Greening the Solar System

Edwin Kite & Robin Wordsworth

A future where life flourishes beyond
Earth is closer than you think.
How, precisely, will we get there?

The idea of bringing life to other worlds captured the imagination of many scientists and thinkers, from Konstantin Tsiolkovsky in the 1890s to Freeman Dyson, Carl Sagan and other 20th century visionaries. Today, we know much more about spaceflight, biology, and the nature of habitable environments. We are entering an era of rapid and cheap access to space, and with it, we find ourselves on the brink of being able to extend Earth's biosphere across the solar system, millions or even billions of times beyond its current bounds.

The possibilities for how we might do this range widely, from terraforming Mars (and possibly the moons of other planets) to generating habitable bubbles on free-floating asteroids. While technological challenges remain, many of these techniques appear surprisingly feasible — making a future detailed assessment of their merits all the more important and interesting.

Greening Mars: first steps

After Earth, Mars offers the most promising place in our solar system for sustaining life. However, despite the 10^{16} watts of sunlight that reaches Mars — the same amount that powers Earth's land biosphere — its surface is, as far as we can tell, sterile. The soil is cold, salty, UV-irradiated, and full of toxins like perchlorate, poisonous to most life. The radiation there would put people at serious risk of developing cancer within a decade. The planet lacks liquid water, and the air is thin and dusty. And yet, Mars is covered by the traces of dry rivers — our rovers have found dry lake beds — and there exists abundant H_2O ice — enough, if it were spread out evenly, to cover the planet with water 100 feet deep.[1] Mars looks as if it fell asleep a billion years ago.

If, as currently seems likely, Mars's surface today is truly lifeless, we can start to think about what would be needed to make it habitable again. The first problem is low temperature: greening Mars would require local or global warming by tens of degrees Kelvin. Such warming could theoretically be achieved with artificial greenhouse gases, but these would require mining huge amounts of fluorine from the surface. This would involve processing the soil across the globe to a depth of one meter, causing massive environmental damage.[2] So attention has turned to other methods that might better "work with the grain" of Mars's materials.

One promising approach would be to warm the Martian surface regionally, rather than globally. This would allow life-essential volatiles like water, which might otherwise evaporate, to be kept in one place — important

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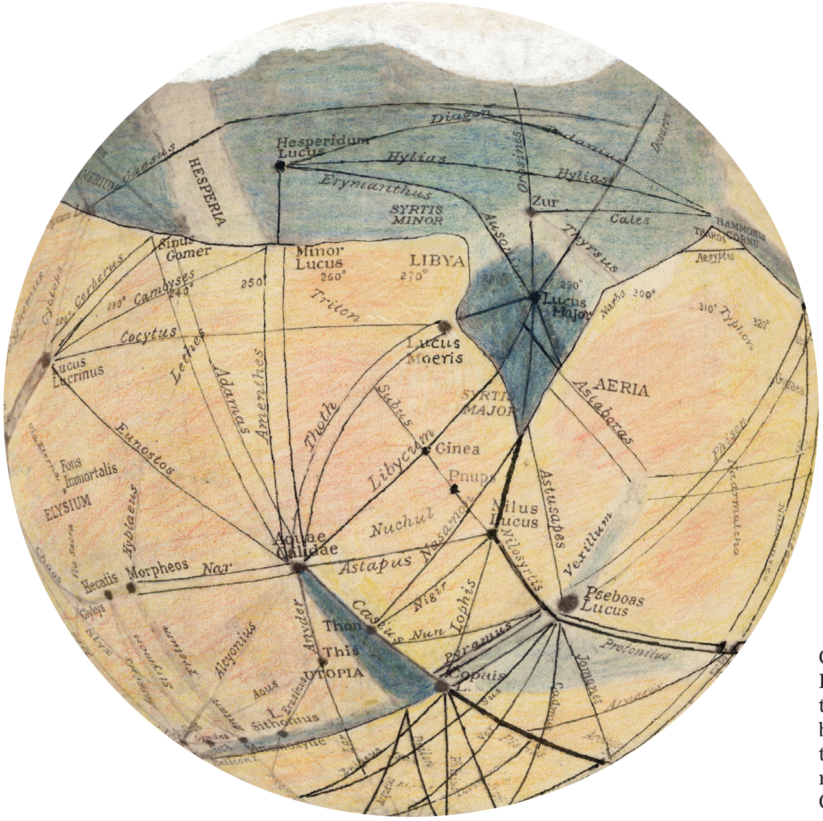
[1] Gareth A. Morgan, Nathaniel E. Putzig, Matthew R. Perry, Hanna G. Sizemore, Ali M. Bramson, Eric I. Petersen, Zach M. Bain et al., "Availability of subsurface water-ice resources in the northern mid-latitudes of Mars," *Nature Astronomy* 5, no. 3 (2021): 230–236.

