On laboratory simulation and the evaporation rate of water on Mars

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[1] In order to better understand the stability of water on Mars, and factors likely to affect that stability, we have measured the evaporation rate of water in a CO₂ atmosphere at 7 mbar and $\sim 0^{\circ}$ C in a large environmental chamber that minimizes fluctuation in conditions. The average evaporation rate we measured was 1.01 ± 0.19 mm/h. This includes correction for water vapor build-up in the chamber, but not the effect of Mars' lower gravity. When corrections for this are applied, our predicted evaporation rate for water on Mars at 0°C and 7 mbar is 0.73 \pm 0.14 mm/h. This is in very good agreement with the value calculated by assuming that evaporation depends on diffusion and buoyancy. The consistency of these results suggests that - at least for these conditions - our approaches to the calculations and the laboratory simulations are reasonable. Citation: Sears, D. W. G., and S. R. Moore (2005), On laboratory simulation and the evaporation rate of water on Mars, Geophys. Res. Lett., 32, L16202, doi:10.1029/2005GL023443.

1. Introduction

[2] The stability of liquid water on Mars is of obvious significance for understanding martian surface processes in the present and past epochs, geomorphology and exobiology. The presence of liquid water on the surface of Mars is contrary to a view originally popularized by Ingersoll [1970] that the evaporation is so high that liquid water would not exist on the surface, a view that remains popular today [e.g., Haberle et al., 2001], although Malin and Edgett [2000] have recently described gullies that are unequivocal evidence that a liquid of some sort has flowed on the surface in recent times. This has led to an interest in the experimental determination of the evaporation rate of water under Mars-like conditions. Kuznetz and Gan [2002] reported four measurements made in a dessicator and Hecht [2002] reported three series of experiments made in a simulation chamber. There are serious discrepancies in the data from these authors, who performed measurements at a variety of pressures, some approaching atmospheric, and then extrapolated down to the pressure of Mars. We are interested in measuring the evaporation rate of water under a variety of conditions likely to occur on Mars, such as through a layer of ice [Clow, 1987], through a layer of dust [Farmer, 1976], or in the presence of a large concentration of salts [Malin, 1974], but as a first step we investigated the evaporation of pure water. By performing, for the first time, an intensive study of the evaporation of water at martian pressures, we hope to refine the experimental evaporation

rate for water on Mars and, by showing this is close to the expected theoretical value, demonstrate the feasibility of our simulation chamber for performing studies of the factors affecting water evaporation on Mars. Preliminary measurements, as we developed our equipment and procedures, were reported at a number of conferences [Sears et al., 2003, 2004a, 2004b, 2005; Sears and Moore, 2004], but the present paper supersedes those presentations.

2. Experimental

[3] Our chamber is the same as that used by *Fanale et al.* [1982], stripped down and completely refurbished (Figure 1). It is a stainless steel tube with an internal diameter of 61 cm and length of 208 cm, sealed at the bottom with a four inch outlet to a Kinney KDH (83 CFM) vacuum pump via a cyclone filter (Metra Inc.) and cold finger (U tube passing through coolant) and a lid that is removed with a one-ton hoist. The chamber is surrounded by 52 meters of half-inch copper cooling coils through which coolant is pumped with a gravity fed General Electric 1.5 HP pump. Fifty meters of Chromalox heating cable is also wrapped around the chamber and the whole is wrapped in about 20 cm of glass fibre insulation and encased in an aluminum cabinet 4' by 4' by 8'. The coolant used for the present work is methanol into which blocks of dry ice are dropped to maintain the desired temperature.

[4] Eight chromel-alumel thermocouples operated through Doric 5000 control units were placed throughout the chamber, four on the walls, two in the atmosphere over the sample, one in the coolant reservoir and one on the water surface. Two hygrometers manufactured by the Cooper Instrument Corporation (SRH 77A) were placed in the chamber, one 2.5 cm above the water surface and one at 20 cm. The hygrometers included thermistors to measure temperature at the point humidity was measured. Convection (SenTorr) and Pirani (Kurt J. Lesker) gauges were used to measure the pressure. A seven-watt lamp was installed that could be momentarily turned on to view the water.

