Mars Climate Warming Mechanisms and Suitability for Life, Past and Future.

E. S. Kite[1,2], A. Kling[1], A.S. Braude[1], M.A. Mischna[3], F. Sharipov[4]. 1. *Astera Institute, Emeryville, CA, USA (edwin.kite@astera.org).* 2. *University of Chicago, Chicago, IL, USA.* 3. *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA.* 4. *Universidade Federal do Paraná, Paraná, Brazil.*

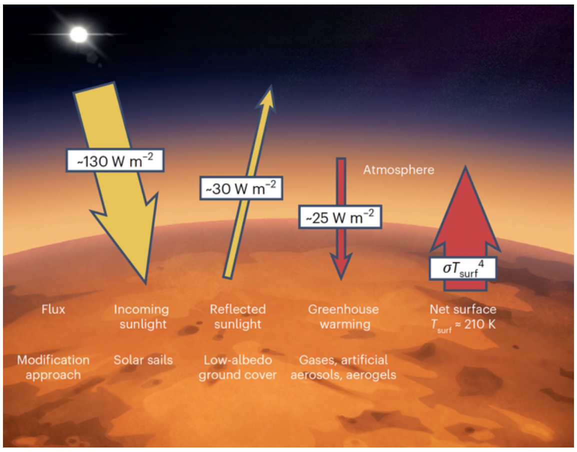

***Fig. 1** (from [10]). Energy sources and sinks on present-day Mars. At present, the net absorbed energy is $E = 125$ W m^{-2}, resulting in a surface temperature of $T_{surf} \approx 210$ K. σ, Stefan–Boltzmann constant. Figure: D. Zhou.*

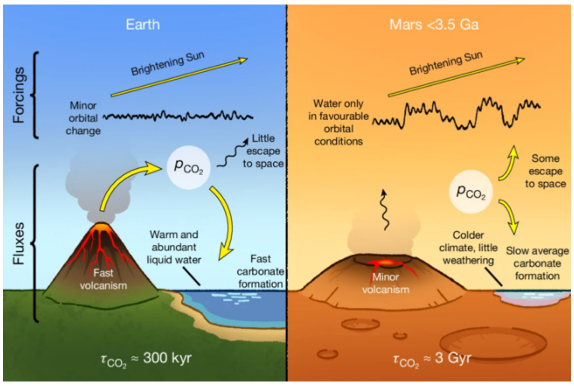

***Fig. 2.** Fluxes and feedbacks for climate and habitability regulation on post-3.5 Ga Mars and Earth, according to [5]. On Earth, temperature increase from vigorous volcanic outgassing of CO_2 is balanced by fast carbonate formation. On Mars, in the ref. [5] hypothesis, slow temperature increase from solar brightening is balanced by slow (time-averaged) carbonate formation. The locally high rate of carbonate formation once liquid water is available assures that on Mars the climate has only infrequent liquid-water oases (during orbital optima). This model does not account for pre-3.5 Ga valley networks. τ_{CO2}, residence time in (atmosphere + surface water) reservoir. Figure: D. Zhou.*

Introduction: Mars' present surface conditions are hostile to life. Frigid temperatures (Fig. 1), high UV radiation, low atmospheric pressure, salty soil containing perchlorates, and absence of liquid water, all work against growth of any Earth microbe. However, both Mars' past and future offer more promising prospects for habitability. Exploration by an international flotilla of orbiters and landers has identified evidence of past climates that supported rivers and lakes [1-2], although the mechanisms driving these warmer, wetter periods remains debated [3-5] (Fig. 2). ESA's Rosalind Franklin rover will target deposits of one of these climates. Looking forward, Mars' surface might become habitable either through natural processes (over billions of years as solar luminosity increases) or through human intervention on faster timescales [6-9]. A recent review [10] highlights several newly proposed surface-warming techniques that offer greater efficiency and/or feasibility compared to previous approaches [11-15].

Here, we emphasize temperature increase, which is a necessary (but insufficient) condition for surface habitability for photosynthetic life; many additional challenges remain [16-18].

The question of whether humans should warm Mars has been debated for decades, with arguments both for [19] and against [20]. Currently, we lack sufficient information to make an informed choice. For example, the need to do more to show that life is absent on other worlds before making them more habitable to life from Earth is particularly true for Mars. Many unknowns remain about Mars atmosphere-surface exchange, and these would need to be resolved before any substantial climate modifications. Thus, further exploration, including a sample return mission, is on the critical path toward making a choice between possible futures for Mars (Fig. 3).