[2] Margarita M. Marinova, Christopher P. McKay, and Hirofumi Hashimoto, "Radiative convective model of warming Mars with artificial greenhouse gases," *Journal of Geophysical Research: Planets* 110, no. E3 (2005). Pollack and Sagan wrote in 1994, "mining much of Mars ... down to depths of hundreds of meters or more [would] represent a wholly irresponsible waste of solar system resources and the loss of irreplaceable scientific knowledge." There are loopholes for the gas option. For example, some locally abundant concentrations of fluorine have been found by the Mars rover *Curiosity*, although none of these are large enough to mine.



Color Drawing of Mars by Percival Lowell, made in 1905. Lowell believed that an intelligent civilization had built canals on the surface of Mars to bring water from the poles to the rest of the planet. Courtesy Lowell Observatory Archives.

for a dry planet like Mars. So-called "supergreenhouse" materials like silica aerogel could let sunlight through but trap both thermal infrared radiation and heat.[3] These materials could be used, together with polymer films, to construct habitats. Or they could be laid on top of the planet's soil, where they would melt ground ice and create local warm bubbles in which plants could flourish.

Aerogels could be manufactured on Mars using silica from rocks and compressed carbon dioxide from the atmosphere. Although major new advances in synthetic biology would be required, aerogel-like materials might eventually also be produced directly by living organisms, similar to how ocean microalgae make silica cell walls today. Bioplastics could also play an important role in habitat construction, since they don't require fossil fuels and could be recycled to avoid unnecessary waste. Still, all of this remains hypothetical; more research is needed to understand the best approach to creating habitat materials that could resist solar and cosmic radiation, while also sustaining internal pressures suitable for humans.

Another idea to warm the planet is to use spacecraft propelled by the pressure of sunlight — dubbed "solar sails" — as mirrors to reflect more of this light onto Mars.[4] Solar sails have already flown past Venus,[5] and could fly from medium Earth orbit to Mars orbit. Once in Mars orbit, they could redirect sunlight onto the surface. The biggest challenge for this plan is that it would require reducing the mass per square meter of solar sails by a hundredfold — without sacrificing pointing stability or resilience over decades of use. Solar sails repurposed as orbiting mirrors might also be used to quickly release the CO_2 currently sequestered at Mars' icy poles. This is less of a futurist plan than it sounds — there are already startups which use orbital mirrors to power solar farms after sunset on Earth.

A final alternative to greenhouse gases would be to use engineered nanoparticles — for example, conductive rods or carbon nanoparticles such as graphene nanoplatelets — to forward-scatter sunlight to the surface and warm Mars's atmosphere by blocking upwelling thermal infrared radiation. Simple engineered nanoparticles are four orders of magnitude more mass-efficient for warming than the best gases.[6] Nanoparticles could be manufactured on Mars's city-sized moons or could be made on the planet's surface.

Alternatively, one can imagine a Mars-surface-based terraforming engine that used only sunlight and the Martian atmosphere. According to this concept, Mars' atmospheric CO_2 is split[7] using sunlight energy to yield carbon and O_2. The carbon is used to make small carbon disks, translucent in visible light, whose size is selected to resonate with (and in doing so, block) thermal infrared. The disks could be released into Mars's atmosphere and blown around the planet by the wind. The mass needed for warming by nanoparticles is in the low millions of tons for the entire planet. Still, a challenge for engineered nanoparticles is that they must degrade to avoid littering Mars's surface.

Together, these three proposed warming techniques suggest that we could — if we tried — potentially raise Mars's temperature by 30°C well within this century.

