Defining the minimum physical requirements for life in space

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Abstract

Standard definitions of habitability assume that life requires the presence of planetary gravity wells to stabilize liquid water and regulate surface temperature. Here the consequences of relaxing this assumption are evaluated. Temperature, pressure, volatile loss, radiation levels and nutrient availability all appear to be surmountable obstacles to the survival of simple life in space. Biologically generated barriers capable of transmitting visible radiation, blocking UV, and sustaining temperature gradients of 25-100 K and pressure differences of 10 kPa against the vacuum of space would allow carbon-based photosynthesis to be sustained between 1 and 5 AU. Hence closed-loop ecosystems capable of generating their own habitable conditions could plausibly be developed, given the known capabilities of existing life on Earth. Living habitats that can persist in extraterrestrial environments with minimal intervention would have major benefits for human life support, as well as sustainability in space. Further afield, future biosignature research should consider the possibility of such structures around other stars.

1   Introduction

Earth is currently our only known example of a planet that sustains life. As a result, a common working assumption in astrobiology is that Earth-like environments are required for life to exist anywhere. Exceptions to this rule do exist, in the form of speculations about exotic life on gas giants, Titan and Venus, for example [Sagan and Salpeter, 1976, McKay and Smith, 2005, Seager et al., 2021]. However, in biosignature definitions and mission planning, it is often argued that a focus on conservative definitions of habitability is most appropriate [Kasting et al., 2014]. In keeping with this view, most astrobiology research over the past few decades has focused on increasing our understanding of life's diversity and evolution on Earth, and searching for Earth-like environments (past or present) in the solar system and beyond.

One obvious yet often neglected fact in this debate is that we already have direct evidence of life surviving beyond Earth, in the form of human space missions. Given current developments, it seems reasonable to assume that within the next few decades, the permanent presence of human life beyond low Earth orbit will be possible. Of course, this presence will be sustained by technology, which is ultimately a product of human intelligence. However, as humans are simply a particularly complex form of life, it is interesting to consider *how much* complexity is really needed for a sustained biosphere to exist beyond Earth, especially in the absence of technology. In order words, what is the minimal physical structure that could sustain habitable conditions beyond Earth, and could it be generated by simple life?

Here we suggest that this question is both experimentally testable and worthy of serious investigation, and describe how some of the key physical challenges can be overcome. We propose that further research on this topic will aid fundamental science, as well as being highly complementary to emerging efforts in synthetic biology to support human space exploration and increase sustainability [Nangle et al., 2020, Berliner et al., 2021, Santomartino et al., 2023]. To provide focus, we mainly consider carbon-based life in the solar system, but wider possibilities are also briefly discussed.

Consideration of life in space has a long history in the scientific and popular literature, and we build here on ideas discussed qualitatively in the past. Written speculation on how living organisms might survive in space date back to the 19th century [Tsiolkovsky, 1895]. The topic was later discussed by authors such as Freeman Dyson in popular science works [Dyson, 1979, Sagan, 1997]. Most recently, adaptation of biology for the purposes of constructing small-scale interstellar space probes has also been proposed [Church, 2022].

Here, taking a quantitative approach, we first define the physical requirements for life beyond Earth, and then show how they could be met by simple biological systems. We focus on habitability for simple (e.g., single-celled) life rather than complex multicellular life (e.g., humans), although our conclusions have implications for human life support. We also mostly focus on requirements for habitability in deep space, although much of the following discussion also applies to more benign environments such as the martian surface.

2 Planetary Habitability

To understand the constraints for life beyond Earth, we can start by reviewing why our home planet is a good habitat for life in the first place. Earth has a well-defined surface at which temperature and pressure are in the right range to allow the vital solvent H_2O to exist in liquid form. At this surface, a huge source of free energy is nonetheless available in the form of the Sun's photons, which our solar-powered biosphere exploits via photosynthesis. The key elements C, H, N, O, P and S required to construct biochemical machinery are often limited, but nevertheless available to life, and when the biosphere happens to convert them into inaccessible waste products such as recalcitrant organic matter, they are slowly recycled back into more accessible forms via plate tectonics and volcanic outgassing. Finally, Earth is oxidizing in some regions (the atmosphere, surface environments) and reducing in others (deep subsurface, locally in surface soils, ocean sediments), allowing the exploitation of redox gradients for metabolic purposes. These are the key features of our planet that have allowed it to remain habitable over the last four billion years (Fig. 1).