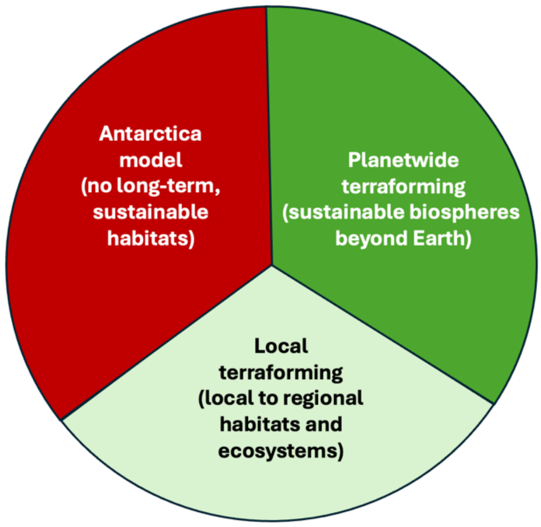

***Fig. 3.** Possible futures of Mars.*

What Caused Warmer/Wetter Climates In Mars' Past?: CO_2 alone cannot warm Mars sufficiently to account for rivers on Early Mars [21]. The kinetic energy of impacts is not enough to explain the data

[22-23]. Freezing-point depression by acids might contribute to chemical weathering ([24], but see also [25]), but does not explain rivers. Volcanic SO_2 is a strong greenhouse gas, but within weeks forms aerosols that cause net cooling [26-27]. Other warming gases such as NH_3 and H_2O_2 have short photochemical lifetimes and few large-flux sources [28]. N_2 may have been more abundant on Early Mars, but (for 0.5 bars of N_2) adding N_2 provides ≤ 13K warming (e.g., [29]).

Collision-induced absorption between H_2 and CO_2 (H_2-CO_2 CIA) has been proposed as a mechanism for warming Mars [3,30]. The H_2 might have been supplied by reactions between reducing impactors and H_2O [31], or by outgassing of H_2 produced by (e.g.) serpentinization [32]. This mechanism predicts that river-forming episodes were individually brief (~10^5 years) and can only produce rivers and lakes if Mars once had >0.5 bars of CO_2.

Alternatively, water ice clouds can produce strong surface warming provided that ice particle size is large [33-35].

A sample return mission (for example by CNSA's Tianwen-3 or a future NASA-sponsored commercial mission) would greatly aid in distinguishing between these warming hypotheses.

The duration of river-forming climates was probably a small fraction of Early Mars' history, because Mars is not as deeply eroded as would be expected if rivers flowed for a billion years [36]. However, the time gap between the first and last river-forming climates was at least 20-200 Myr [37], probably much longer. Late river-forming climates were more arid (e.g., [66]), and left traces that were topographically lower [67], spatially patchy, and, but still featured strong peak discharge [68]. This combination of attributes has been argued to favor water-ice-cloud warming [35].

In between the river-forming episodes, sedimentary rocks formed, likely over a time span of 3 Gyr [38]. The Mars Science Laboratory *Curiosity* rover is currently inspecting older sulfate-rich sedimentary rocks and should inspect young "rhythmite" rocks in 2026.

A proposed mechanism to explain fluctuations of climate around the liquid-water-allowing threshold is liquid-water-dependent carbonate formation [5].

Given the hostility of the surface environment, it is possible that the best place to look for evidence of life on Mars is the deep subsurface [39], or megabreccia that preserves very old rock.

What Does Past Warming Tell Us About Mars' Future Potential for Life?: Mars was a desert planet for most of its history [40]. Most of the geomorphic evidence for a wetter early Mars is Gyr old [41]. Some potential early Mars warming mechanisms probably could not recur in the future, for example, strong H_2-CO_2 CIA warming. Others, such as water ice cloud greenhouse warming, will likely recur [34], but are unlikely to cause enough warming for widespread meltwater at the current low atmospheric pressure. Some aspects of Mars' changes are irreversible, most importantly loss of H_2O to space [42-43]. Others are almost certainly reversible, such as release of CO_2 from the polar caps [44]. Thus, Mars' history does not provide a simple lesson for humans contemplating establishing sustainable habitats beyond Earth. Mars' lack of plate tectonics and low rate of volcanism prevents the geochemical recycling that on Earth closes element mass budgets. Although Mars is volatile-poor relative to Earth, Mars' atmosphere/ice-caps/soil retain life-essential elements in easily-volatilized forms in quantities that can support a biosphere. Mars shows that a planetary habitat does not necessarily persist for the long duration that was required on Earth before conscious beings evolved [45-46]. It is likely that planets that like Mars are marginally uninhabitable are abundant in the Universe.