[5] 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 typically contained about 70 mL of distilled water and ice cubes, with copper gauze holding the ice below the surface. Two digital television cameras viewed the beaker and enabled the balance to be read. An operator in the adjacent control room logged the data into an Excel spreadsheet.

[6] A typical experiment involved cooling the chamber to the desired temperature, evacuating to about 0.07 mbar (to completely dry the chamber), filling to one atmosphere with dry gaseous CO_2 from a cylinder (Linde),



Figure 1. Schematic diagram of the apparatus used for the present work with the sample-balance set-up shown in the inset.

opening the chamber and placing the beaker on the balance, adjusting the cameras and checking the thermocouples, closing and evacuating to 7 mbar, the last few minutes of pumping being at a slow rate while the beaker was monitored via television. As soon as 7 mbar was reached, logging of data began, recording mass, pressure, temperature, humidity and appearance of sample every ten minutes. The pressure was maintained between 6 and 8 mbar. As data were recorded, the lamp was turned on and if bubbling was observed throughout the water, or ice was observed on the surface, the experiment was terminated. After about an hour, ice formation on the surface invariably terminated the experiment.

[7] We checked for internal consistency of the balance and pressure gauges by ensuring that the mass lost was in agreement with the pressure gained when the system was closed, and we checked the long term stability of the balance by monitoring the mass of a dry beaker for \sim 5 hour. We also checked that the mass of the sample did not change during our set-up procedures, so that mass loss only occurred when the pressure reached 7 mbar and data logging began.

[8] The surface of the water was maintained close to zero by the presence of ice, although evaporative cooling sometimes lowered the temperature a few degrees. We were able to maintain the wall temperatures to within $\pm 1^{\circ}$ C of zero throughout most of the height of the chamber, and under these conditions the atmospheric temperature was close to zero. However, for several runs momentary use of a heat lamp to prevent ice formation on the surface of the water caused the air temperature to rise, usually by a few degrees but sometimes higher.

3. Results

[9] Figure 2 shows a typical example of the data produced during these experiments. Mass decreased at a

steady, but slightly decreasing rate as water vapor in the atmosphere slowly built-up. The water vapor pressure 2.5 cm and at 20 cm above the sample were the same within the precision of the hygrometers. As expected, a second-order curve fits the mass data very precisely (R^2 better than 0.992).

[10] The main challenge in these experiments is correcting for the effect of water buildup in the chamber. We handled this by using the second curve to extrapolate to the beginning of the experiment – before there was any mass loss – and determining the evaporation rate at that time. Thus although we are interested in the evaporation rate at t = 0, the long-term mass loss curves are critical to our method.

[11] Even though the sample was at 0°C when placed in the chamber, by the time the pressure in the chamber had reached 7 mbar and evaporation had begun, the temperature of the water surface had usually fallen a few degrees, and on one occasion the water was higher than 0°C, perhaps by excessive use of the lamp. It was clear from the imagery that the water was still liquid, and thus supercooled, and this was the case even when the atmosphere was warm. The evaporation rates for water in a dry CO_2 atmosphere at 7 mbar obtained during our experiments ranged from 0.7 mm/h to 1.34 mm/h with a mean of 1.01 mm/h and a standard deviation of 0.19 mm/h (Table 1). It is clear that this spread is mostly the result of variations in atmospheric temperature and further work with the chamber will remove some of this scatter.

4. Discussion

4.1. Evaporation Rate

[12] Our average evaporation rate of 1.01 ± 0.19 mm/h can be compared with previous measurements and with model predictions. *Ingersoll* [1970] calculated the evaporation rate of water from the expression whereby free convection driven by density difference between water vapor and ambient air (and not applicable to wind-driven advection). With minor modification, his expression is:

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

Where E is the evaporation rate in mm/h, ρ_w is the density of water (1 kg/m³), $\Delta\eta$ is the concentration difference at the



Figure 2. Example of the data produced during a typical experimental run. The filled symbols represent the mass of the sample while the open symbols represent the partial pressure of water vapor 2.5 cm from the surface (diamonds) and 20 cm from the surface (squares).

