PLANETARY SCIENCE AND ENGINEERING CHALLENGES OF WARMING MARS IN THE 21ST CENTURY.

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Introduction: Warming Mars could be a step toward making it suitable for life, but would represent a major challenge for planetary science and engineering. Recent work suggests physically feasible methods [1,2], including engineered-aerosol warming [3]. However, before we can assess whether warming Mars is worthwhile, relative to the alternative of leaving Mars as a pristine wilderness, we must confront the practical requirements, cost, and possible risks [4]. In order for engineered aerosol global warming of Mars to start to melt the ice, basic challenges include that particles must be made on (or transported to) Mars, they must:- be released without clumping together, disperse globally, increase the warm-season average temperature of parts of Mars with shallow ground ice by >35 K, persist in the atmosphere for years, and degrade gracefully (without posing a hazard to human health). Moreover, making Mars' surface suitable for life would involve many additional steps beyond initial warming, for example, soil chemistry and suitability for biology.

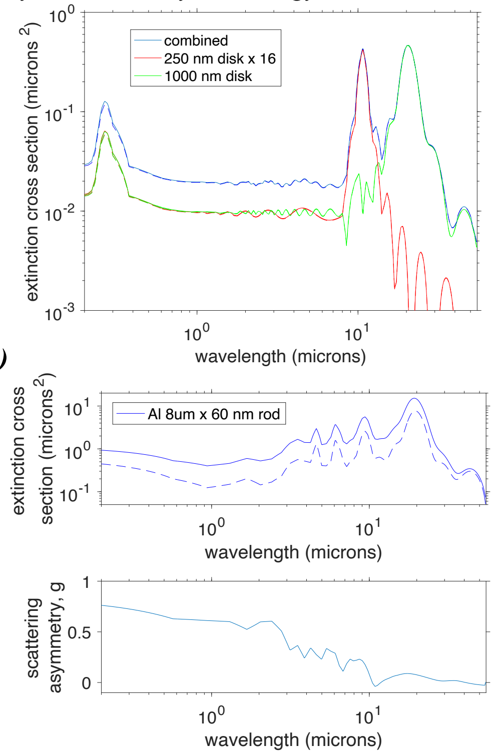

Fig. 1. Spectra for engineered aerosol. (a) *Graphene disk extinction spectrum from 0.3-55 μm. Sizes are disk diameters. Dashed lines show absorption contribution (close to 100%). Scattering asymmetry ≈ 0.* ***(b)*** *Al rod (8 μm, 60 nm wide) extinction spectrum. Dashed lines show the absorption contribution. Lower panel: scattering asymmetry.*

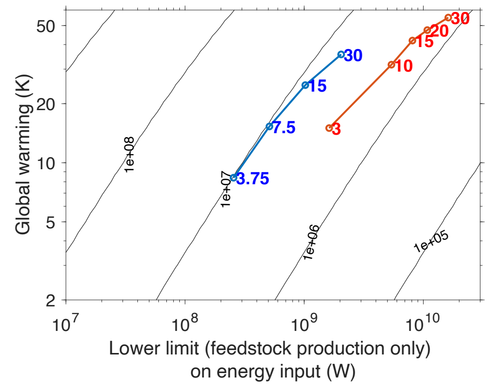

Fig. 2. Steady-state temperature response as a function of energy required to produce feedstock, for graphene disk mix (blue), and for thin Al rods (red). This feedstock energy requirement is only a lower limit on total energy required. *Warming calculated using a plume-tracking GCM. Colored numbers correspond to loading rates in L/s. The labels on the thin black contours correspond to the approximate energy gain factor using this method, approximating the power emitted by the surface as σT_{av}^4.*

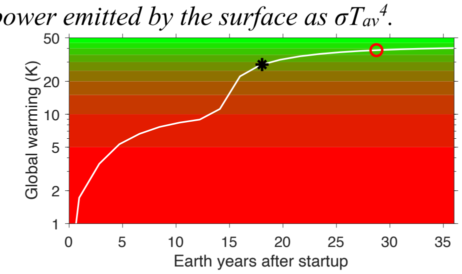

Fig. 3. Time evolution figure, assuming a 3.75 L/s global warming test for the first ~12 Earth years, followed by a choice to increase to 30 L/s. *At 18 Earth-yr, the average warm-season temperature at 50°S is >273 K (black star), and warm-season temperature at 50°S is >283 K after 28 Earth-yr (red circle). Graphene mix assumed.*

