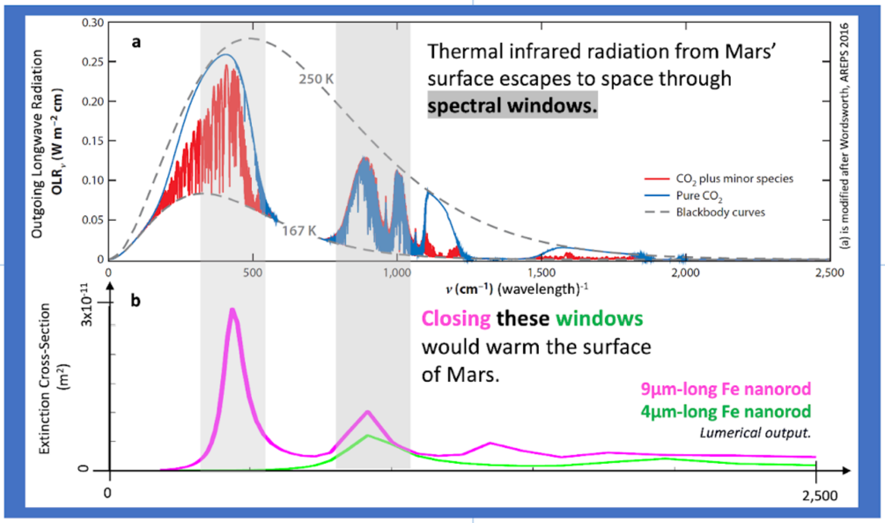
Gardening Mars with glitter

Overview chart.

Gardening Mars with glitter

Innovation: Elevate Mars global surface temperature using artificial aerosols (e.g. Fe nanorods), designed to interact strongly with upwelling thermal radiation (e.g., half-wavelength conductive dipoles), swept through atmosphere by natural winds.

Impact: 1000x more efficient (on a per-unit-mass-in-the-atmosphere basis) than the current state-of-the-art for Mars global surface warming.



Mission: Extended settlement on Mars' surface (e.g., goal of SpaceX Mars plan).

Approach: Iteration between design of optical structures (finite-difference-time-domain approach) and Mars weather modeling (3D approach, including two-stream radiative transfer) to calculate warming.

Summary.

To establish a photosynthetic biosphere on the surface of Mars, warming the surface by 10s of K is required. For warming Mars, the optimal mix of artificial greenhouse gasses is already known and the large mass of this mix and its need for ingredients known to be rare on Mars' surface (e.g. Fluorine) seemingly pushes planet-scale gardening of Mars into the far future. However, we discovered that artificial aerosols made from materials that are readily available at the surface of Mars – specifically, iron nanoparticles with a long-dimension size similar to that of childrens' play glitter – warm Mars 1000x more effectively than gasses. Such particles, which are in effect half-wavelength metal dipoles tuned to resonate with upwelling thermal infrared, are readily swept high into the Mars atmosphere similar to natural Mars dust, allowing near-surface particle injection. To go beyond what we have now – finite-difference-time-domain proof-of-concept spectra for a single particle design (as detailed below) - we need to iterate between design of manufacturable particles and climate modeling. This requires funding for both particle design and Mars climate modeling.

Introduction: So far in 2023, most of the world's orbital launches have been carried out by a company, SpaceX, that has the goal of building a self-sustaining settlement on Mars [1]. For any extended settlement of Mars, a key limiting factor is low surface temperature. Low temperature precludes photosynthetic life that might feed people.. The prevailing (incorrect) view is that 50K of global warming is not possible with present-day technology [2], so work on warming Mars' surface has focused on local-scale methods [3]. We discovered that global warming is possible 1000× more easily, on a warming-per-unit-mass basis, than the current state-of-the-art [4-5]. The innovation is to use artificial aerosols: for example, iron nanorods with lengths similar to that of natural Mars dust. The nanorods are designed to absorb and back-scatter upwelling thermal infrared (IR) radiation, while forward-scattering downwelling sunlight, a combined effect that yields positive greenhouse effect. In the concept, the particles are manufactured on the Mars surface, and injected into the atmosphere a few meters above the surface. Just as for natural Mars dust, daytime winds sweep the particles to heights O(20) km, strengthening the greenhouse warming. Individual particles settle out, but are also lofted by winds, so, just as the Mars sky always has some dust, there is a steady-state atmospheric concentration of particles.