On smaller planets, habitable environments can still exist, but problems begin to emerge as the planet ages. First, internal cooling proceeds more quickly, which leads to an early shutdown in tectonic activity, as happened on Mars in the first billion years of its history. Second, surface gravity decreases, which makes it easier for any volatiles to escape to space. Again, Mars is the poster child for volatile loss in our solar system: isotopic analysis tells us that the vast majority of its CO_2 atmosphere, as well as much of its surface water inventory, has been lost to space over its lifetime [Jakosky, 2021]. Because H escapes more easily than O or C, this has also made the chemistry of Mars more oxidizing, generating iron oxides on its surface and building up compounds such as perchlorates that at high concentrations can limit habitability [Wadsworth and Cockell, 2017].

Further out in the solar system, many icy moons and dwarf planets are rich in life-supporting elements, but their surfaces are far too cold to allow liquid water. Moons such as Europa that experience tidal heating have subsurface oceans that likely support habitable conditions [Carr et al., 1998]. However, tens of kilometers of ice separate these regions from the Sun's photons, making solar radiation inaccessible as a direct energy source for photosynthesis. At the end of the Sun's evolution on the main sequence, icy moons like Europa may pass through a transient stage where surface liquid water is possible, but their atmospheres will be highly unstable to loss to space [Arnscheidt et al., 2019]. At still lower masses, volatile-rich icy bodies become comets: if they get close to the Sun, they degas directly to space without the water on their surface ever passing through a liquid phase at all.

For low-mass objects outside of planetary gravity wells, then, pressure, temperature and long-term volatile retention are all fundamental challenges to habitability for Earth-like life [Cockell et al., 2021]. Additional challenges include UV and cosmic ray radiation, availability of nutrients, and chemical toxicity. To persist beyond Earth, any living organism must therefore modify or adapt to its environment enough to overcome these challenges. In the following sections, we evaluate each of these challenges in turn and show how they can be overcome in practice.

3 Pressure

Habitable regions surrounded by a vacuum or low pressure atmosphere must maintain an internal pressure gradient if they are to stabilize liquid water. The minimum (triple point) pressure required to sustain liquid water at $0°C$ (273 K) is 611.6 Pa. For organisms adapted to the $15-25°C$ temperature range, the H_2O saturation vapor pressure rises to a few kPa. For context, sea level pressure on Earth is 101 kPa, while the atmospheric pressure at the summit of Mount Everest is about 30 kPa. The survival of humans and other large land animals at low pressure is limited by the requirement of sufficient O_2 for respiration, but this limit does not apply to simpler organisms. For example, cyanobacteria in a liquid medium will grow in chambers with air headspace pressures of as low as 10 kPa, provided that their nutrient needs are met and light and pH levels are within an acceptable range [Verseux, 2020].

>1000 km	1-100 m	~1 μm
Habitable Planet	**Living Space Habitat**	**Micro-organism**

Habitable Planet
- Atmosphere and surface water retained by gravitational force
- Surface temperature elevated by atmospheric greenhouse effect
- Atmosphere permeable to visible radiation, impermeable to UV

Living Space Habitat
- Interior liquid H_2O stabilized by bioplastic / biomineral habitat wall
- Interior temperature elevated by solid-state greenhouse effect
- Habitat wall permeable to visible light, impermeable to UV, volatiles

