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A New Mechanism to Make Mars Habitable

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Abstract. To establish an Earth-derived biosphere on the surface of the cold desert planet Mars in future, it is necessary to raise Mars' surface temperature, Ts. We review published warming schemes, synthesize recent relevant discoveries, and propose a new warming scheme.

1. Background. The idea of extending life beyond Earth is as old as science [1-2]. Analyzing Mars warming schemes is intellectually interesting: it forces us to think in a broader sense about effective geo-engineering strategies that can change the atmosphere and climate of an entire planet. This has implications beyond Mars: for example, it can also allow us to speculate on the best strategies - for an intelligent extraterrestrial life form - to make a planet habitable, and thus identify possible detectable markers of such influence on a planetary environment. Although *Mariner 4* confirmed that Mars is cold and dry today, Mars remained a tempting site for establishing a photosynthetic biosphere in the future [3]. During the 1970s and 1980s, Sagan, Murray, Bradbury – and many others – envisaged a possible future where humans enable Mars to support photosynthetic life. Some scientists suggested methods for turning these thought experiments into reality [4]. However, as of the mid-1990s, data didn't match the ideas: then-current understanding suggested an environment that was extremely harsh throughout Mars history [5], and we knew little about the distribution of Mars' volatile resources. Now, thanks to NASA+ESA missions, we have a much better understanding of the present-day distribution of buried volatiles that are relevant to environmental change [e.g., 6,7]. Moreover, the idea of a warm and more-habitable Mars has gained succor from rover data showing that Mars once had lakes that (at least for microbes) were habitable [e.g., 8]. Thus, Mars and Earth both had surface water bodies that were habitable ~3.5 Gya. However, neither 3.5 Gya Mars nor 3.5 Gya Earth had O_2 levels that were breathable. Similarly, if the objective is to use 21st-century technology to allow people to walk on Mars' surface unaided, then no scheme has been identified that could achieve that objective [9][1]. An easier task is re-establishing a warm climate. This is in part because today's Mars, which is uninhabitably cold, nevertheless receives 40% more energy from the Sun than did Mars when the planet was naturally warm enough to be habitable. Given today's knowledge, it is timely to again ask: Could we get Mars' rivers running again?

2. The challenge. Photosynthesis on Mars is currently prevented by high surface UV, soil chemistry, and low T_s. T_s can be raised using gases (e.g. chlorofluorocarbons), but this would require large amounts of F [10,11]. We introduce an alternative warming agent, half-wavelength metal dipoles (nanoantennae). This agent is more efficient (on a warming-per-mass-in-the-atmosphere basis) than previously published schemes. Moreover, the method relies only on Mars resources that have been proven to exist by in-situ analysis [12]. The method draws inspiration from improvements in models of mechanisms to explain 3.5 Gya Mars rivers [e.g., 13-14]. We consider a basic nanoantenna – a ~5-10 μm-long, <100 nm-diameter nanorod. (Real applications would use multiple rod lengths). Rod extinction efficiency peaks at upwelling thermal-IR wavelengths [16]. Nanorods settle 10^2-10^3 times more slowly than Mars dust [17], are taken up by dry deposition and by seasonal ice, and are re-released to the atmosphere by sublimation and dust lifting [17-18].

3. Scaling a warming method.

Radiative forcing: Simplistic calculations (ch. 5 & 12 of [16]) suggest {Fe,Al} nanorod extinction efficiency $Q_a \gtrsim O(10)$ for $\lambda = 10$ μm; results using `meep` simulations [19] will be reported at the conference. A figure of merit is the nanorod volumetric injection-to-the-atmosphere rate:

$$\dot{V} = \frac{V}{\Delta t} = \frac{\tau\, a}{Q_a\, \Delta t}\left(\frac{V_r}{A_r}\right)$$

where τ is the optical depth needed for strong warming (~5, [13-15]), a is Mars surface area, V_r is rod volume, A_r is rod cross-sectional area, and Δt is nanorod lifetime in the atmosphere. Then,

$$\dot{V} = 10^3\,\frac{\mathrm{m}^3}{\mathrm{d}}\left(\frac{10\,\mathrm{yr}}{\Delta t}\right)\left(\frac{10}{Q_a}\right)\left(\frac{r_r}{33\,\mathrm{nm}}\right)$$

i.e., a volume of nanorods equal to a cube with 10m sides must be injected into the atmosphere every day to keep Mars at a habitable T_s. The spin-up time for steady injection is ~Δt. Δt is the biggest unknown: Δt = 10 yr is slightly optimistic if nanorods do not individually self-loft, but very pessimistic for more sophisticated nanoantennae that might individually self-loft (and also act as sunscreen) [20-21]. If Δt is very long, then the one-shot volumetric injection for $\tau = 5$ corresponds to a volume 0.004 km^3. *Winds:* To warm Mars, nanorods must get to high altitude [14,22]. Natural dust distribution caps out at 25 km [18]; by analogy to [13-15], we expect this to be sufficient, although more detailed calculations are