It's also worth noting that while nuclear explosions were once considered as a means of space propulsion, there is zero role for nuclear explosions in warming Mars. Indeed, an inventory of nuclear explosives equivalent to that of the entire U.S. strategic nuclear arsenal would have to be detonated every ninety seconds to supply enough energy (by itself) to warm Mars to Earth-like temperatures. Even if this were possible, there are other concerns with the use of such large numbers of nuclear explosives.[8]

A warmed Mars

A globally warmed climate on Mars would differ from Earth's in a few important ways. The thin air on Mars cannot transport heat effectively, so the poles would still be cold. Seasonal and day to night temperature variations would remain substantial. As Mars warms, the natural water cycle would also change — theory predicts surface ice deposits would shift from the high latitudes toward high ground near the equator.[9] Stronger winds stir up more dust, but the moisturized atmosphere would tend to form more snow that could remove the dust from the atmosphere; we still need to understand more to know whether dust or moisture would win. After warming, the most valuable real estate might be the deep Hellas basin. Hellas, whose area is 4 million km^2 (about the same as the Western United States), would have the warmest temperatures, the longest growing season, and the highest partial pressure of oxygen — provided water could be sustained there.

[3] Silica aerogel — essentially a nanoporous foam of SiO_2 — has already found deep-space applications. It was used by the Stardust mission to capture dust from the tail of a comet moving at 6 km/sec relative velocity.

[4] C. J. Handmer, "How to Terraform Mars for $50B with Solar Sails," *LPI Contributions* 3007 (2024): 3025.

[5] The IKAROS mission, led by Japan.

[6] Samaneh Ansari, Edwin S. Kite, Ramses Ramirez, Liam J. Steele, and Hooman Mohseni, "Feasibility of keeping Mars warm with nanoparticles," *Science Advances* 10, no. 32 (2024).

[7] Mars' atmosphere CO_2 splitting to make O_2 on Mars has been flight-proven on the *Perseverance* rover. Jeffrey A. Hoffman, Michael H. Hecht, Donald Rapp, Joseph J. Hartvigsen, Jason G. SooHoo, Asad M. Aboobaker, John B. McClean et al., "Mars oxygen ISRU experiment (MOXIE) — preparing for human mars exploration," *Science Advances* 8, no. 35 (2022).

[8] Mars emits 2×10^{16} W, which must be approximately doubled to warm Mars by 35 K. US nuclear arsenal = 3.4×10^{18} J. For isotropic explosive, half of energy is lost spacewards. Assuming all shock energy is dissipated as heat and that little of the energy is lost as fallout, while also neglecting water vapor feedback.

[9] Robin D. Wordsworth, "The climate of early Mars," *Annual Review of Earth and Planetary Sciences* 44, no. 1 (2016): 381–408.

The wetter soil on a warmed Mars could be suitable for microbes and hardy plants, although even these would face challenges. Thin air by itself is not a problem for life,[10] and although the low nitrogen levels would potentially pose a problem for nitrogen fixation, the nitrate abundance in Mars's soil is comparable to that of Earth's. Otherwise, Mars' surface contains all the key nutrients needed for life to grow. Toxins like perchlorates in the soil could be bioremediated by perchlorate-metabolizing bacteria, which produce O_2 without sunlight. And the high levels of ultraviolet radiation on Mars needing to be blocked to avoid DNA damage could be achieved through physical shields, or through the chemical compounds that many organisms on Earth already produce naturally.

Even if Mars were warmed enough to host a photosynthetic biosphere, the air would still be too thin and low in oxygen for humans to walk unaided on the surface. (Conveniently, the thickness of atmospheric O_2 needed to stop galactic cosmic radiation is also the minimum for most humans to breathe). During photosynthesis, plants take in carbon dioxide and emit oxygen, so they might slowly oxygenate the atmosphere — with an emphasis on slowly. The fastest possible oxygenation timescale is 200 years,[11] even for an extremely optimistic global 5% efficiency to convert sunlight energy to O_2. However other technologies will develop during this time, including gene therapy and synthetic biology, so it's hard to predict how this timeline might shift.

Another basic speed limit is the centuries needed for surface warming of Mars to conductively heat the subsurface to unlock (desorb) CO_2 adsorbed in soil. CO_2 is important not only as a greenhouse gas: it also acts as an electron acceptor for O_2 released from water by photosynthesis, preventing it from dissipating. If the adsorbed reservoir is at the low end of the possible range, then alternative electron acceptors such as sulfate or ferric iron will be needed, and these are much more difficult to obtain in the needed quantities. Local habitable regions would get around this problem because they could hold the oxygen needed for breathing close to the ground.