Table 1. Experimental Determinations for the Evaporation Rate of Water in a Dry CO_2 Atmosphere at 7 mbar Compared With the Calculated Evaporation Rate for Water on Mars

Experiment	Evaporation Rate, mm/h
1	0.70
2	0.91
3	0.71
4	1.03
5	1.07
6	1.13
7	1.16
8	1.34
Experimental average	1.01
Experimental std dev.	0.19
Corrected average ^a	0.73
Corrected std dev. ^a	0.14
Theory ^b	0.83

^aCorrected for the difference in gravity between Earth and Mars in the manner described in the text.

^bCalculated in the present work using the method of *Ingersoll* [1970] in the manner described in the text.

surface and at distance, ρ is atmospheric density, D is the diffusion coefficient for water in CO₂ (1.4 \times 10⁻³ m²/s), g is acceleration due to gravity (3.75 m/s²), and ν is the kinematic viscosity of CO₂ (6.93 \times 10⁻⁴ m²/s). The term $\Delta\eta$ is calculated from:

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

where VP(H₂O) refers to the saturated 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 CO₂ density difference at the surface and at distance divided by the density at the surface, is calculated from:

$$\Delta \rho / \rho = \frac{VP(H_2O) \times [m(CO_2) - m(H_2O)]}{\{m(CO_2) \times P_{atmos} - [m(CO_2) - m(H_2O)] \times VP(H_2O)\}}$$
(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. Our experimental value is in reasonable agreement with this calculated value, but about 20% high.

4.2. Comparison With Previous Results

[13] Figure 3 summarizes the data from two previous experimental determinations for the evaporation rate of water on Mars. *Kuznetz and Gan* [2002] performed four measurements at 6.6, 11.0, 15.7, 67.8 mbar, and reported evaporation rates of 0.25. 0.26, 0.23 and 0.19 mm/h, respectively, which are significantly below the present value. These values also show a surprisingly small range, given the order of magnitude range in pressure. *Hecht* [2002] reported three sets of measurements, also over a wide range of pressures. Set 1 lie on a line that extrapolates to 4 mm/h, set 2 lie on a line that extrapolates to 2 mm/h, and five out of six data points for set 3 lie on a line that extrapolates to 1 mm/h. Thus while our data differ signif-

icantly from Kuznetz and Gan's they agree with the larger of Hecht's three datasets. Since our data required no extrapolation to Mars' pressures, and show less experimental scatter than previous data, we suggest that we have achieved new levels of precision and accuracy in determining an experimental value for the evaporation rate for water on Mars.

4.3. Implications of the Present Results

[14] Our result should not agree with the calculated value, or with Hecht's data, because we performed the experiment in a CO_2 atmosphere in Earth's gravity field. The effect of the Earth's greater gravity field is to increase evaporation rate relative to that on Mars by increasing the buoyancy of water vapor in the CO_2 atmosphere. Hecht allowed for this by performing his experiments in nitrogen instead of carbon dioxide. We preferred to use a CO_2 atmosphere and to apply a correction for the difference in gravity field. From Ingersoll's equation, we can see that evaporation rate on Mars will be 0.726 times that on Earth.

$$E_{Mars}/E_{Earth} = (g_{Mars}/g_{Earth})^{1/3} = (3.75/9.81)^{1/3} = 0.726$$
 (4)

Thus we suggest that our experiments indicate an evaporation rate for water on Mars of 1.01×0.726 mm/h with a standard deviation of 0.19×0.726 mm/h. Thus

$$E = 0.73 \pm 0.14 \text{ mm/h.}$$
(5)

[15] The now excellent agreement between this experimental value for the evaporation rate of water on Mars and the calculated value of Ingersoll's lends credibility to both approaches.

