ENABLING MARTIAN HABITABILITY WITH SILICA AEROGEL VIA THE SOLID-STATE GREENHOUSE EFFECT.

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Introduction: The low temperatures [1,2] and high ultraviolet (UV) radiation levels [3] at the surface of Mars today currently preclude the survival of life anywhere except perhaps in limited subsurface niches [4]. Several ideas for making the martian surface more habitable have been put forward previously [5-7], but they all involve massive environmental modification that will be well beyond human capability for the foreseeable future [8]. Here we present a new approach to this problem based on the physics of the solid-state greenhouse effect [9-11]. We demonstrate via experiments and modelling that under martian environmental conditions, a 2 to 3-cm thick layer of silica (SiO_2) aerogel [12] will simultaneously transmit sufficient visible light for photosynthesis, block hazardous ultraviolet radiation, and raise temperatures underneath permanently to above the melting point of water, without the need for any internal heat source. Placing silica aerogel shields over sufficiently ice-rich regions of the martian surface could therefore allow photosynthetic life to survive there with minimal subsequent intervention (Figure 1). This regional approach to making Mars habitable is much more achievable than global atmospheric modification. In addition, it can be developed systematically starting from minimal resources, and can be further tested in extreme environments on Earth today. The astrobiological risks associated with this approach to enabling martian habitability will need to be weighed carefully against the benefits to Mars science and human exploration in future.

Methods: Our experimental setup consists of a layer of silica aerogel particles / tiles on a low reflectivity base surrounded by thermally insulating material (Figures 2-3). The apparatus is exposed to visible radiation from a solar simulator. The broadband flux incident on the layer is measured with a pyranometer, and temperature is recorded by calibrated glass-bead thermistors. We also performed coupled radiative-thermal calculations for the evolution of martian subsurface temperatures in the presence of a solid-state greenhouse silica aerogel layer. Our model includes aerogel radiative transfer, thermal conduction both in the aerogel and the regolith, and the latent heat associated with melting/freezing of regolith ice, and includes seasonal variations in insolation based on the Mars Climate Database v5.3 Climatology scenario [2,13].

Results: Figure 4 shows the experimental results for both aerogel particle and tile layers vs. received visible flux in the 100-200 W/m^2 range. For comparison, Earth's global mean received flux is 342 W/m^2, while that of Mars is 147 W/m^2. As can be seen, temperature differences of over 45 K are achieved for aerogel particle layers of thickness 3 cm receiving a flux of 150 W/m^2. Aerogel tiles, which have higher visible transmission, cause temperature differences that are around 10 K higher, reaching >50 K at just 2 cm thickness. Our experimental results show that under Mars-like insolation levels, warming to the melting point of liquid water or higher can be obtained under a 2-3 cm thick silica aerogel layer. The peak obtainable warming is likely even higher, because we performed the experiments at 1 atm pressure and heat is lost in our experimental setup via sidewall and base thermal losses. We also measured the transmission of the aerogel particles and tiles in the ultraviolet and found strong attenuation of UV-AB, and near-total attenuation of the most hazardous UV-C radiation. Finally, our one-dimensional simulations for Mars at locations where surface ice is known to be present show that given an assumed 2.5-cm thick aerogel layer, near-surface temperatures are high enough to allow liquid water continuously after a few years (Figure 5).

Discussion: Our results show that via the solid-state greenhouse effect, regions on the surface of Mars could be modified in the future to allow life to survive there with much less infrastructure than via other approaches. Additional habitability constraints due to internal pressure variations, nutrient availability and dust deposition are important but likely manageable [14]. In future work, we plan to investigate the ease with which traditional aerogel manufacturing techniques can be adapted to conditions on Mars. More speculatively, it is also interesting to consider the extent to which organisms could eventually contribute to sustaining martian habitable conditions themselves. On Earth, multiple species already exist that utilize silica as a building material. Diatom phytoplankton in particular can grow up to several mm in length, produce frustules from 1-10 nm diameter amorphous silica particles (smaller than the mean pore diameter in silica aerogel networks) [15] and are already known to have high potential for bionanotechology applications in other areas [16]. It will therefore be interesting in the future to investigate whether high visible transmissivity, low thermal conductivity silica layers could be produced directly via a synthetic biology approach. If this is possible, in combination with the results described here it would allow a step towards the development of self-sustaining habitable regions on Mars.