Micro-organism
- Temperature set by environment
- Cell membrane permeable to visible light, O_2, CO_2
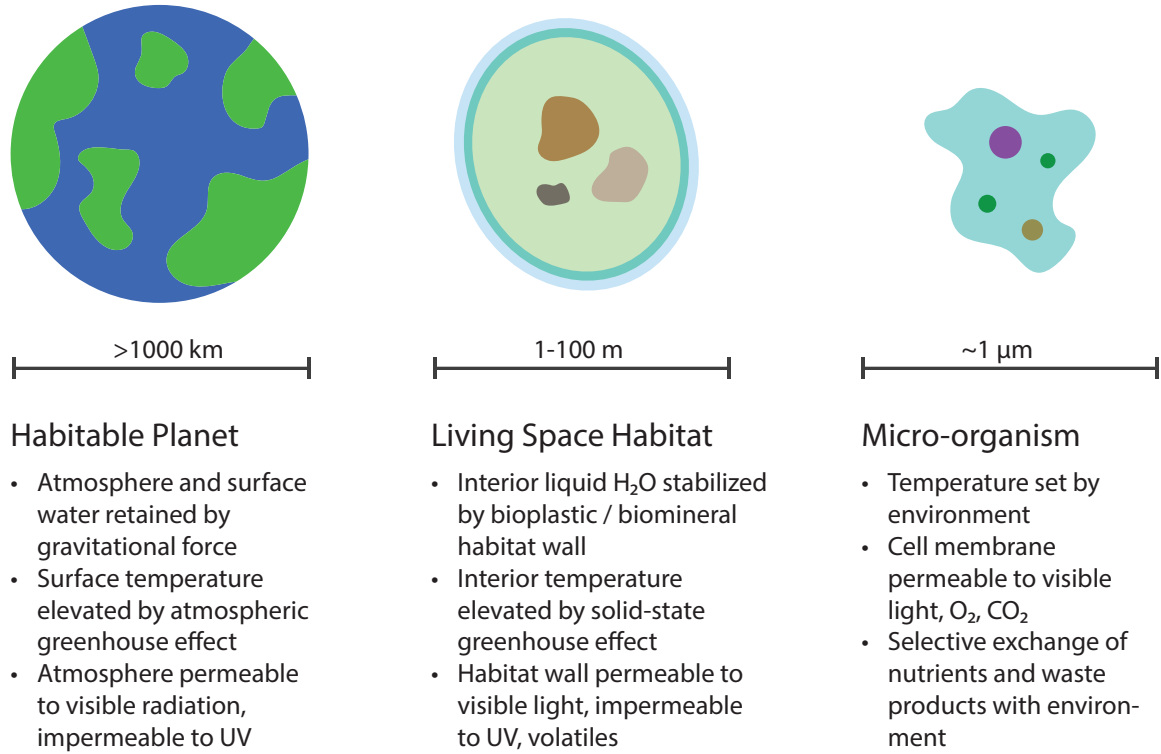- Selective exchange of nutrients and waste products with environment

Figure 1: Schematic summarizing the key similarities and differences between a habitable planet, a minimal-complexity living habitat in space, and a micro-organism, with a focus on their physical properties and exchange of mass and energy with their environments.

Internal pressure differences of order 10 kPa are common in macroscopic organisms on Earth. Using the hydrostatic equation $p = \rho gh$, it is easy to see that the blood pressure increase from the head to the feet of a 1.5-m tall human is around 15 kPa, given gravity $g = 9.8$ m s^{-2} and blood density $\rho \sim 1000$ kg m^{-3}. In the tallest land mammals, this rises to about 50 kPa. In plants, the seaweed species Ascophyllum nodosum has been reported to sustain internal float nodule pressures of 15-25 kPa due to daytime O_2 gas release from photosynthesis [Damant, 1937].

Given an idealized thin-walled spherical habitat, the hoop stress can be written as

$$\sigma_\theta = \frac{pr}{2t}, \tag{1}$$

where p is internal pressure, r is the habitat radius and t is the wall thickness [Goodno and Gere, 2020]. If $r = 1$ m, $p = 10$ kPa and $t = 0.05$ m, $\sigma_\theta = 0.1$ MPa. For comparison, translucent bioplastics based on polysaccharides such as agarose have tensile strengths in the 10-40 MPa range [Hernández et al., 2022]. Integration of silica or calcium carbonates into wall material would increase robustness further, particularly when combined with the capability of biology to optimize material properties down to nanometer scales. For example, the calcite shells of windowpane oysters (Placuna Placenta) are near-transparent (up to ~80% transmittance of visible light given thicknesses of a few mm) but have almost order-of-magnitude greater resistance to localized fracture damage than crystalline calcite minerals [Li and Ortiz, 2014]. Overall, therefore, maintaining sufficient interior pressure is unlikely to present a serious impediment to habitability.