Methods of Warming Mars in the Future: Mars will warm in the future because the Sun will brighten over time [6]. In the relatively near future (decades to millenia), it is possible that this natural process will be artificially accelerated by human activity.

The most impactful geologic, and biogeochemical agent on planet Earth is the only known spacefaring species, humans. Human activity dominates Earth's C, N, and sediment cycles; and most of Earth's land is used by humans. Earth's climate is now set by human decisions; this will be true for as long as humans exist [52]. Human population has increased 10× in the past 250 years; energy use has increased 10× in the past 100 years [53].

So far, humans have launched <10^6 kg into interplanetary space, too little to establish factories of the scale needed to modify a planet's climate. If humans decide in the future to create sustainable habitats and ecosystems beyond Earth, then science will have a critical role to play. This defines a growing research field of "applied astrobiology" (e.g., [8, 10-17, 54-56]), which both complements and is a subset of existing fields (astrobiology, in-situ resource utilization, etc.) As this research field is new, many possible warming methods remain underexplored or unexplored.

Here we consider only warming: other challenges include high UV levels, water cycle and dust cycle feedbacks, perchlorate in the soil, and extremely low O_2 levels until photosynthesis has built up oxygen.

Important factors to consider in evaluating proposed warming methods and their sustainability include the following:

- energy costs (joules per kilogram),
- mass requirements (kilograms per Kelvin of warming),
- ease of manufacture (complexity, abundance of source material, processing steps, other consuma-

bles needed for production),

- biocompatibility, ease of disposal, and reversibility (which is often closely connected to the time to reach steady state),
- and the diversity and biological productivity of the biosphere that could be supported.

Several misconceptions must be addressed before discussing methods for warming Mars. For example, it is not true that Mars would swiftly lose its atmosphere if it were warmed: loss rate is geologically slow at present (~1 mbar/Gyr) [62], and would remain geologically slow on warming. Mars' atmospheric pressure is sufficient for life (given liquid water): twenty species of extremophiles grow at 6 mbar [63]. Runaway warming of Mars cannot occur: pressure will rise by (2-20×) if Mars is warmed, depending on how much CO_2 is desorbed from Mars regolith. Although this is a positive feedback, it is not enough for runaway warming [64]. Finally, Mars cannot be warmed sustainably using explosives, due to the very high sustained energy input needed (~10^{16} W): this method is inelegant and unnecessary.

Engineered warming of Mars in the future might occur via gases, particles (either in the atmosphere or in orbit), mirrors reflecting sunlight down to the surface, or local approaches such as aerogel tiles [11], a 'worldhouse', or biologically produced bioplastic habitats [15]. The thermal emission emitted by Mars's surface must be at least twice the present value to enable melting. We now consider each warming method in turn.

An optimal greenhouse-gas mix requires 10^{14} kg of fluorocarbons [9, 57] to warm Mars by >35 K. This is impractical because F is sparse in Mars soil and rocks and F-rich deposits are not known on Mars. For 100-year buildup, mass input would be 10^{12} kg/yr, neglecting photolysis losses, invoking 10^{12}-10^{13} W of power for fluorocarbon synthesis. However, gas warming remains a live possibility because other gases, such as chlorocarbons, or NH_3 produced from N_2, have not been evaluated in detail. (Although chlorocarbons would reduce the concentration of UV-screening O_3, UV can be screened by other method, such as C-rich haze [14]).

