Evolution and Transport of Water in the Upper Regolith of Mars. T. L. Hudson[1], O. Aharonson[1], N. Schorghofer[1], M. H. Hecht[2], N. T. Bridges[2] and J. R. Green[2], [1]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, 9112. [2]Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109. (thudson@gps.caltech.edu)

Motivation: Long standing theoretical predictions [1-3], as well as recent spacecraft observations [4] indicate that large quantities of ice is present in the high latitudes upper decimeters to meters of the Martian regolith. At shallower depths and warmer locations small amounts of H_2O, either adsorbed or free, may be present transiently. An understanding of the evolution of water based on theoretical and experimental considerations of the processes operating at the Martian environment is required.

In particular, the porosity, diffusivity, and permeability of soils and their effect on water vapor transport under Mars-like conditions have been estimated, but experimental validation of such models is lacking.

Goal: Three related mechanisms may affect water transport in the upper Martian regolith. 1) diffusion along a concentration gradient under isobaric conditions, 2) diffusion along a thermal gradient, which may give rise to a concentration gradient as ice sublimes or molecules desorb from the regolith, and 3) hydraulic flow, or mass motion in response to a pressure gradient. Our combined theoretical and experimental investigation seeks to disentangle these mechanisms and determine which process(es) are dominant in the upper regolith over various timescales.

A detailed one-dimensional model of the upper regolith is being created which incorporates water adsorption/desorption, condensation, porosity, diffusivity, and permeability effects. Certain factors such as diffusivity are difficult to determine theoretically due to the wide range of intrinsic grain properties such as particle sizes, shapes, packing densities, and emergent properties such as tortuosity. An experiment is being designed which will allow us to more accurately determine diffusivity, permeability, and water desorption isotherms for regolith simulants.

Background: Ball et al [5] highlight the important distinction between gas diffusion and hydraulic flow. Gas diffuses along a concentration gradient but flows along a pressure gradient.

Diffusion is governed by Fick's Law:

$$J_D = -D \frac{\partial c}{\partial x} A \qquad (1)$$

where J_D is the flux in moles/sec, D is the diffusion coefficient m^2/sec, c is the concentration in moles/m^3, and A is area. Hence the concentration obeys the diffusion equation:

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \qquad (2)$$

Laminar flow in response to a pressure gradient is given by Darcy's Law:

$$q_h = -k_h \frac{\partial h}{\partial x} A \qquad (3)$$

where q_h is the flux in m^3/sec, k_h is the hydraulic conductivity (m/s), h is the hydraulic head (m). This can be rewritten as

$$Q = -\frac{K}{\eta} \frac{dp}{dx} \qquad (4)$$

where Q is in m/s, K is the permeability (cm^2), η is the dynamic viscosity (g/cm•s), and dp/dx is the pressure gradient.

These processes may be difficult to distinguish, even in a controlled laboratory setting. An evolution of water vapor from ice (free or adsorbed) within a soil will produce a local elevation in P_{H2O}. This will drive both diffusion to the dry atmosphere and flow to an area of lower pressure.

Clifford and Hillel [6] considered Knudsen diffusion as an important mechanism for flow through porous media on Mars, where the mean free path (~ 10μm) falls in the middle of the estimated pore-size distribution for fine-grained soils. (1 to 100μm). Their models, based on a subliming layer of ice buried beneath 1 m of soil and a dry atmosphere, found that gaseous transport in the Knudsen regime occurred preferentially within the larger pores of a given pore size distribution.

In addition to the above, general studies of flow through porous media have shown that flow velocity is proportional to the porosity and the square of the particle size, thereby making the flow rate proportional to the fourth power of particle size [7-8].

Thus, if there is a desiccated layer of fine-grained soil above the ice-bearing layer, its low permeability may permit the development of local pressure gradients that overwhelm diffusion processes, particularly if the evolution of water vapor is rapid. One goal of this investigation is to determine if internal pore-space pressures built up under a permeability barrier may develop quickly enough to overcome soil cohesion forces and disturb the surface of the soil in some form of geyser. If it proves to be the case that these phenomena can occur for reasonable Martian soils and T,P conditions, they may provide a trigger for the formation of surficial geomorphic features known as slope-streak as suggested by Schorghofer et al [9].

The role of thermal vapor diffusion has been considered by Clifford [10], though his work was concerned more with geothermal-scale gradients, rather than near surface temperature profiles which vary on seasonal or diurnal timescales.

Materials: To model the upper Martian regolith, several potential soils and soil simulants are being considered. JSC Mars-1 can be crushed so as to simulate a fine dust with particles from 50 µm to sub-micron size. Sieving will allow the attainment of particular size bins with the smallest attainable being ~10µm and below. Also available are Carbondale red clay, and Xerox toner, both of which have been used in some Martian wind tunnel experiments [11-12]. Spheres of pure silica in the 10 to 40 mm range may also be used for experiments which eliminate the variables of grain surface morphology and composition.