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[1] This is in part because orbital reconnaissance has not identified a reservoir of Mars volatiles that is both big enough to thicken the air above the Armstrong limit, and also relatively easy to release [9].

needed. Natural dust injection from the surface is by dust devils, gusts, daytime upslope winds, and self-lofting. Nanorods might be injected above the surface layer (e.g., pipe connected to balloon). Nanorods are small enough that (neglecting magnetic effects, e.t.c.) they will collide with the ground before they have a chance to clump together. A key unknown is nanorod reentrainment rate from realistic (dusty, sandy, rocky) surfaces. Zero reentrainment is unlikely; Mars' sky is always dusty. *Nanorod production and injection:* Along the MSL traverse post-sol-700, XRD shows (10±5) wt% Fe_2O_3/Fe_3O_4 [e.g., 12]. For a prismatic mine of half-width 225 m bracketing MSL's path, with a side-wall slope of 20°, it is necessary to mine a length of 800 m/yr (for Δt = 10 yr) to obtain Fe-oxide minerals and sustain $\tau = 5$. (A similar mass balance can be done for Al from Al-rich materials at Mawrth; Fe_3O_4 rods are another alternative.) Following metal extraction, thin coatings might be added to slow oxidation. Mineral processing is energy intensive. Falcon Heavy launches (conservatively) 5 t to Mars' surface. Earth seafloor mining robots mass >200 t; mining hardware could be launched in segments. If 3D metal printing technology can be proven in space (https://www.relativityspace.com/), then boot-strapping may be a workable alternative. *Feedbacks:* For Δt = 10 yr, each kg of nanorods redirects the sunlight-energy equivalent of a nuclear explosion, albeit for peaceful purposes. As Mars warms, ice caps release H_2O vapor. This has two effects: (1) H_2O greenhouse warming (vapor+cloud) [23-24]; (2) increased water-ice scavenging of nanorods. The relative importance of these effects depends on the coupling of the dust and water cycles, which is not well understood. We do not know what effect adding nanorods would have on dust storms. (A worst-case is that global dust storms occur every year and the dust storm season lengthens. If so, little sunlight would reach the surface during the growing season). ~6 mbar of CO_2 can be released from South Polar ice caps, and a poorly quantified (but <40 mbar) CO_2 from regolith de-adsorption. So, under warming, atmospheric thickness would increase by a factor of 2-10 (timescale centuries without human intervention). CO_2 release would provide a modest boost in T_s, favor liquid water, and possibly cause H_2O snowfall at low latitudes [25]. Our predictive power is limited for 2-5K of human-induced warming on Earth [26]; although Mars is a simpler system, T_s must rise by $\gg$5K for a habitable surface. So, it is hard to anticipate how feedbacks will pan out (and therefore, how many nanorods will be needed) on the real Mars. *Alternatives:* An alternative to atmospheric injection is Phobos-derived Mars-orbiting particles. This option would require a Poynting-Robertson-nulling rod design, radiator fins, and a plane-change mechanism. *Asbestosis:* Nanorods will accumulate on the surface until oxidized. Even if humans are restricted to sealed habitats, nanorods will be brought into human-occupied spaces through airlocks. One way to deal with asbestosis hazard would be to make nanorods that dissolve or fragment in liquid water [27].

4. Discussion and conclusions.

Human-robot synergies: Intentional warming of Mars does not require humans on Mars' surface, but might go faster with human help. A hybrid strategy would use polymer sheets to minimize evaporitic cooling and water loss and provide physical greenhouse warming for shallow ground ice adjacent to human habitats. Working alongside global atmospheric warming, this local boost could bring forward the date of (re-?)establishment of a surface biosphere. **Warming, by itself, is not enough:** Small engineered aerosols can fix the surface UV problem. We have not characterized Mars soil sufficiently to solve the soil chemistry problem, but we do know that the problem is severe. For example, perchlorate is toxic, and perchlorate is everywhere. Perchlorate-reducing bacteria (PRB) convert perchlorate to O_2 gas [28]; it is not known if PRB can partly detoxify Mars soil. **Outstanding science questions:** Examples include (1) 3D atmospheric modeling of the warm-up. (2) 600 Pa wind-tunnel data for rod reentrainment rate on realistic rough surfaces. (3) Mesoscale modeling of nanorod lofting (passive tracer and self-lofting). (4) End-to-end engineering system modeling. (5) Trial self-lofting. (6) Tracking of plumes from orbit (cubesats) to constrain Δt. (7) Proving of CO_2 ice reserves. **Take-home:** Raising Mars' temperature, by itself, is not sufficient to make the planet's surface habitable again. Nevertheless, nanoantenna warming is near to fundamental physical limits on the efficiency of intentional planetary warming, and merits attention (alongside previously proposed schemes, e.g., [11]) from engineers.

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