4 Temperature

Earth today is kept warm by an atmospheric greenhouse effect: incoming sunlight is absorbed by the surface, but upwelling infrared radiation cannot escape to space until it reaches high, cold regions of
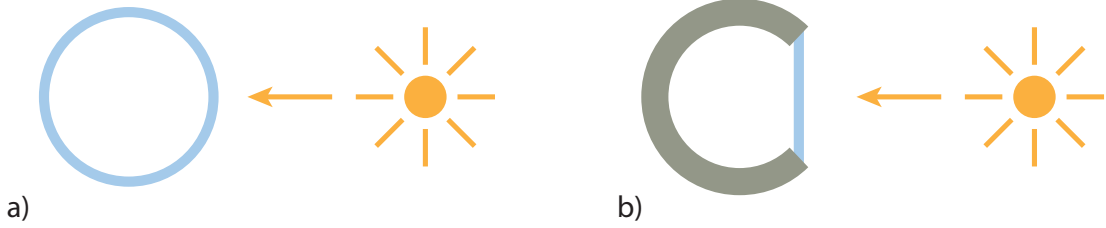
Figure 2: Geometry for a) spherically symmetric and b) Sun-facing habitat thermal calculations. Blue color represents translucent solid-state greenhouse material of thickness a few cm, while grey represents a thicker layer of opaque, thermally insulating material.

the atmosphere, which leads to a net warming of the surface [Pierrehumbert, 2010]. In space, where retaining a sufficiently dense atmosphere is impossible for low-mass objects, the same effect would need to be achieved via solid-state processes.

For a free-floating object in a vacuum, the internal temperature in equilibrium can be calculated by equating the absorbed solar radiation to the emitted infrared radiation. The absorbed solar radiation is $A_1 F_0 \alpha / d^2$, where A_1 is the cross-sectional area of the object facing the Sun, α is visible absorptivity, $F_0 = 1362$ W m^{-2} is the received solar flux at 1 AU, and d is orbital distance in AU. The emitted infrared radiation is $A_2 \epsilon \sigma T^4$, where A_2 is the emitting area, ϵ is IR emissivity and σ is Stefan's constant. Equating these quantities and writing equilibrium temperature $T_{eq} = T$ leads to the expression

$$T_{eq} = \left(\frac{f F_0}{\sigma d^2} \frac{\alpha}{\epsilon} \right)^{1/4} \tag{2}$$

The geometric factor $f \equiv A_1/A_2$ takes the value 0.25 for a sphere, and 0.5 for a flattened disk. On Earth today, changes in both α and ϵ are already utilized by living organisms to regulate temperature. Saharan silver ants, for example, have evolved the ability to enhance both their surface near-infrared reflectivity and their thermal emissivity, allowing them to survive in ambient temperatures above the range of all other known arthopods [Shi et al., 2015].

In addition to surface absorptivity and emissivity, the *solid-state greenhouse effect* provides a powerful means to regulate habitat temperature. This effect arises in translucent solid layers that transmit visible radiation but limit thermal radiation and conduction. The solid-state greenhouse can be potent under the right conditions: silica aerogels, for example, have been shown to raise temperatures by 50 K over 2-3 cm layers at 1 bar pressure, given a visible flux of 150 W m^{-2} [Wordsworth et al., 2019]. In a vacuum, aerogel warming potential is higher still, because there is no longer a contribution to thermal conductivity from interstitial air molecules [Dorcheh and Abbasi, 2008].

Silica aerogels are industrially produced materials consisting of interlocking nanoscale SiO$_2$ networks that have no direct biological equivalent. However, many organisms do exist in nature that produce complex silica structures. Diatoms, for example have the ability to manipulate silica particles on 1-10 nm scales, which is below the mean pore scale for modern manufactured silica aerogels. In addition, organic materials such as cellulose can achieve similar thermal effects [Smalyukh, 2021]. Aerogel-like materials could therefore be produced from biogenic feedstocks, and in future perhaps directly by living organisms.

