Mars: Occurrence of Liquid Water

Abstract. *In the absence of juvenile liquid water, condensation of water vapor to ice and subsequent melting of ice are the only means of producing liquid water on the martian surface. However, the evaporation rate is so high that the available heat sources cannot melt pure ice. Liquid water is therefore limited to concentrated solutions of strongly deliquescent salts.*

The purpose of the study reported here was to determine whether sunlight or other heat sources could melt water ice on Mars; the action of sunlight is probably the most likely mechanism by which liquid water might naturally occur on the martian surface. If all the water were to condense out of the atmosphere, it would cover the surface with a layer 10 to 20 μm thick (*1*). On the other hand, if this amount of water vapor were mixed uniformly with other atmospheric gases, condensation would occur at temperatures between 190° and 200°K (*2*). This means that only ice will condense directly out of the atmosphere, and also that frosts at temperatures above 200°K will cool by evaporation unless there is an adequate heat source. Thus, the circumstances most favorable to melting occur when the rate of evaporation of a frost at 0°C is at its minimum.

In order to estimate this minimum rate, I have assumed that there is no wind, and that the only atmospheric motions are those generated by the evaporation itself. However, water vapor is intrinsically lighter than carbon dioxide, the principal constituent of the martian atmosphere, and so the saturated fluid layer near the ground is dynamically unstable. The situation is analogous to thermal convection above a heated horizontal surface, and thus I have used thermal convection data to estimate the evaporation rate.

There are two aspects of the similarity between heat convection and mass exchange (*3*): The distributions of T and $1/m$ are governed by the same conservation equation, where T is the temperature and m is the mean molecular weight; in addition, equal relative changes of T and $1/m$ have the same effect on buoyancy. The analogy is not exact, however, but the error leads to our underestimating the evaporative loss. In the first place, evaporation implies a velocity normal to the wall, for which there is no analog in thermal convection. This normal velocity carries additional mass; thus the evaporation rate should be greater than that estimated from the thermal convection analogy (*4*). Second, when concentration gradients are large, the analogy fails because of thermal diffusion effects. Again this leads one to underestimate the evaporation rate, since heat tends to diffuse toward fluid of lower molecular weight (*5*), thereby increasing the instability of the system.

Thus the estimate which follows will be a lower bound on the evaporation rate of water ice on Mars. The basic experimental data are measurements of heat flux above a heated horizontal plate in air as a function of the physical properties of air and the temperature difference between the plate and its surroundings. Using these data (*3*, p. 535) and the thermal convection analogy (*3*, p. 593), I obtain

$$E = (0.17)\ \Delta\eta\rho D \left[\frac{\left(\frac{\Delta\rho}{\rho}\right) g}{\nu^2} \right]^{\frac{1}{3}} \qquad (1)$$

for the mass flux of water vapor E above an evaporating frost. Here $\Delta\eta$ is the difference between the water vapor concentration (by mass) of the gas at the evaporating surface and that of the gas away from the surface; ρ is the total density of gas at the surface; D is the diffusion coefficient of water vapor in carbon dioxide; g is the acceleration of gravity on Mars; ν is the kinematic viscosity of carbon dioxide; and $(\Delta\rho/\rho)$ is the difference between the density of the ambient gas and that of the gas at the surface, divided by the density of the gas at the surface. Since the gas is saturated near the frost, and since the surroundings are almost completely dry, we have

$$\Delta\eta = \frac{\rho_{\mathrm{w}}}{\rho} \qquad (2)$$

where ρ_{w} is the saturation density of water vapor at the temperature of the frost T_0. Moreover, since both components of the mixture behave approximately as ideal gases, we have

$$\Delta\rho/\rho = \frac{(m_{\mathrm{c}} - m_{\mathrm{w}})e}{[m_{\mathrm{c}}P_0 - (m_{\mathrm{c}} - m_{\mathrm{w}})e]} \qquad (3)$$

where e is the saturation vapor pressure of ice at temperature T_0; P_0 is the martian surface pressure; and m_{w} and m_{c} are the molecular weights of water and carbon dioxide, respectively. In this derivation the change in pressure across the saturated boundary layer is neglected; this procedure is valid provided the layer is thin relative to the atmospheric scale height $H = RT/g$, where R is the gas constant of the atmosphere.

Combining these equations and multiplying by the heat of vaporization of ice λ, we obtain an expression for λE, the rate of heat loss of a frost at temperature T_0 in a carbon dioxide atmosphere at pressure P_0 (Table 1). These results are based on published values of the gravitational acceleration on Mars, the vapor pressure and heat of vaporization of ice, the viscosity of carbon dioxide, and the mass diffusivity of water vapor in carbon dioxide (*6*). The rate of evaporation, and hence the necessary heat flux, varies directly as the partial pressure of water vapor, and inversely as the martian surface pressure.

On the basis of these data the most favorable martian sites for the occurrence of liquid water are those at low elevations where the surface pressure is high. Slopes that face the sun directly during part of the day are also favored. However, the solar constant at the orbit of Mars is about 0.85 cal cm^{-2} min^{-1}, and the mean surface pressure is about 5 to 7 mb (*7*). Even at points of lowest elevation the pressure is probably less than 10 mb (*8*), and, since the albedo of frost is high, it appears that water ice may never melt on the martian surface. Under these circumstances, a frost exposed to sunlight simply evaporates at a temperature below the melting point.