The advantage of aerosols over gasses for greenhouse effects is well known [6-10]. Indeed, the IR radiative effects of clouds and CO_2 on Earth are comparable, even though the average column mass of CO_2 is ~100× less than that of cloud aerosol. It is, therefore, perhaps surprising that there has been no previous work on artificial-aerosol solar radiation management for Mars. We have performed computationally intensive finite-difference-time-domain numerical simulations that verify the desirable optical properties and "tunability" of Fe nanorod aerosol (Fig. 1). Because the improvement in extinction cross-section per unit mass is so large relative to the state-of-the-art, this motivates research to determine the manufacturability of aerosol in the context of improved weather modeling of the warming. The payoff would be a new assessment of the practicality/feasibility of intentional global warming of Mars. This concept is unexplored to our knowledge. Prior work focuses on gasses [4-5], not aerosols.

Preliminary work is summarized in Fig. 1. These calculations were performed on Northwestern's "Quest" cluster. Strong IR scattering is as desired for a strong greenhouse effect [11]. Previous work indicates that, for a well-mixed absorber, an optical depth of τ ~3 is required to warm Mars's surface to habitable temperatures (e.g. [13]) (this is approximate; τ varies from 2-10 depending on details of the calculation, scattering asymmetry, etc). From Fig. 1, the corresponding column mass (kg m^{-2}) is just

$$m = \tau\rho\Delta Z(\sigma_{geom})/(\sigma_{ext,r}) \approx 3 \times 8\ \mathrm{g/cc} \times (1.6\times10^{-7}\ \mathrm{m}) \times (1.4\times10^{-12}) / (1\times10^{-11})\ \mathrm{m}^2 \approx 500\ \mathrm{mg/m}^2$$

Here, ρ is nanorod density, ΔZ is the thickness of iron nanorod, σ_{geom} is the perpendicular-to-long-axis geometric cross section, and $\sigma_{ext,r}$ is the orientation-averaged extinction cross-section in the spectral window (orientations are tumbled by Brownian motion, and magnetic forces are too weak on Mars to restore alignment) (Fig. 1). This result is 1000 times better than the previous state of the art [4-5]. On Earth, this would correspond to a tenuous cirrus cloud.