Once Mars has an oxygen-rich atmosphere, there would still be various long-term management issues to contend with. These include handling the mud released from the melting of the permafrost and avoiding the leaking of groundwater deeper into the pore space kilometers below the surface. Another basic limit for soil fertility is Mars' lack of plate tectonics: only infrequent lava flows refresh the soil. By contrast, the leak of atmosphere into space is and will remain negligible on million-year timescales: a non-problem. Mars also lacks a global magnetic field, though this is not a problem for life.

The most dramatic solution to Mars' habitability problem would involve importing the critical ingredients for life from elsewhere in the solar system. Humans have already altered the orbit of a volatile-bearing asteroid,[12] but doing this on a scale relevant for the greeningof Mars presents unsolved challenges. First, the mass required would be enormous. To

[10] Andrew C. Schuerger and Wayne L. Nicholson, "Twenty species of hypobarophilic bacteria recovered from diverse soils exhibit growth under simulated martian conditions at 0.7 kPa," *Astrobiology* 16, no. 12 (2016): 964–976.

[11] This can be understood by comparing the energy in sugar to the power of sunlight. Making glucose from its ingredients, CO_2 and water, requires ~3 MJ/kg and emits six oxygen molecules. If photosynthesis at Mars's surface used 30 W/m^2 on average, one year of sunlight will make 300 kg/m^2 of oxygen. But if the entire Mars atmospheric column is to be oxygenated to the level needed for humans, that would require over 3,000 kg/m^2 of oxygen. Thus at least 200 years are required at 5% global efficiency. Workarounds include a "worldhouse."

[12] America's DART (Double Asteroid Redirection Test), successfully completed in 2023, supplemented by Europe's *Hera*.

[13] F. E. DeMeo and B. Carry, "The taxonomic distribution of asteroids from multi-filter all-sky photometric surveys," *Icarus* 226, no. 1 (2013): 723–741.

[14] R. Wordsworth and C. Cockell, "Self-sustaining living habitats in extraterrestrial environments," arXiv preprint arXiv: 2409.14477 (2024), in press at *Astrobiology*.

access enough volatiles to double the thickness of Mars' thin atmosphere would require an asteroid of over 100 km. This would in turn necessitate propulsion technology that humans have not yet achieved. A big bolide, if it were to reach Mars intact, could require humans (if they're there) to leave the planet for months due to planetwide post-impact rainout floods. Second, orbital mechanics imposes a trade-off between the size of nudge and the wait time for a volatile-rich body to reach Mars. Volatile-rich bodies in the Main Belt in between Mars and Jupiter would require big nudges. The only easily nudged massive bolides are beyond Pluto, and once nudged, their free-fall timescale would require centuries.

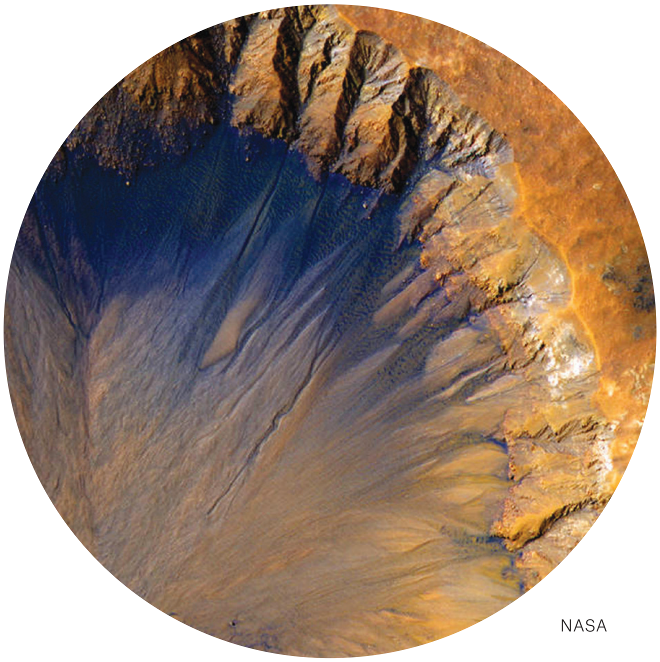
Greening the main belt

Beyond Mars lies the vast, icy expanse of the main asteroid belt. The total mass of asteroids in the main belt adds up to less than 4% of the Moon's,[13] but their combined surface area is significant. Many contain the right combination of elements needed to support life. There would still be more than enough sunlight for photosynthesis, and the toxic soil problem that Mars suffers would be less apparent. Also, because liquid water is essentially absent on asteroids, there would be no concern that greening efforts might accidentally interfere with any existing life.

