STABILITY AND EXCHANGE OF SUBSURFACE ICE ON MARS.

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1 The Equilibrium Theory of Ice Stability

The Martian atmosphere has low absolute humidity, but it is often close to saturation. In particular, when vapor enters a sufficiently cold subsurface void it will freeze out as frost. On the other hand, any ice exposed to an unsaturated atmosphere will sublime away over time.[1,2,3]

The vapor flux due to a gradient in partial pressure p is[4,5]

$$J = -D \frac{18}{RT} \frac{\partial p}{\partial z}, \qquad (1)$$

where D is the diffusion coefficient and R the universal gas constant. An ice layer of thickness h can migrate over a time scale τ according to

$$\frac{h}{\tau} \rho_{ice} = \frac{D}{\Delta z} \frac{18}{RT} \Delta p. \qquad (2)$$

Removing or depositing $1 \mu m$ of subsurface ice by diffusion, at an effective diffusivity of $1 cm^2/s$ requires three months. At the same diffusivity, changing the ice depth by 1 meter requires 100,000 years. If there can be substantial redistribution of subsurface ice by diffusion during obliquity cycles, then a large fraction of the atmospheric vapor must be able to exchange with the subsurface ice in months. The density of ice ($\rho_{ice} \approx 10^3 kg/m^3$) is higher than that of vapor ($\rho_v \approx 10^{-6} kg/m^3$) by a factor of 10^9. For example, 10 km of atmospheric vapor correspond to about 10μm of solid ice. The density ratio of 10^9 connects ice migration over orbital cycles with vapor diffusion over seasons.

There are two contrasting views of subsurface water ice on Mars. One is to imagine an atmosphere which has no contact with the subsurface ice buried under a protective layer of dry material. Low diffusivities $\ll 0.1 cm^2/s$ would isolate the subsurface from changes in atmospheric humidity over obliquity variations. The other view is that the ground ice rapidly exchanges vapor with the present atmosphere. Ground ice and atmospheric vapor are in or close to thermodynamic equilibrium. The latter view is supported by 1) theoretical and experimental estimates of effective diffusivities for connected void spaces and 2) the fact that the geographic boundary of the subsurface ice[6,7] resembles the frost line of the current climate[6,3].

A basic theoretical estimate for the diffusion coefficient in a dilute gas at Martian pressure conditions[8,9] is $D \sim 10 cm^2/s$. Elsewhere[10] we will elaborate on experimental and theoretical estimates of diffusion coefficients of water vapor through dust. This more detailed analysis confirms that diffusion coefficients should be of this order of magnitude.

Model predictions are made for ground ice in thermodynamic equilibrium with the water vapor in the present-day atmosphere. Temperatures are obtained with a one-dimensional thermal model of the subsurface, using thermal inertia map[11], albedo map[12], orbital elements[13], and partial surface pressures obtained from the Thermal Emission Spectrometer over a Martian year[14].

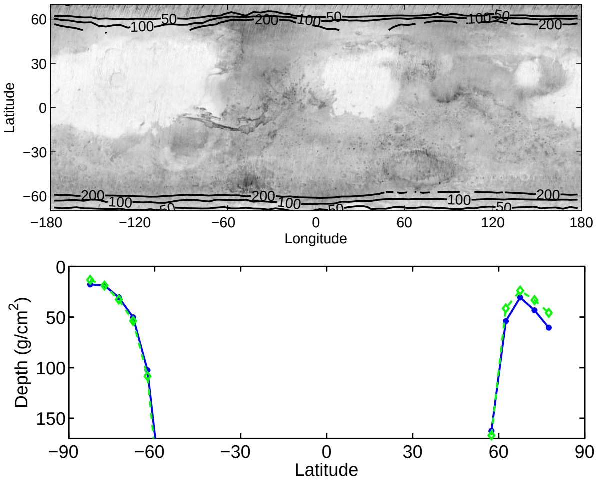

Figure 1: Depth to the ice table in g/cm^2 when ice is in thermodynamic equilibrium with the atmospheric water vapor. The change in thermal properties due to the presence of ground ice and geographic variations in humidity are taken into account. Upper panel: Contours indicate depth. The background map is thermal inertia[11]. Lower panel: Zonally averaged burial depths. Solid and dash lines correspond to an ice volume fraction of 40% and 70%, respectively.

The conversion of vapor column abundance h (usually expressed in precipitable micrometers) to partial pressure of H_2O on the surface depends on the vertical distribution of water vapor. We use the approximate relation

$$p_{\text{surf}} \approx \frac{44}{18} \frac{g h \rho_{\text{liquid}}}{1 - e^{-H_C/H}}. \qquad (3)$$

H is the scale-height of the atmosphere and H_C the height of the water vapor condensation level[14]. According to this formula, 1 precipitable micrometer may correspond to ~0.1 Pascal (1μbar). Missing data in the humidity map are interpolated with fits of low-order spherical harmonics. According to this analysis the global average surface partial pressure of H_2O is 0.13 Pascal, which corresponds to a frostpoint of 198 K. The average for the northern hemisphere is 0.17 Pascal (200 K) and 0.09 Pascal (196 K) for the southern hemisphere.