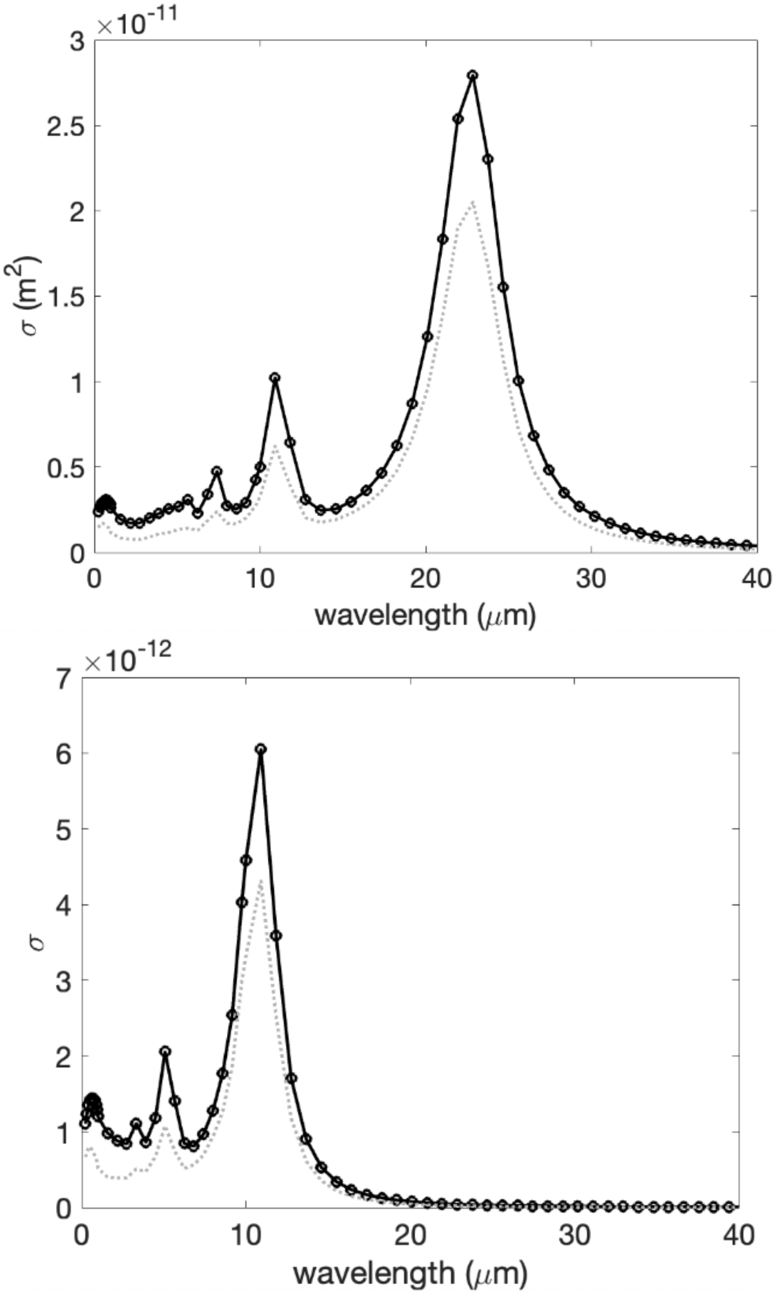


Fig. 1. *Preliminary work (with a 3D Finite-Difference Time-Domain (FDTD) approach) shows that Fe nanorods can warm Mars' surface by plugging the spectral windows in which CO_2 absorbs poorly and through which Mars' surface cools to space ([12] and Overview Chart). Orientation-averaged spectra for (left panel) 9 μm-long Fe nanorod (0.16 μm diameter), which plugs the 22-μm spectral window, and (right panel) 4 μm-long Fe nanorod (also 0.16 μm diameter), which plugs the 10-μm spectral window. Solid lines correspond to total extinction, dashed lines to scattering. Strong thermal infrared effect, weak effect on sunlight, and large breadth of the extinction peak all support strong warming.*

<u>Significant feasibility issues of the proposed concept remain, to be addressed by the proposed research.</u> To establish feasibility, 3D climate modeling including radiative transfer is needed. We

are currently carrying out 3D simulations using the Mars Weather Research and Forecasting (MarsWRF) model at UChicago. This work has low implementation risk, because it involves adapting already-completed fixed-cloud simulations from the PI's group (Fig. S2 from [14]), swapping out the optical properties of natural aerosol (specifically single-scattering albedo, scattering asymmetry, and absorption cross-section), for artificial-aerosol optical properties (Figs. 1-2).

