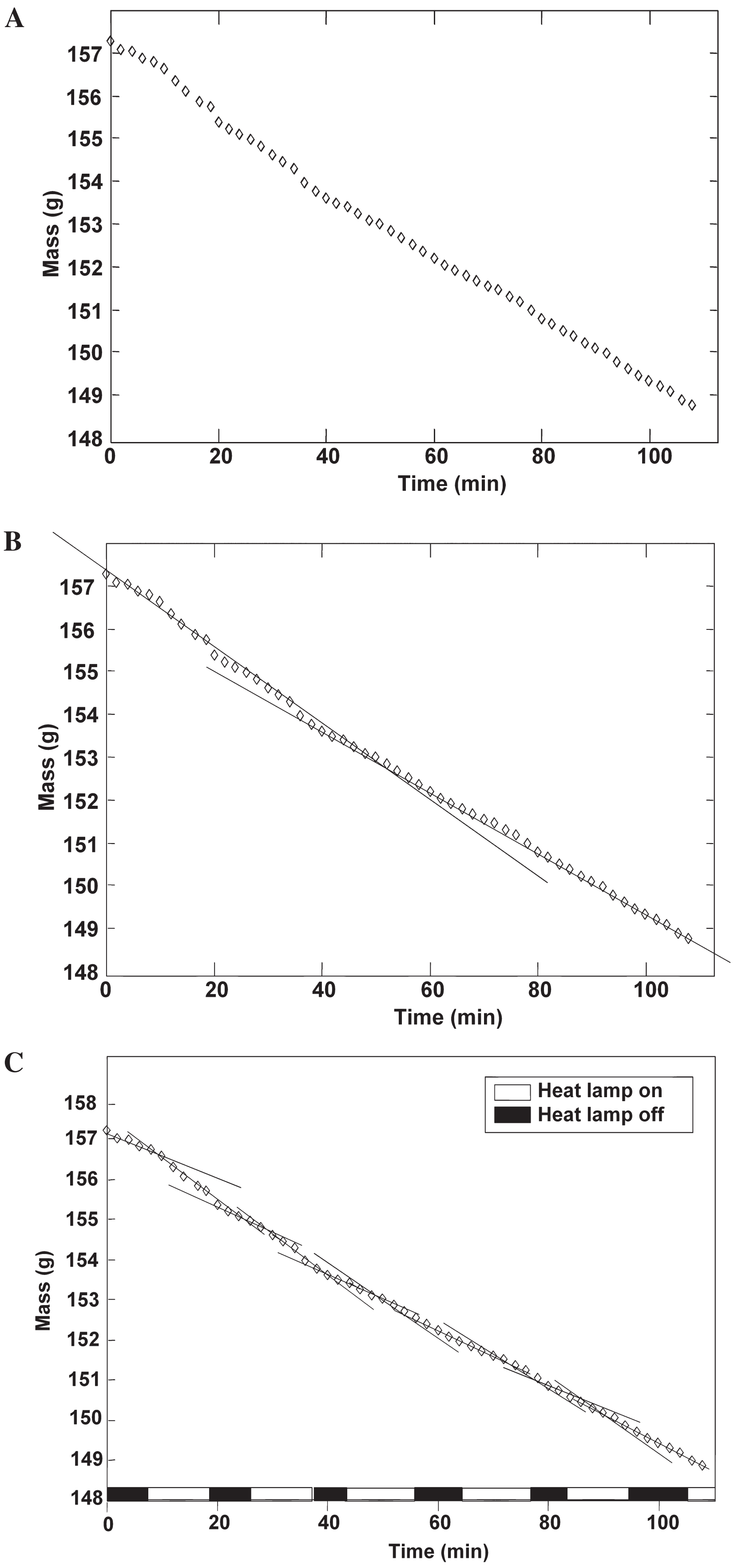

FIG. 3. (**A**) Mass of the water, beaker, and associated apparatus as a function of time through the experiment. Notice the high level of precision in the data: the experimental uncertainties are smaller than the size of the symbols. (**B**) The rate of evaporation was not constant throughout the experiment but showed a smooth long-term decrease from 1.17 mm/h to 0.94 mm/h (corrected for the gravity difference between Earth and Mars). This behavior is typical of experiments performed in the laboratory under these conditions and reflects the slow buildup of water vapor in the atmosphere. (**C**) Superimposed on the long-term trends were small-scale variations associated with the heat lamp being turned and off as the experimental conditions were cycled. For each interval of time an evaporation rate was measured. The average evaporation rate with the lamp on is 1.17 ± 0.94 mm/h and with the lamp off is 0.84 ± 0.08 mm/h, with both values having been corrected for gravity. The small variations of the curve reflected changes in evaporation rate and were attributed to the appearance and disappearance of a thin layer of ice on the surface of the water that was visible by closed-circuit television.