References: [1] Martinez G. et al. (2017) *Space Science Reviews*, 212(1-2):295, 338. [2] Forget F. et al. (1999) *JGR*, 104:24155-24176. [3] Cockell C. et al. (2000) *Icarus*, 146(2):343-359. [4] Michalski J. et al. (2018) *Nature Geoscience*, 11(1):21. [5] McKay C. et al. (1991) *Nature*, 352:489-496. [6] Zubrin R. and McKay C. (1993) In *29th Joint Propulsion Conference and Exhibit*, p. 2005. [7] Gerstell M. et al. (2001) *PNAS*, 98(5):2154-2157. [8] Jakosky B. and Edwards C. (2018) *Nature Astronomy*, 2(8):634. [9] Brown R. and Matson D. (1987) *Icarus*, 72(1):84-94. [10] Pilorget C. et al. (2011) *Icarus*, 213(1):131-149. [11] Kaufmann E. and Hagermann A. (2017) *Icarus*, 282:118-126. [12] Dorcheh A. and Abbasi M. (2008) *Journal of Materials Processing Technology*, 199(1-3):10-26. [13] http://www-mars.lmd.jussieu.fr/mars/. [14] Wordsworth R., Kerber L. and Cockell C. (2019) *Nature Astronomy*, under review. [15] Kroger N. and Poulsen N. (2008) *Annual Review of Genetics*, 42:83-107. [16] Nassif N. and Livage J. (2011) *Chemical Society Reviews*, 40(2):849-859.

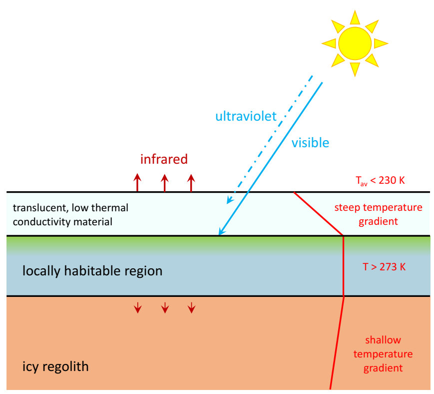

Figure 1. Schematic of the silica aerogel solid-state greenhouse habitability concept for Mars. A thin translucent layer of low thermal conductivity material transmits visible light but blocks ultraviolet and infrared, directly replicating the radiative effects of Earth's atmosphere.

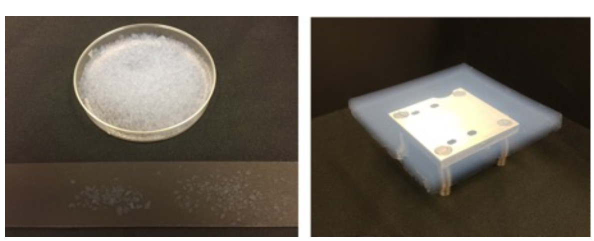

Figure 2. Image of the silica aerogel used in the experiments. (left) Silica aerogel particles with radii between 700 um and 4 mm; (right) Large homogenous silica aerogel tiles (10 cm × 10 cm × 1 cm).

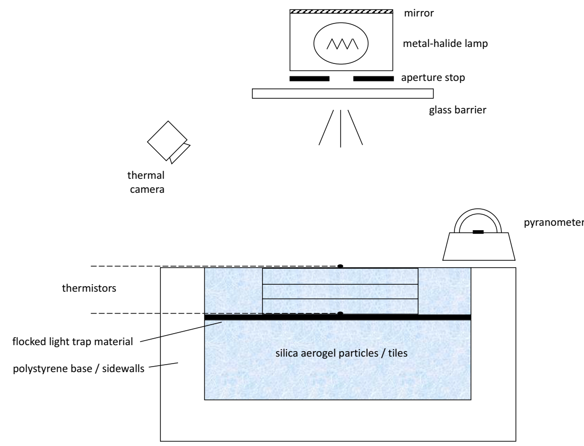

Figure 3. Schematic of the experimental setup.

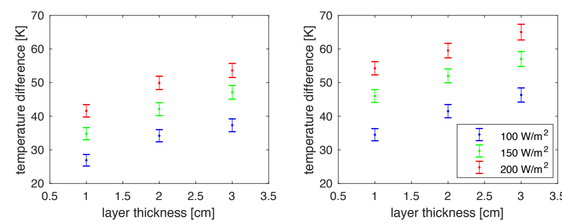

Figure 4. Results of the silica aerogel solid-state greenhouse warming experiments. Temperature differences between the surface and top of the layer are shown, for aerogel particles (left) and tiles (right), as a function of the layer thickness. Colors indicate different incident visible fluxes. For reference, the annual mean flux on Mars between 45S and 45N varies from about 130 to 170 W/m^2, with diurnal mean values from 50 to 250 W/m^2 over the course of the martian year. Error bars indicate the standard deviations of the measurements due to a range of error sources [14].

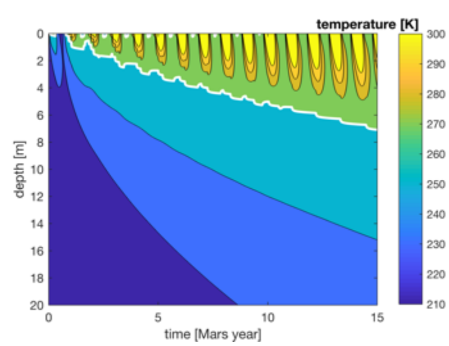

Figure 5. Simulated warming underneath a solid-state greenhouse habitat on Mars. Contours show temperature vs. time in an ice-rich regolith underneath a 2.5-cm silica aerogel layer on Mars in the Arabia Terra / Deuteronilus Mensae region (40N, 340W).