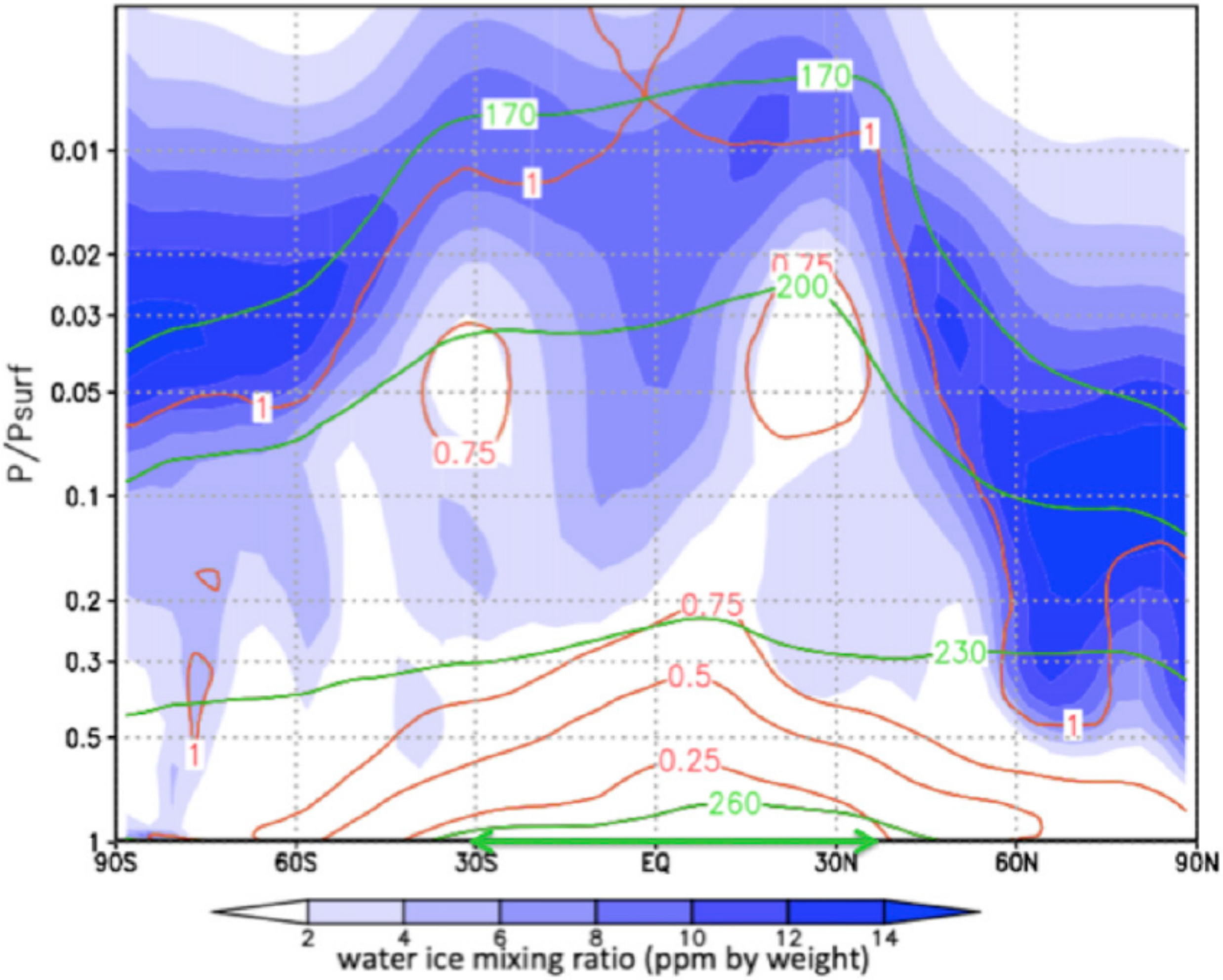
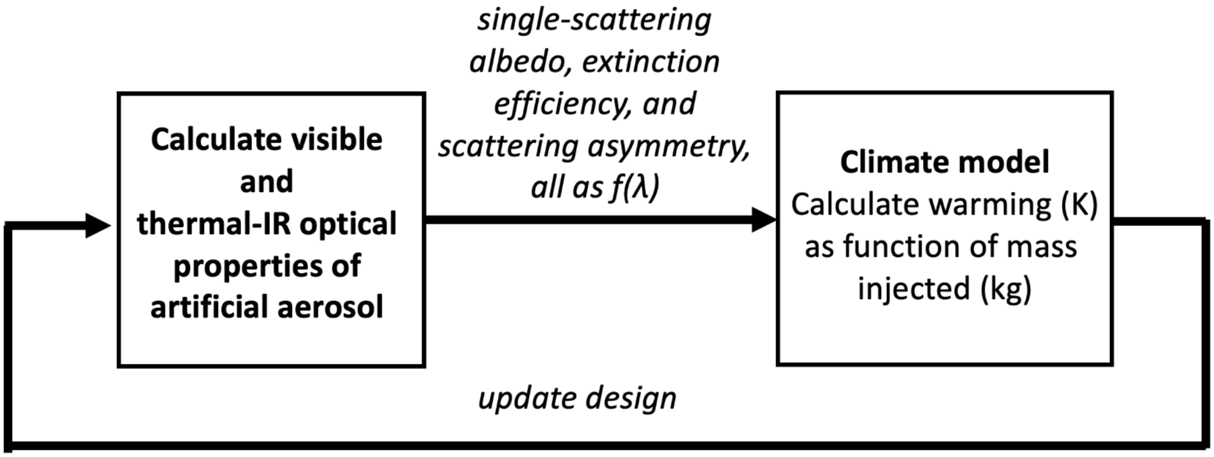