[16] The central issue, of course, is how these measurements relate to the evaporation rates to be expected on Mars. What factors may increase or decrease the actual rate in comparison to the measured one? Winds? Air temperature? Pressure variations? How does the evaporation rate of



Figure 3. Summary of previous experimental data for the evaporation rate of water under simulated martian conditions with the present data superimposed. *Hecht* [2002] performed three sets of measurements, each with a different trend line that can be extrapolated to 7 mbar. The values for evaporation rate at 7 mbar are indicated in mm/h. *Kuznetz and Gan* [2002] reported four measurements that lie of a line that extrapolates to 0.25 mm/h at 7 mbar.

liquid water differ from the sublimation rate of ice? Modeldependent theoretical treatments suggest that a 10–15 m/s wind increases evaporation rates by a factor of ~10 [Sears et al., 2005], while data gathered during the present measurements suggest that a 20°C increase in air temperature – all else being equal – will cause a factor of two increase in evaporation rate. The pressure dependence of evaporation rate is apparent from Figure 3, and is very minor for pressures likely to prevail on Mars. Finally, our own measurements seem to indicate that the evaporation rate of ice is about half that of liquid water. These topics will be discussed elsewhere.

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References

- Clow, G. D. (1987), Generation of liquid water on Mars through the melting of a dusty snowpack, *Icarus*, *72*, 95–127.
- Fanale, F. P., J. R. Salvail, W. B. Banerdt, R. S. Saunders, and L. A. Johansen (1982), Seasonal carbon dioxide exchange between the regolith and atmosphere of Mars: Experimental and theoretical studies, *J. Geophys. Res.*, 87, 10,215–10,225.

Farmer, C. B. (1976), Liquid water on Mars, Icarus, 28, 279-289.

- Haberle, R. M., C. P. McKay, J. Schaeffer, N. A. Cabrol, E. A. Grin, A. P. Zent, and R. Quinn (2001), On the possibility of liquid water on presentday Mars, J. Geophys. Res., 106, 23,317–23,326.
- Hecht, M. H. (2002), Metastability of liquid water on Mars, *Icarus*, 156, 373.

Ingersoll, A. P. (1970), Mars: Occurrence of liquid water, *Science*, *168*, 972. Kuznetz, L. G., and D. C. Gan (2002), On the existence and stability of

- liquid water on the surface of Mars today, *Astrobiology*, 2, 183. Malin, M. C. (1974), Salt weathering on Mars, *J. Geophys. Res.*, 77, 3888–3894.
- Malin, M. C., and K. S. Edgett (2000), Evidence for recent groundwater seepage and surface runoff on Mars, *Icarus*, 288, 2330.
- Sears, D. W. G., and S. R. Moore (2004), Stability of water on Mars, paper presented at 36th meeting, Div. for Planet. Sci., Am. Astron. Soc., Louisville, Ky.
- Sears, D. W. G., C. B. Farmer, M. S. Kareev, and S. R. Moore (2003), Laboratory studies of the behavior of water under Martian atmospheric conditions, paper presented at 35th Meeting, Div. for Planet. Sci., Am. Astron. Soc., Monterey, Calif.
- Sears, D. W. G., J. Chittenden, S. R. Moore, A. Meier, M. Kareev, and C. B. Farmer (2004a), Evaporation rates of brine on Mars, *Proc. Lunar Planet. Sci. Conf. 35th*, abstract 2159.
- Sears, D. W. G., S. R. Moore, A. Meier, J. Chittenden, M. Kareev, and C. B. Farmer (2004b), Evaporation rates for liquid water and ice under current Martian conditions, *Proc. Lunar Planet. Sci. Conf.* 35th, abstract 2112.
- Sears, D. W. G., L. A. Roe, and S. Moore (2005), Stability of water and gully formation on Mars, *Proc. Lunar Planet. Sci. Conf. 36th*, abstract 1496.

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