TABLE 1. EXPERIMENTAL DETERMINATIONS FOR THE EVAPORATION RATE (E^*) OF WATER IN A CO_2 ATMOSPHERE AT 7 MBAR AT TEMPERATURE (T) VALUES JUST ABOVE AND BELOW THE FREEZING POINT COMPARED WITH THE THEORETICALLY CALCULATED EVAPORATION RATES FOR WATER AND ICE ON MARS

	N	T (°C)	E* (mm/h)
Lamp off 1	3	−2.5	0.74
Lamp off 2	2	−2.1	0.79
Lamp off 3	3	−2.3	0.79
Lamp off 4	3	−1.7	0.92
Lamp off 5	4	−1.8	0.91
Lamp off 6	3	−1.9	0.89
Average		−2.05	0.84
Standard deviation		0.31	0.08
Lamp off 1	5	2.9	1.38
Lamp off 2	5	2.9	1.35
Lamp off 3	4	2.9	1.23
Lamp off 4	4	1.9	1.13
Lamp off 5	2	2.5	1.10
Average		2.74	1.24
Standard deviation		0.48	0.12
Interval			
0–50 min	26	0.4	1.17
50–108 min	27	0.0	0.94
Theory (equilibrium)[a]			
Liquid		3	1.24
Ice		−2	0.66
Theory (metastable)[a]			
Liquid		−2	0.68
Ice		3	1.31

N refers to the number of data points used to determine E^*, which is the evaporation rate corrected for the difference in gravity between Earth and Mars by multiplying the experimental values by: $E_{\text{Mars}}/E_{\text{Earth}} = (g_{\text{Mars}}/g_{\text{Earth}})^{1/3} = (3.75/9.81)^{1/3} = 0.726$. See the equation of Ingersoll (1970) described in the text. Note that the solid diamonds shown in Fig. 2 are included in the number of data points used to determine E^*.

[a] Calculated in the present work using the method of Ingersoll (1970) in the manner described in the text.

system was not in transition and at an average temperature of −2.05 ± 0.31°C was 0.84 ± 0.08 mm/h. In contrast, the average evaporation rate determined with the lamp on when the system was not in transition and with the average surface temperature of 2.74 ± 0.48°C was 1.24 ± 0.12 mm/h. For each of the ~3°C intervals, evaporation rates decreased from 1.38 mm/h to 1.10 mm/h as mean temperatures for the interval decreased from ~3°C to ~2°C. At the approximately −2°C intervals, evaporation rates increased from 0.74 mm/h to 0.89 mm/h as mean temperatures for the interval increased from approximately −3°C to approximately −2°C. Though only two to six data points were measured within each interval average, the consistent long-term trends and their correlations with temperature indicate a strong temperature dependency of evaporation rate even under conditions where other major forces, such as the presence and disappearance of ice, are present.

DISCUSSION

Comparison with previous experimental evaporation rates

Our average evaporation rates of 0.84 ± 0.08 mm/h at −2°C and 1.24 ± 0.12 mm/h at 3°C can be compared with previous experimental measurements. Kuznetz and Gan (2002) found values of 0.25, 0.26, 0.23, and 0.19 mm/h at pressures of 6.6–67.8 mbar, evaporation rates much lower than the values presented here, which did not show the expected pressure dependence. Hecht (2002) measured at high pressures, ranging from about 10 mbar to almost 1 bar, evaporation rates that ranged from 1 mm/h to 4 mm/h when extrapolated to 7 mbar. As discussed by Sears and Moore (2005), these earlier experimental values do not approach the data presented here with regard to precision and accuracy. Using the same apparatus and procedures reported in this experiment, Sears and Moore (2005) found an average of eight independent measurements for the evaporation rate for water on Mars at 0°C and 7 mbar to be 0.73 ± 0.14 mm/h, which is in excellent agreement with the evaporation rates measured in the experiment reported in this paper. Sears and Chittenden (2005) reported an evaporation rate of 1.09 ± 0.28 mm/h for a brine evaporated at −0.47 ± 1.17°C, which is also in agreement with the evaporation rates measured in this experiment.

Comparison with calculated evaporation rates

Ingersoll (1970) modeled the evaporation of water on Mars using diffusion of water molecules into a CO_2 atmosphere aided by the buoyancy of the water in the heavier gas and slowed down by the viscosity effects. Allowing for a few other minor effects and giving E in mm/h, the relationship is:

$$E = 0.612\ \Delta\eta\rho D\ [(\Delta\rho/\rho)g/\nu^2]^{1/3}/\rho_w \qquad (1)$$

where E is the evaporation rate in mm/h, ρ_w is the density of water (1 kg/m^3), $\Delta\eta$ is the concentration difference at the surface and at distance, ρ is atmospheric density, D is the diffusion coefficient for water in CO_2 (1.4×10^{-3} m^2/s), g is acceleration due to gravity (3.75 m/s^2), and ν is the kinematic viscosity of CO_2 (6.93×10^{-4} m^2/s). The term $\Delta\eta$ is calculated from:

$$\Delta\eta = VP(H_2O) \times m(CO_2)/P_{\text{atmos}} \times m\ (H_2O) \quad (2)$$

where $VP(H_2O)$ refers to the equilibrium vapor pressure of water, P_{atmos} refers to the atmospheric pressure, and the m terms refer to molecular weights. Under these conditions, this expression yields a value of 0.352 at 0°C and 7 mbar. The term $\Delta\rho/\rho$, the CO_2 density difference at the surface and at distance divided by the density at the surface, is calculated from:

$$\Delta\rho/\rho = \frac{VP(H_2O) \times [m(CO_2) - m(H_2O)]}{m(CO_2) \times P_{\text{atmos}} - [m(CO_2) - m(H_2O)] \times VP(H_2O)} \quad (3)$$

which yields a value of 1.053 at 0°C. From these relationships, the evaporation rate at 0°C at 7 mbar in a dry CO_2 atmosphere is calculated to be 0.83 mm/h. The results of Ingersoll (1970) are in excellent agreement with the evaporation rates measured in our experiment reported here.