Figure 1 shows the model predictions for an equilibrium ice table. In the southern hemisphere, the burial depth is measured to be $15 \pm 5\ g/cm^2$ or less[15]. Geographic variations in surface humidity primarily introduce a southward shift of the frost line by several degrees of latitude on both hemispheres, compared to globally averaged humidity. Both, the geographic boundaries and the burial depths are consistent with GRS measurements.

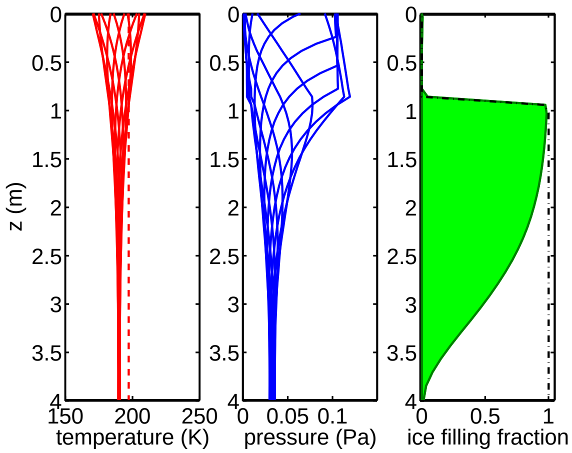

Figure 2: Temperature, partial pressure of H_2O, and pore space filling after 10^5 years, starting with either dry regolith (shaded green) or a regolith filled with ice (dash-dot line). The same depth to the ice table is established for both initial conditions. This simulation neglects the thermal effect of ice.

2 Subsurface Vapor Dynamics

Conservation of mass requires $\partial_t(\bar\rho_v + \bar\rho_f + \bar\rho_a) + \partial_z \bar J = 0$. Subscripts are v for vapor, f for free ice (solid), and a for adsorbed H_2O. The overbar denotes densities per total volume and the flux per total area, which are related to the actual densities by factors of regolith porosity ϵ and the fraction of void space not filled with ice $\varphi = 1 - \rho_f/\rho_{ice}$. Here, ρ_f the ice density in the volume not occupied by regolith.

Transport of H_2O is due to vapor diffusion as described by eq. (1) for constant air pressure and small thermodiffusion coefficients. The density of adsorbed H_2O is determined by the ambient temperature and partial pressure, that is, $\bar\rho_a = A(p,T)$. Conservation of mass becomes

$$\partial_t\left(\frac{p}{T}\varphi+\frac{R}{18}\rho_f\right)+\frac{R}{18\epsilon}\left(\frac{\partial A}{\partial p}\partial_t p+\frac{\partial A}{\partial T}\partial_t T\right)=\partial_z\left(\frac{D\varphi}{T}\partial_z p\right) \tag{4}$$

The equation takes into account phase transitions between vapor, ice, and adsorbate and is solved numerically on an irregularly spaced grid. The scheme can become numerically unstable where the subsurface is close to full with ice, which can be remedied with an appropriate choice of spatial discretization. Figure 2 shows the accumulation of an ice layer when the deep subsurface is below the frost point. The transition to the ice table is found to be abrupt for a wide range of diffusion coefficients.

The partial pressure of H_2O is close to constant between the surface and the ice table. Hence it is justified to compare the frost point temperate on the surface with the temperature deeper in the ground (which is close to, but not exactly the same as the annual mean surface temperature). The ice table begins where the peak temperature equals the frost point temperature.

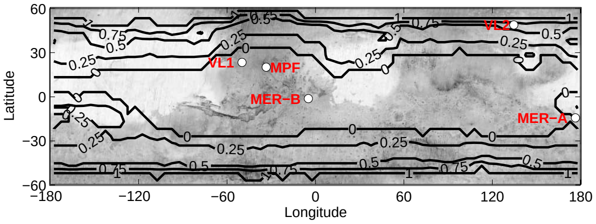

Figure 3: Seasonal stability of subsurface frost for the current climate. The contours indicate the duration (in units of Mars years) over which subsurface temperatures at any depth deeper than 3 diurnal skin-depths fall below the frost point. Humidity variations with longitude, latitude, and areocentric longitude are taken into account. Seasonal frost can extend to latitudes of 25° or less. White dots indicate lander sites.

3 Frost at Lower Latitudes

If the equilibrium theory of subsurface ice is correct, it has further consequences.

Due to the rapid exchange of water vapor seasonally stable regions can accumulate frost. Figure 3 shows the duration of seasonal stability on the globe. Small amounts of frost will accumulate during the cold season down to latitudes of 25°, in a layer below the penetration depth of diurnal temperature variations and above the penetration depth of seasonal variations.

Contact with the subsurface ice may also cause rapid dilution of the atmospheric deuterium/hydrogen ratio [16].

Subsurface ice can also be present at lower latitudes due to slope effects, which can lower the mean annual temperature [17]. This effect does not naturally explain the geographic distribution of the equatorial hydrogen observed by GRS.

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