Particle warming of >35 K requires 10^9-10^{10} kg of engineered aerosol for atmospheric deployment from near-surface release [12,14]. Aerosols may either warm or cool a planet's atmosphere depending on their size, shape and composition. For comparison, cooling Earth by 2K using aerosols added to Earth's stratosphere (either released naturally by volcanic eruption or artificially by aircraft release) also requires 10^9-10^{10} kg of aerosol [58]. Challenges with this approach include particle agglomeration, trade-offs between particle efficiency and ease of production, quantifying water vapor feedback, uncertainties in the dry-deposition rate of submicron particles on Mars, and ensuring particle biocompatibility and degradation. The corresponding steady-state energy requirement, assuming Martian manufacturing, would be 10^9-10^{10} W. Orbital deployment of dust as an alternative remains to be considered.

Global warming via orbiting mirrors would require ~10^{14} m^2 of reflective surface area, corresponding to ~10^{12} kg using 20 g/m^2 lightweight space mirror technology [59]. Mirrors might be deployed at smaller scales to accelerate volatile release from the polar caps in conjunction with a warmed climate, as both aerosols and gases warm Mars' poles inefficiently. Orbiting mirrors are being researched as a source of nighttime solar power to Earth [60]. Such mirrors could potentially be manufactured on Phobos (soon to be sampled by JAXA's MMX mission) or deployed as solar sails from Earth [13].

Adding volatiles to Mars in quantities sufficient to significantly alter its atmospheric thickness exceeds current technological capabilities. For example, adding CO_2 equal to Mars' current atmospheric mass (2.5×10^{16} kg) by delivering objects containing 10 wt% of the target volatile and applying $\Delta V = 5$ km/s would require 10^{16} W of energy sustained over 100 years, assuming 10% efficiency. This is 10^3× current global energy consumption.

Any warming method can be enhanced by darkening the surface, potentially using rapidly dispersible carbon-based aerosols. However darkening the surface, by itself, is not enough to start to melt the ice.

Local terraforming approaches appear feasible, including silica aerogel tiling [11], or bioplastic habitats for bioplastic-producing organisms [15]. The latter could extend rapidly over the surface, limited primarily by the availability of 3D printers to produce new bioplastic habitats and accessible water resources [61]. A key advantage for localized terraforming is that many organisms capable of producing useful materials for humans can tolerate a much wider range of pressure and oxygen levels than humans themselves. Thus, lower-pressure, warm-temperature habitats can usefully coexist with the higher-pressure, warm-temperature habitats needed for humans [65]. Synergies are possible: for example, materials produced by biospheres enabled by local terraforming could contribute to global terraforming.

Overlapping Priorities Between Mars Climate/Paleoclimate Research and Assessing Mars' Future Suitability for a Habitable Climate: While human travel to Mars will likely occur, the nature of that future engagement is uncertain. Assessing Mars' future suitability for a habitable climate offers fresh impetus for existing priorities [10], including:

- Sample return, to do more to search for life on Mars, assay for potential toxins, confirm organic matter content, et.c.
- Better-equipped weather stations with the ability to monitor dry deposition [47].
- Climate modeling of response to polar warming

(e.g. [48])

- Ice cores to understand past response to polar warming [49].
- Improved maps of the distribution of H_2O ice, a key resource for any possible human-involved future for Mars (Fig. 3) [50].
- Probing for deep groundwater using electromagnetic methods [51]: a potential relic of Mars' wet era, a potential resource for terraforming, and a potential habitat for astrobiological investigation.
- Extension and improvement of from orbit climate monitoring, to monitor natural variability and also precursor/test terraforming experiments.
- Model intercomparison studies (e.g., CUISINES), to assess inter-model discrepancies.
- International cooperation, building on existing frameworks such as the International Mars Exploration Working Group (IMEWG).

Current Work: Our ongoing research includes analysis of water vapor feedback, cloud feedback, and the redistribution of ground ice - these are all critical components of any regional or global warming scenario.

For engineered aerosols, we are conducting Large Eddy Simulation (LES) modeling of deployment plumes. The H. Mohseni group at Northwestern University is manufacturing small test batches of particles to experimentally validate their radiative properties.

We recently released the open-source tool TerraScreen (https://github.com/mars-terraforming-research/TerraScreen), a one-dimensional model based on the NASA Ames Mars GCM [69] that simulates representative Martian atmospheric and surface temperatures in the presence of natural or engineered aerosols. Led by A. Kling, this development enables us to compare different candidate warming particles, including metals, carbon-based nanoparticles, and natural particles such as salts. We are also evaluating porous particles (with parameters provided by the A. Raman group at UCLA).

At the conference, we will present new results for this engineered-aerosol method.

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