Using Impedance Spectroscopy to Measure Water/Ice Content of Simulated Martian Soils

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1. Introduction: Detecting water/ice in planetary regoliths is crucial for manned exploration and understanding the geologic history of planetary surfaces. A simple apparatus is being developed that uses impedance spectroscopy to quickly determine the amount of water/ice using two probes that contact the regolith. Coarse silica sand (~500 µm) samples were measured with 0.05 to 10 wt.% water with KCl or $MgSO_4$ from 25 to -65 °C. Results indicate that we can measure water/ice content of coarse silica sand with > 0.05 wt.% water content and > 0.5 wt.% ice content. For C^* concentration of ions in solution or defects in ice and a water/ice content of θ_g, the conductivity is $\sigma(S/cm) = 2.7 \times 10^{-5} \cdot C^*(M) \cdot [\theta_g(wt.\%)]^{1.8}$.

2. Experiments: Measurements were performed using the Electrical Properties Cup (EPC) and recently developed Electrical Properties Probe (EPP) [1]. Both of these probes use two stainless-steal electrodes to contact the regolith. The probes are connected to a Wayne-Kerr 6430 Impedance Spectrometer used to measure the admittance and phase angle of our samples between 20 Hz and 500 kHz from which we extract *dielectric constant* and *conductivity* values. In this paper, we present *conductivity* results for they are used to quantify the water/ice content of our samples.

3. Water/Ice Physics: In natural waters with dissolved mineral salts when water freezes, the salts are mostly rejected from the ice and accumulate between ice forming fingers. As the temperature drops, salts continue to increase in concentration between the ice fingers and form brines. At low temperatures, the ice/brine mixture freezes [2]. Salts are not completely rejected from the ice for certain compounds can be incorporated in low concentrations (~ppm) into ice. The halides (F- and Cl-) and ammonia can enter ice and increase its conductivity which depends on four protonic defects: #1 H_3O^+, #2 OH-, #3 D-defects (two protons per hydrogen bond) and #4 L-defects (empty hydrogen bonds). Our external electrical field, polarizes or moves these defects about their equilibrium positions. Water and ice represents a viscous medium that dampens the motion of protonic defects [3] which is measured as electrical impedance.

4. Doped Water Results: In our doped-water experiments we added salts to DI (dionized) water with concentrations between 0.1 mM and 1 M and measured the conductivity from 25 to -65 °C. Water/ice results, reported at 10 kHz in Figs. 1a-c, demonstrate the following: (1) For water, the conductivity depends mainly on ion concentration and only weakly on

temperature or *ion type* (ionic mobility) [1]. (2) For ice, the conductivity is much lower than for water and depends on the concentration of protonic defects. For KCl, Cl- adds to the conductivity by entering the ice and creating additional L- and H_3O^- defects. For $MgSO_4$, SO_4^{2-} does not enter ice and thus, does not enhance its conductivity. These features are shown in Figs. 1a-c. (3) When water freezes, there is a drop in conductivity. The temperature at which the conductivity drops depends on the concentration of ions in solution due to freezing point depression.
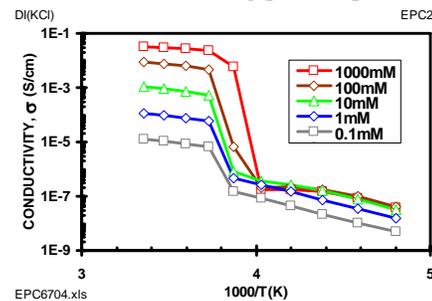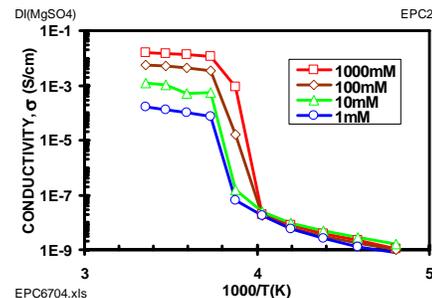

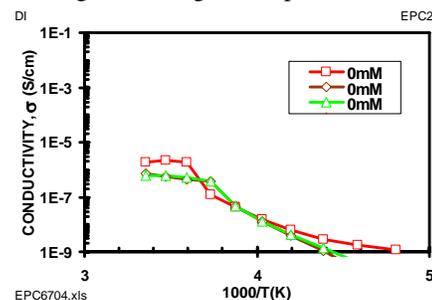Figure 1a. KCl-doped water

Figure 1b. MgSO₄-doped water.

Figure 1c. DI water.

5. Moist Sand Results: In our moist sand experiments, we (a) doped DI water with 100 mM of either KCl or $MgSO_4$, (b) introduced a gravimetric fraction into a 50-g silica sand sample and (c) measured its conductivity from 25 to -65 °C. Moist sand results, Figs. 2a-c, demonstrate the following high-level results: (1) For water and ice, log

conductivity vs log water content has a slope of 1.8; see the solid black and dashed lines in Fig.2. (2) Our lower limit of detection is 8×10^{-11} S/cm.