Raising an asteroid's temperature would be harder than warming Mars, though not by much. More importantly, the low gravity of even the largest main belt objects like Ceres (which has a radius of 294 miles) and Vesta (around 163 miles, though it is shaped like a potato) means that sustaining an atmosphere is impossible, requiring other ways to keep water stable. And, as on Mars, "working with the grain" and using local materials that are already present is the most promising and sustainable approach.

Most main belt asteroids are a mixture of ices, carbon, silicates, and clays. From these raw materials, we could manufacture aerogels to elevate temperature and glasses or plastics with the strength needed to keep habitats pressurized. Water ice also has the potential to serve as a construction material — it's abundant, easy to process, and mostly transparent when purified. To support humans, habitats would need to be very carefully constructed, but for plant growth alone, it would probably be enough to elevate pressures just a little above the point needed to stabilize liquid water. There would be some upsides as well. The extremely low gravity of asteroids, for one, lends itself to a wide range of architectural possibilities.

Looking a little further ahead, it's likely that biology itself will become the key to greening the asteroid belt. Biologically produced materials including silica, calcite and long-chain organic polymers are fully capable of protecting life from vacuum,[14] and self-sustaining ecosystems that generate their own habitat walls break no physical or chemical laws. The biggest long-term challenge to greening the asteroid belt may be volatile loss, as there is little gravitational attraction to keep water and gases safe. Beyond Earth orbit, water is a precious resource that will need to be used wisely by future generations of explorers.



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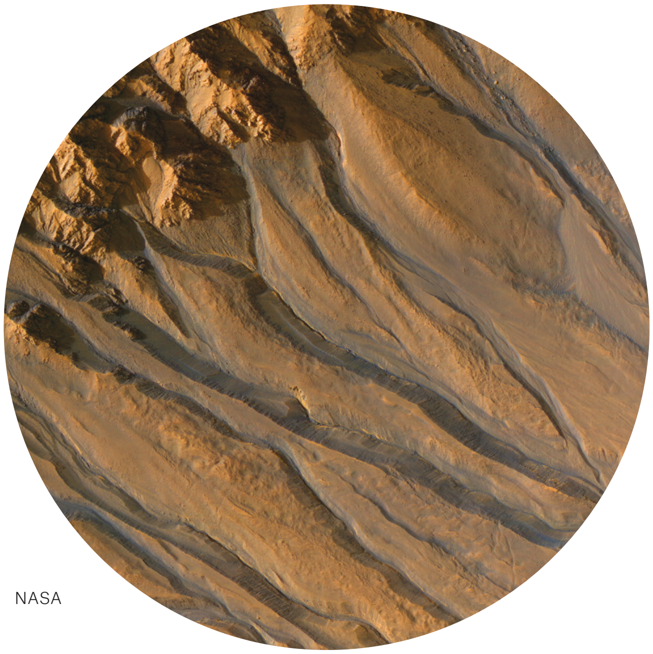

NASA

Venus, Titan and beyond

More exotic possibilities for greening are found both closer to the Sun and much farther from it. Venus, often dismissed as "Earth's evil twin," has a greenhouse effect hot enough to melt lead at its surface, but high up in the air above its thick cloud layer, it's a relatively benign place. It's been claimed that microbial life could exist in Venus' cloud layer even today,[15] but this is controversial as the clouds are composed of sulfuric acid. We may know more soon; the privately funded Venus Life Finder mission, which will test this hypothesis, is scheduled to launch by January 2025.

A (relatively) modest greening proposal for Venus would involve seeding the planet with enough comets to dilute the acid and create water clouds and rain in the upper atmosphere. Floating life might then be able to exist there, either in artificial gondolas or suspended in the water droplets. A more extreme approach would be to try to revert Venus back fully to an Earth-like state. This could be done slowly (on the order of centuries, at least) using mirrors in space or highly reflective particles in the atmosphere, which would need to cool the surface enough for carbon dioxide to begin condensing. After this, a method to trap the atmospheric carbon dioxide in surface rocks would be needed, and water would still have to be delivered from elsewhere, unless the desired outcome was an Arrakis-like desert planet.