Initial experiments will concentrate a single soil type, JSC-1. The first steps in characterizing soil samples of various particle size distributions has already begun.

Experimental Design: The Extraterrestrial Materials Simulation Laboratory at JPL is particularly suited to studying the behavior of Martian soil simulants in appropriate environmental conditions (Figure 1,2). Experiments will be performed in a large stainless steel vacuum chamber equipped with thermal control and gas feed-throughs, a cryo-shroud, and diaphragm pump for the maintenance of Mars-like conditions and atmosphere. A solar simulator mounted outside the chamber can be adjusted to produce incident radiation energies equivalent to any latitude and season on Mars.

Thoroughly dried soil will be introduced into the chamber and allowed to equilibrate with a known amount of water. The soil will then be frozen to ~ 240K. The soil will warm up in a controlled fashion from 240K to 275K. Total chamber pressure and partial pressure of water will be monitored throughout the course of an experiment, as well as soil water content and temperature.

Initial experiments will permit the determination of desorption isotherms. A second phase of the experiment will use a capillary tube to simulate a diffusion and hydraulic flow barrier.

References: [1] Farmer, C.B. (1976), Icarus, 28, 279-289. [2] Paige D.A., Nature, 356(6364), 43-45. [3] Mellon, M. T., and Jakosky, B.M, JGR, 100(E6), 11,781-11,799 [4] Boynton, W.V. et al, (2002), Science, 297(5578), 81-85 [5] Ball, B.C et al. (1981), J. Soil Science, 32, 323-333. [6] Clifford, S. M., Hillel, D., (1986) Knudsen Diffusion, J. Soil Science, 41(4), 289-297. [7] Carman, P.C., Flow of Gases Through Porous Media. Academic Press, New York. 1956. [8] De Wiest, R. J.M., Flow Through Porous Media. Academic Press, New York 1969. [9] Schorghofer, N. et al. (2002), 29(23), 2126. [10] Clifford, S. M. (1991) GRL, 18, (11), 2055-2058. [11] Greeley, R. et al, (2000), Planetary & Space Science, 48, 1349-1355. [12] Greeley, R. (2002), Planetary & Space Science, 50, 151-155.

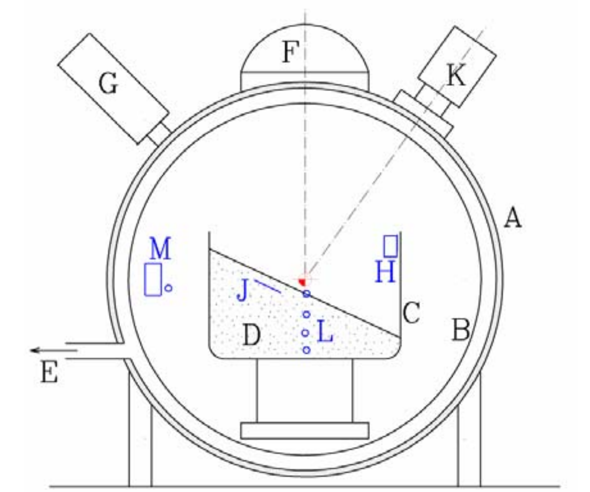

Figure 1: Schematic drawing indicating the experimental components including (A) vacuum chamber, (B) cryo-shroud, (C) sample container, (D) dust + ice mixture, (E) pumps, (F) solar simulation lamp, (G) mass spectrometer, (H) dew point hygrometer, (J) thermal and electrical conductivity probes, (K) camera (L) temperature, and (M) pressure sensors.

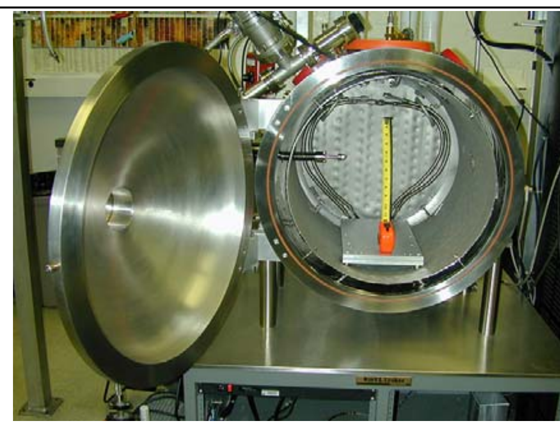

Figure 2: Cryo-shrouded vacuum chamber located the JPL's Extraterrestrial Material Simulation Laboratory.