Fig. 2. *Example output plot from the PI's published work with MarsWRF [14]. This a simulation of warming of Early Mars by natural aerosols, and is included ito show MarsWRF's aerosol-handling capabilities. Results from cloud greenhouse simulation showing warm, arid, stable early Mars climate. Zonally averaged, annual-average output for water ice mixing ratio (ppm by weight, blue shading), atmospheric temperature (K, green contours), and relative humidity (red contours). Y-axis uses terrain-following σ-coordinates (σ = P/Psurf). The green double-headed arrow corresponds to the latitudinal extent of surfaces with T > 273 K, warmed by the ice cloud aerosol greenhouse warming effect. For details, see* https://www.pnas.org/doi/10.1073/pnas.2101959118

We will iterate between climate model results and particle design:



Other significant unknowns remain and warrant further study, e.g.: (1) Energy cost of nanoparticle manufacture. Options for scalable manufacture (including possible oxidation-preventing coatings) to be explored include (1a) using solar concentrators (lightweight-Fresnel lens) for vaporization, followed by condense-from-vapor, (1b) on-wire lithography [B15], (1c) wet-chemistry methods [16]. To evaluate these possibilities, we will do the following: *Detailed 3D optical modeling of nanoparticles.* We will use different simulation methods and tools, such as finite element method (FEM) and finite-difference time-domain (FDTD) to evaluate the key optical properties of nanoparticles as a function of electromagnetic wavelength, including absorption cross-section, back-scattering cross-section, and g-factor. *Experimental and theoretical evaluation of nano-manufacturing.* We will explore different nano-manufacturing methods, including vacuum evaporation and colloidal growth, to find the most suitable method(s) for high-volume production of nanoparticles with the desired geometry and composition. We will also evaluate the feasibility of different methods given the Martian environment. One of the most important parameters we will evaluate is the total amount of energy required to produce a unit weight of the desired nanoparticle. *Nano-manufacturing test.* We will experimentally test the most attractive nano-manufacturing methods, such as nanosphere lithography and nano-imprint lithography. The Co-I, Professor Mohseni, has extensive experience of carrying out and leading all of these tasks. Feedstock is unlikely to be limiting as hematite is abundant on Mars's surface [17]. We acknowledge the possibility of delivering nanoparticles to Mars from Earth orbit by solar sail. However, for simplicity, we will restrict our study to manufacture on the Mars surface, and our goal will be to estimate energy costs to within a factor of three. (2) Iteration between particle design and climate modeling holds the potential to improve the efficiency of the concept by orders of magnitude. For example, self-lofting has been shown to work for Earth solar radiation management artificial aerosol [18], greatly reducing "maintenance" injection requirements. A natural question is whether this could work for Mars as well. We plan to parameterize particle turbulent lofting, at least initially; dynamic aerosol tracking has been done with MarsWRF by the PI [14], but is extremely computationally intensive. (3) Radiative details: Our model output shows backscattering in the thermal infrared, which if optimized further would increase the strength of the greenhouse effect.