A separate issue concerns the lifetime of a frost of typical thickness relative to the time necessary to melt it. Even if all the atmospheric water vapor were to condense out during the martian night, the morning frost layer would be only 10 to 20 μm thick. On the basis of the data in Table 1 and a value for λ of 676 cal/g, the lifetime of such a frost at −10°C would be several minutes, and, since the frost is likely to spend more time than this in warming from −10° to 0°C, it will probably disappear before the temperature reaches the melting point. The greatest accumulation of frost probably occurs at the poles during the martian winter (*9*). However, the solar heating is also more gradual at the poles, since it follows an annual rather than a daily cycle so that the frost lifetime is still short compared with the time necessary to melt the frost.

Another possible source of liquid water is the melting of ice in soil interstices (*10*), where evaporation is slowed by the close packing of soil

Table 1. Heat fluxes (in calories per square centimeter per minute) necessary to maintain an evaporating frost deposit at constant temperature, for various temperatures and pressures.

T_0 (°C)	Heat flux at various pressures P_0 (mb)			
	6	10	15	25
0	1.25	0.76	0.55	0.38
−5	0.62	.41	.30	.21
−10	.33	.22	.17	.12

above the melting level. Let us assume that this water collects by condensation of vapor to ice, and that the vapor must diffuse down from the atmosphere at night. Then, since the partial pressure of water in the atmosphere is some 10^{-4} of the vapor pressure at −10°C, the lifetime of the accumulated deposit at −10°C will be only 10^{-4} of the accumulation time. This lifetime is about ½ hour at the pole and 10 seconds elsewhere; thus this mechanism does not increase the likelihood of melting.

This argument applies when the only source of water is the atmosphere. Liquid water from the interior of the planet might occasionally reach the surface to form hot springs (*10*), although there is no indication that such a process occurs on the earth. Most evidence suggests that terrestrial hot springs contain recycled rain water (*11*), although small amounts of juvenile water may also be present.

Water from the interior of the planet might also exist as permafrost at some depth below the surface, and this water might occasionally melt under the action of sunlight. However, temperatures above 0°C occur only at middle and lower latitudes at depths less than about 10 cm. Permafrost this close to the surface must be in equilibrium with atmospheric water, and this is possible only at the poles (*2*). Thus melting of permafrost is extremely unlikely.

Let us now compare the effects of wind with the effects of compositional density differences already mentioned. Measured rates of evaporation under conditions of neutral stability on the earth give (*12*):

$$E = (0.002)\rho_w U \qquad (4)$$

where U is the wind velocity 1 m above the surface. However, even for the case where $U \doteq 100$ m/sec, the additional evaporation due to wind is less than the rates implied in Table 1. The opposite question is whether wind could supply the necessary heat to the surface to melt water ice, but here again the effect appears to be negligible. In fact, the turbulence necessary to mix heat downward to the surface would also cause an increase in evaporation, thus leading to a net cooling. For, if ΔT is the temperature difference between the warm atmosphere and the cool surface, then the flux of heat to the surface will be $\rho U_0 c_p \Delta T$, where c_p is the specific heat of the gas and U_0 is some velocity characteristic of the process. However, at the same time the evaporative cooling will be $\rho U_0 \lambda \Delta \eta$, which is larger than the heating for all reasonable choices of parameters for frost temperatures greater than −10°C.

All of the above remarks apply only to pure water ice. Dissolved salts lower both the melting temperature of ice and the pressure of water vapor in equilibrium with ice at a given temperature. As an extreme example, the equilibrium vapor pressure over a saturated solution of $CaCl_2$ is about 1/5 that over pure water at the same temperature, and the melting point of such a solution is some 50°C lower than that of pure water (*13*). Under these conditions the evaporative cooling is negligible, and the lifetime is effectively infinite.

It is probable that pure liquid water does not occur on the martian surface or in the surface soil. The available heat sources cannot balance evaporative cooling, and any frost will evaporate completely before it reaches the melting point. Liquid water might occur in concentrated salt solutions, provided the salts are available in the martian soil.

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2 February 1969; revised 17 November 1969 ■

Metamorphic Waters from the Pacific Tectonic Belt of the West Coast of the United States

Abstract. *Waters unusually rich in ammonia, boron, carbon dioxide, hydrogen sulfide, and hydrocarbons are found in more than 100 localities along the Pacific coast of the United States. The waters are believed to be products of low-grade metamorphism of marine sediments. The marine sedimentary rocks would have to be tectonically emplaced below crystalline rocks in many places. Mercury ore deposits are probably also products of the low-grade metamorphism.*

Natural waters of unusual compositions (examples are given in Table 1) are found in a tectonically active belt about 160 km wide along the Pacific coast of the United States from southern California to Alaska. Although the fluids vary widely in their compositions, they are characteristically rich in CO_2 (up to 15,000 mg/liter HCO_3^-) and may contain as much as several hundred milligrams per liter each of NH_3, H_2S, and B. Commonly I^-/Cl^- ratios are far in excess of that in seawater. In many places hydrocarbons are found associated with the waters, and methane and ethane may be found escaping with the CO_2, as at Wilbur Springs, California. Many of the anomalous fluids are found issuing from known or inferred faults. Volcanic rocks, metavolcanic rocks, mica schist, graywacke, granite, serpentinite, and Mesozoic and Tertiary marine sedimentary rocks are all found to yield these unusual fluids. The anomalous fluids are frequently associated with mercury deposits, as White pointed out (*1*).

At the southern end of this belt in