It is possible to determine the evaporation rate at 3°C and −2°C when the surface of the water is liquid or frozen by substituting the appropriate value of $VP(H_2O)$ from the vapor pressure equations, which is determined by fitting lines through the data in Weast (1986). For liquid water we have:

$$\log VP(H_2O) = \frac{-2342}{T} + 9.358 \quad (4)$$

while for ice we have:

$$\log VP(H_2O) = \frac{-2666}{T} + 10.551 \quad (5)$$

Thus we calculate the values for the evaporation rate from the equilibrium phase and assumed metastable phases at 3°C and −2°C for water and ice listed in Table 1.

The evaporation rate of metastable liquid water at −2°C is not very different from the evaporation rate of ice at −2°C. Similarly, the evaporation rate of liquid water at 3°C is not very different from the evaporation rate of metastable ice at 3°C. In other words, the presence of ice on the water should not significantly affect the evaporation rate. On the other hand, the difference in evaporation rate of liquid water at 3°C and ice at −2°C is in close agreement to the difference in evaporation rates we observed: *i.e.*, 1.24 ± 0.12 mm/h measured for liquid water at 3°C, compared with 1.24 mm/h calculated, and 0.84 ± 0.08 mm/h measured for ice at −2°C, compared with 0.66 mm/h calculated.

IMPLICATIONS

Many factors will increase or decrease the rate of evaporation of water on Mars. Model-dependent theoretical treatments suggest that a 10–15 m/s wind increases evaporation rates by a factor of ~10 (Sears *et al.*, 2005), while temperatures as low as, say, −20°C will cause sufficiently concentrated brine solutions to decrease their evaporation rates by two orders of magnitude relative to solutions at the freezing point (Sears and Chittenden, 2005). Unpublished data from our laboratory suggest that a 20°C increase in air temperature—all else being equal—will cause a factor of 2 increase in evaporation rate, while pressure variations likely to occur on Mars cause very minor changes in evaporation rates (see Fig. 3 or Sears and Moore, 2005). The present results indicate that, while our theoretical and experimental procedures are capable of predicting and observing significant differences in evaporation rate as the temperature oscillates 5°C about the freezing point, the formation of ice as the temperature drops below freezing does not significantly affect the evaporation rate.

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REFERENCES

Boynton, W.B., Feldman, W.C., Squyres, S.W., Prettyman, T.H., Bruckner, J., Evans, L.G., Reedy, R.C., Starr, R., Arnold, J.R., Drake, D.M., Englert, P.A., Metzger, A.E., Mitrofanov, I., Trombka, J.I., D'Uston, C., Wanke, H., Gasnault, O., Hamara, D.K., Janes, D.M., Marcialis, R.L., Maurice, S., Mikheeva, I., Taylor, G.J., Tokar, R., and Shinohara, C. (2002) Distribution of hydrogen in the near surface of Mars: evidence for subsurface ice deposits. *Science* 297, 81–85. Epub 2002 May 30.

Clow, G.D. (1987) Generation of liquid water on Mars through the melting of a dusty snowpack. *Icarus* 72, 95–127.

Hecht, M.H. (2002) Metastability of liquid water on Mars. *Icarus* 156, 373–386.

Ingersoll, A.P. (1970) Mars: occurrence of liquid water. *Science* 168, 972–973.

Kuznetz, L.G. and Gan, D.C. (2002) On the existence and stability of liquid water on the surface of Mars today. *Astrobiology* 2, 183–195.

Malin, M.C. and Edgett, K.S. (2000) Evidence for recent groundwater seepage and surface runoff on Mars. *Icarus* 288, 2330–2335.

Sears, D.W.G. and Chittenden, J.D. (2005) On laboratory simulation and the temperature dependence of the evaporation rate of brine on Mars. Geophys. Res. Lett. 32(23), L2303, doi: 10.1029/2005GL024154.

Sears, D.W.G. and Moore, S.R. (2005) On laboratory simulation and the evaporation rate of water on Mars. Geophys. Res. Lett. 32, L16202, doi:10.1029/2005GL023443.

Sears, D.W.G., Roe, L.A., and Moore, S. (2005) Stability of Water and Gully Formation on Mars [abstract 1496]. In *36th Annual Lunar and Planetary Science Conference Abstracts,* LPI Contribution No. 1234, Lunar and Planetary Institute, Houston.

Weast, R.C., ed. (1986) *Handbook of Chemistry and Physics*, 66th ed., CRC Press, Boca Raton, FL.

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