Methods: We consider two particle types for Mars warming: Al nanorods (60nm-width, 8μm long; one-eighth the mass of the particles in [3]) and graphene disks [7] (mix of 250nm and 1000nm diameters in 16:1 number ratio). Both target Mars' thermal infrared windows at ~10μm and ~20μm. We calculate optical properties using FDTD electromagnetic simulation (Fig. 1) and estimate production requirements using a plume-tracking MarsWRF Global Climate Model (GCM) including radiative-dynamical feedbacks for 158°W 40°N release (Fig. 2). Fig. 2 assumes an energy expenditure of 200 MJ/kg for Al (metal regolith electrolysis), and 30 MJ/kg for C. Graphene disks offer both advantages and disadvantages relative to Al rods. Energy efficiency is significantly improved, as graphite feedstock production via CO_2-electrolysis (demonstrated on Mars [5]) requires less power than Al production. Graphene's UV absorption spectrum fortuitously matches that of ozone (Fig. 1), potentially ameliorating Mars' UV-B challenge to surface life without requiring oxygen production. On the other hand, peak extinction efficiency is lower for graphene disks, and the particle number density is higher, so preventing agglomeration is a bigger problem. Other options worth investigating include nanoribbons, other C nanomaterials, or Mg, and orbital deployment.

Production challenges: As a starting point, we estimate infrastructure requirements for a minimal warming scenario of +5 K global warming. This is three times more than human-induced global warming of Earth, but far below the warming needed to start to melt the ice. For minimal (+5 K) warming using graphene, we assess power requirements for producing graphite (not graphene) of approximately 200 MW. This assumes CO_2 electrolysis power of ~6.25 kW per kg/hr O_2 [6], with 40% additional power for complete reduction to carbon, and a production rate of 2 L/s. This neglects non-electrolysis steps in graphite production (e.g. air compression). CO_2 electrolysis is demonstrated by the Mars OXygen In-situ resource utilization Experiment (MOXIE) on Perseverance [5].

Subsequent steps (conversion of graphite to graphene, size sorting, etc) may be significant in terms of energy. In particular, the graphene disks' optical properties (wavelength of the peak of resonance, the width of the peak, etc.) change with the size of the disk [7]. Hence, the graphene disk size needs to be quite precisely controlled and the disks need to be uniform in size (the disks we have simulated are also very small which can make size control and uniformity more challenging). The methods that can produce high-quality uniform graphene are usually limited in throughput. One might try to generate randomly shaped flakes of graphene and only sort the ones that satisfy the size criteria. However, yield may be low leading to a need for recycling, or significantly more energy. The mass requirements for the electrolysis system [8] are ~10^4 tons excluding compression hardware, with additional mass needed for particle functionalization, anti-clumping systems, production facilities, and power systems. Thus, the electrolysis system alone could require at least ten Starship-class landings [9] annually for a decade. Power might be supplied by compact high-output power sources or by solar panels made in-situ (e.g., Blue Alchemist); in the latter case, the main ingredients for warming Mars might be Mars' air and sunlight. Graphene might be produced from soot via methods like liquid-phase shear exfoliation [10] or flash Joule heating [11]. This simplified workflow omits many practical challenges. Near-release clumping must bes prevented. Precipitation in the warmed climate might remove particles. Non-stick coatings might solve both issues but complicate production. Functionalization (irradiation, doping) and liquid adjuvants may also be required. This could further increase the required number of landings. At the conference, we will discuss production challenges for metal nanoparticles (Al, Mg).

Discussion: Many additional challenges remain outstanding and require further research. These include preventing agglomeration during dispersal, functionalization for optimal performance, and anti-stick coating development. Production would involve scaling graphene production beyond current capabilities. Deployment issues include optimizing release timing and location. For full deployment scenarios targeting >35 K warming, additional uncertainties involve climate feedbacks. These include changes in dust storm frequency and intensity, water vapor feedbacks, and cloud feedbacks [12]. Full warming would harness around 10^{16} W of sunlight energy. Particle atmospheric lifetime may exceed our estimates (see companion abstract) since some particles likely get re-lofted, for example by springtime CO_2 sublimation, rather than being permanently absorbed at the surface. Particles must be engineered to break down in the natural environment. Methods include (for rods) adding spacers, designing for water solubility, further thinning for oxidation frangibility, and functionalization. Graphene particles might offer additional benefits if doped with soil nutrients.

Next steps: Although much more modeling and laboratory work is needed, ultimately small-scale and reversible experiments would be needed to validate models. Initial spacecraft experiments might validate the self-lofting behavior seen in our simulations. If successful, global warming might proceed cautiously and reversibly. Fig. 3 demonstrates this approach using subscale infrastructure (3.75 L/s) to achieve 10 K warming, with many options for climate evaluation and optional offramps before reaching the 273K-season-at-50°S threshold. This work used the MarsWRF GCM [13,14]: see companion abstract for more details.

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