Titan — Saturn's largest moon, which at 3,200 miles in diameter is slightly larger than Mercury — has the opposite problem from Venus: it's so cold that water behaves like a rock, while the lakes are made from natural gas.[16] On the plus side, gravity is so low that humans could fly simply by flapping their arms, provided they're equipped with winged space suits.[17] Because sunlight is so faint and the heat capacity of the thick atmosphere is great, prolonged warming (corresponding to the sunlight reaching Titan over many centuries) would be needed to create liquid water oceans on Titan, and the surface geology would be completely reset in the process. An alternative route might be development of a form of life that can use methane as a solvent, with the usual caveat that we'd need to verify such life doesn't already exist there before attempting such an experiment.

Interstellar destinations such as the habitable-zone, Earth-mass planet Proxima Centauri b are out of reach, at least for now.[18] However, as we continue to learn more about exoplanets through space telescopes such as the James Webb Space Telescope, we will come to understand whether or not they already support life. Expansion of life into the solar system is a first step that will lay the ground for direct exploration of these worlds in the more distant future.

Conclusion

Greening other worlds is a staple of science fiction, but it has so far seen little attention from scientific funding organizations. This is likely to change soon, as our presence in space continues to develop. We've mostly focused on the technical aspects of this topic, but the ethical implications are also profoundly important. With this in mind, we propose a few organizing principles for future research.

First, and most importantly, we need to do more to show that life is absent on other worlds before we consider making them more habitable to life from Earth. This is particularly true for Mars. Most of the remaining possible locations for life on Mars could be searched via robotic missions in the price range of a few billion dollars. Such missions need to be prioritized over the next few years regardless of greening plans, because — as noted by NASA's recent Planetary Protection review — when people start to live on Mars, "they will inevitably introduce orders of magnitude more terrestrial microorganisms to Mars than robotic missions have done or will do."[19]

The second principle, which overlaps with the first, is that we need to keep learning about the solar system. Mars and the asteroid belt still have much to teach us about habitability and the origin of life on Earth, and we must be careful not to erase this archive until we have deciphered it. Sample return has the tremendous potential to teach us about the rise and fall of Mars' ancient, watery climate and about its current freeze-dried state.[20] Human exploration, when it happens, will advance that science even further. As Carl Sagan once said, "advocates of terraforming must first become advocates of ... scientific exploration of other worlds."

The third principle is sustainability: Greening efforts must not irreversibly consume any resources that might be vital to future generations. Creation of local habitats should precede terraforming, and global experiments should incorporate an "off" switch, whereby the planet can readily return to its prewarmed state when terraforming ceases. Humanity's track record of environmental modification on Earth is all the more reason to proceed thoughtfully. With the right approach, though, the knowledge we gain from extending life elsewhere in the Solar System could also bring many benefits to life here on Earth.

Answering the ethical question of when and how to start making other worlds habitable requires a clear understanding of the costs and benefits, which can only be adequately assessed based on sound science. Future progress will require a combination of theory and experiments, with input from diverse fields including physics, chemistry, materials science and biology. As with any new field, many aspects of the path forward remain unclear, but the ultimate promise is a Solar System teeming with diverse new forms of life.[21]

15. J. S. Greaves et al., "Reply to: No evidence of phosphine in the atmosphere of Venus from independent analyses," *Nature Astronomy* 5, no. 7 (2021): 636–639.

16. More precisely, a mixture of methane, ethane, and additional trace species.

17. For an example of the math behind this, see H. N. Lerman, P. Hicks, and B. Irwin, "P5_1 You can fly," *Physics Special Topics* 12, no. 1 (2013).

18. Harry A. Atwater, Artur R. Davoyan, Ognjen Ilic, Deep Jariwala, Michelle C. Sherrott, Cora M. Went, William S. Whitney, and Joeson Wong, "Materials challenges for the Starshot lightsail," *Nature Materials* 17, no. 10 (2018): 861–867.

19. A. Stern, et al., "Final Report of the NASA Planetary Protection Independent Review 369 Board" (2019).

20. Robin Wordsworth, "Mars Rocks Will Change How We See Life on Earth," *Scientific American* (2024).

21. A. Owe, "Greening the universe: The case for ecocentric space expansion," In James S. J. Schwartz, Linda Billings, and Erika Nesvold (Editors), *Reclaiming Space: Progressive and Multicultural Visions of Space Exploration*, (Oxford University Press, 2022): 325–336.

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