The concept offers compelling potential benefit. The proposed work would study the feasibility of a method of global warming for Mars that is 1000× more effective, on a per-unit-mass-in-the-atmosphere basis, than current state-of-the-art. By removing a barrier to using Mars' soil to host a photosynthetic biosphere, this could lower the barriers to self-sustaining settlement on Mars. A central goal of our work is to attract a larger community to the study of this problem by demonstrating its feasibility. The specific representative mission for this proposal is the SpaceX Mars plan (e.g., [1]), which aims for a self-sustaining settlement on Mars. We envision that more complex components would be brought in by Starship, with both additive manufacturing of massive-but-less complex components, and also nanorod manufacture, on the Mars surface. CheMin X-ray diffraction has verified in-situ high abundance of hematite in Mars surface materials [17].

References.

[1] Musk, E., 2017. Making humans a multi-planetary species. New Space, 5(2), pp.46-61.
[2] Jakosky, B.M. and Edwards, C.S., 2018. Inventory of CO2 available for terraforming Mars. Nature Astronomy, 2(8), pp.634-639.
[3] Wordsworth, R., Kerber, L. and Cockell, C., 2019. Enabling Martian habitability with silica aerogel via the solid-state greenhouse effect. Nature Astronomy, 3(10), pp.898-903.
[4] Marinova, M.M., McKay, C.P. and Hashimoto, H., 2005. Radiative-convective model of warming Mars with artificial greenhouse gases. Journal of Geophysical Research: Planets, 110(E3).
[5] Dicaire, I. et al., 2013, 3.10x19180, 64th Int. Astron. Congress.
[6] Teller, E., Wood, L. and Hyde, R., 1997. Global warming and ice ages: I. Prospects for Physics Based Modulation of Global Change, p.20, Lawrence Livermore National Lab., CA.
[7] Bohren, C., & D. Huffman, 1983, Absorption & scattering of light by small particles, Wiley.
[8] Pierrehumbert, R., 2010, Principles of planetary climate, Cambridge University Press.
[9] Angel, R., 2006, NIAC Phase I Study, Practicality of a Solar Shield in Space to Counter Global Warming (PI: Roger Angel, University of Arizona, Tucson)
[10] Angel, R., 2006. Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). Proceedings of the National Academy of Sciences, 103(46), pp.17184-17189.
[11] Forget, F. and Pierrehumbert, R.T., 1997. Warming early Mars with carbon dioxide clouds that scatter infrared radiation. Science, 278(5341), pp.1273-1276.
[12] Wordsworth, R., 2016, The climate of early Mars, Annual Reviews of Earth and Planetary Sciences.
[13] Kite, E.S., Mischna, M.A., Fan, B., Morgan, A.M., Wilson, S.A. and Richardson, M.I., 2022. Changing spatial distribution of water flow charts major change in Mars's greenhouse effect. Science Advances, 8(21), p.eabo5894.
[14] Kite, E.S., Steele, L.J., Mischna, M.A. and Richardson, M.I., 2021. Warm early Mars surface enabled by high-altitude water ice clouds. Proceedings of the National Academy of Sciences, 118(18), p.e2101959118.
[15] Banholzer, M.J., Qin, L., Millstone, J.E., Osberg, K.D. and Mirkin, C.A., 2009. On-wire lithography: synthesis, encoding and biological applications. Nature protocols, 4(6), pp.838-848.
[16] Das, Raja, Javier Alonso, Zohreh Nemati Porshokouh, Vijaysankar Kalappattil, David Torres, Manh-Huong Phan, Eneko Garaio, José Ángel García, Jose Luis Sanchez Llamazares,

and Hariharan Srikanth. Tunable high aspect ratio iron oxide nanorods for enhanced hyperthermia. The Journal of Physical Chemistry C 120, no. 18 (2016): 10086-10093.
[17] Rampe, Elizabeth B., David F. Blake, T. F. Bristow, Douglas W. Ming, D. T. Vaniman, R. V. Morris, C. N. Achilles et al, 2020, "Mineralogy and geochemistry of sedimentary rocks and eolian sediments in Gale crater, Mars: A review after six Earth years of exploration with Curiosity." Geochemistry 80: 125605.
[18] Keith, D.W., 2010. Photophoretic levitation of engineered aerosols for geoengineering. Proceedings of the National Academy of Sciences, 107(38), pp.16428-16431.