In martian soils, we expect to find 0.3 to 3 wt.% water [4] with high (molar) ion content. In Fig. 3 we represent the conductivity of water by a band with ion concentrations between 100 mM and 1 M. For ice, we expect its conductivity to follow the lower curve in Fig. 3. Based on our doped water/ice results, we expect the conductivity of the water/ice/silica sand samples to increase due to inclusion of Cl^- but not SO_4^{2-}. This behavior is reflected in the results presented in Fig. 2 where KCl doped samples show more conductivity at -25 °C (blue curve) than the $MgSO_4$ or DI samples.
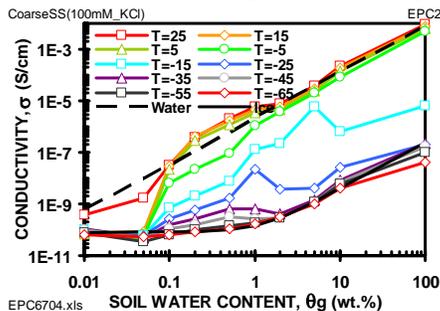

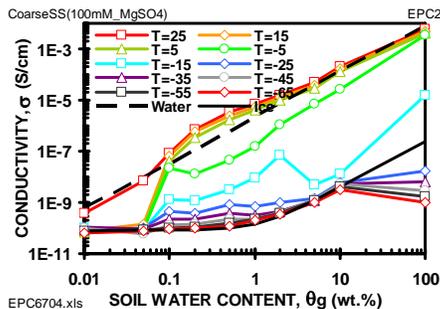Figure 2a. Silica sand with water with 100 mM KCl.

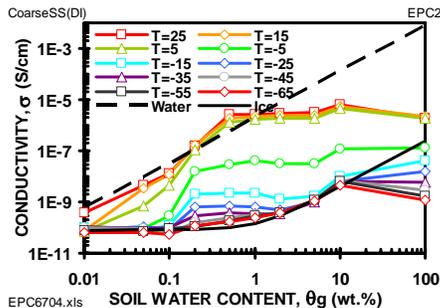Figure 2b. Silica sand with water with 100 mM $MgSO_4$

Figure 2c. Silica sand with DI water

The conductivity in Fig. 2 shows a bulge in the curves around 1 wt.%. This is thought to be due to a transition from *pore* to *capillary water* as depicted in Fig. 4. At 0.1 wt.%, there is a sharp decrease in conductivity and this is thought to be due to a transition from *capillary* to *film water*. Fig. 4 depicts two other transitions from *film* to *adsorbed water* and

then to *dry particles*. Recent data indicates that particle size plays a role in *capillary* to *film water* transition. At low water content, water is so tightly bound to the host mineral that it cannot be polarized hence detected.
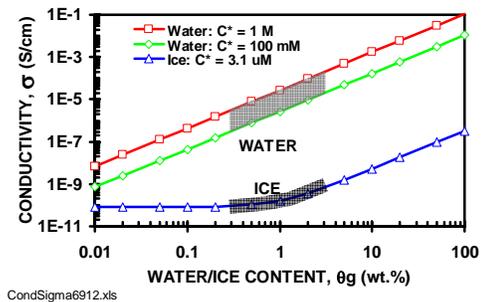

Figure 3. Bounding conductivities for martian water/ice soils simulated by coarse silica sand.
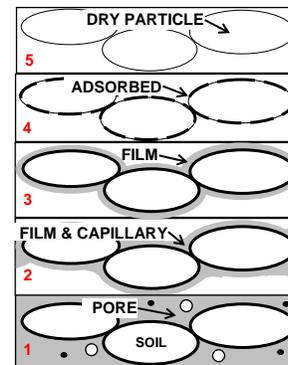

Figure 4. Water-soil model with five water content pathways. Water is indicated by the gray regions.

7. Conclusions:

- Using the conductivity of coarse silica sand, we can detect > 0.05 wt.% water and > 0.5 wt.% ice. The conductivity, with C^*[M] concentration of ions in solution or defects in ice, is σ(S/cm) = $8 \times 10^{-11} + 2.7 \times 10^{-5} \cdot C^*(M) \cdot [\theta_g(wt.\%)]^{1.8}$.
- For water, the conductivity is dominated by salts such as KCl, $MgSO_4$, or NaCl.
- For ice, the conductivity is determined by ions such as Cl^- which induce additional H_3O^- and L-defects in ice. From our experiments we estimate the concentration of defects in ice at 3.1 μM.

8. References:

[1] M. G. Buehler, K. B. Chen, S. Seshadri, D. Keymeulen, R. C. Anderson, and T. A. McCann, "Electrical Properties Probe Measures Water/Ice Content of Martian Soils Using Impedance Spectroscopy", IEEEAC, Paper 1375, March 2007. [2] V. F. Petrenko and R. W. Whitworth, *Physics of Ice*, Oxford Univ. Press (New York, 1999). [3] P. Debye, *Polar Molecules*, Chemical Catalog Co. (New York, 1929). [4] W. V. Boynton, et.al., Science, Vol. 297, 81-85, 2002.