The temperature increase from a solid-state greenhouse layer with thermal conductivity κ and visible extinction coefficient γ_V is

$$\Delta T_{max} = \frac{h \alpha F_0}{\kappa d^2}, \tag{3}$$

where h is the layer thickness [Wordsworth et al., 2019]. α can be written as $e^{-\gamma_V h / \overline{\cos \theta}}$, where $\overline{\cos \theta}$ is the average cosine of the solar radiation incident angle relative to the normal vector of the layer surface and γ_V is the layer's visible extinction coefficient[1]. For a sphere, $\overline{\cos \theta} \approx 0.5$ [Cronin, 2014], while for Sun-facing geometry, $\overline{\cos \theta} = 1.0$ (Fig. 2). If h is optimized to maximize warming, $h = h_{max} = \overline{\cos \theta}/\gamma_V$.

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[1]We conservatively neglect the possibility of photons getting absorbed in the greenhouse layer or scattering into the interior when they are removed from the direct beam. We also neglect non-linearities in (3) due to thermal radiative effects. In the temperature range of interest, this is an acceptable approximation [Caps and Fricke, 1986].

For a representative value $\gamma_V = 30$ m^{-1}, h_{max} is therefore between 1.5 and 3 cm. Combining this result with (2) and (3) and incorporating geometric effects yields an expression for interior habitat temperature:

$$T_i = T_{eq} + \Delta T_{max} = \left(\frac{fF_0}{\sigma d^2} \frac{\mathrm{e}^{-1}}{\epsilon} \right)^{1/4} + \frac{f\overline{\cos\theta}F_0\mathrm{e}^{-1}}{\gamma_V \kappa d^2}. \tag{4}$$

This non-linear equation in d can be solved given values for α, ϵ and γ_V and a required T_i.

Results are shown in Figure 3 for $T_i = 288$ K (15° C). For the red curve, total spherical symmetry of the habitat is assumed, while for the blue curve, the solid-state greenhouse layer is taken to be Sun-facing, with the rest of the habitat surrounded by a thick layer of opaque insulating material. In such a configuration, the thermal flux from the opaque part of the habitat can be made arbitrarily small as the layer thickness is increased, until the energetic cost of increasing the layer mass becomes prohibitive. Here we take the opaque region thermal loss to be 20% of the value from the translucent solid-state greenhouse region.[2]

As can be seen, maintaining internal temperature at 288 K is possible for a wide range of orbital distances. This calculation assumes a free-floating habitat, but similar considerations apply for habitats in contact with the surface of an asteroid or moon. Because access to and retention of life-supporting volatiles such as C, N and H becomes a major challenge to habitability close to the Sun (Section 5), orbital distances greater than 1 AU are more favorable, and in general the ability to increase internal habitat temperature is therefore likely more important than the ability to lower it.
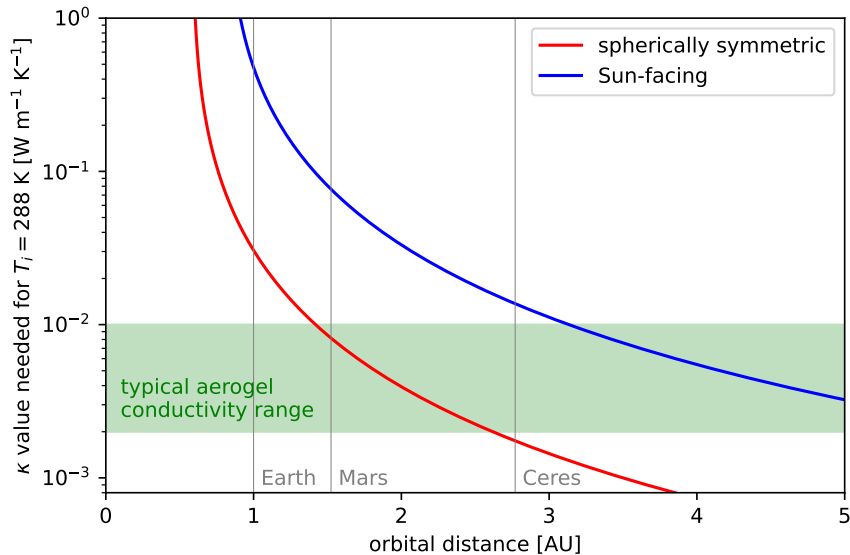

Figure 3: Passive solid-state warming to enable habitability beyond Earth. Plot shows thermal conductivity of solid-state greenhouse layer vs. orbital distance based on (4), given a habitat interior temperature of 288 K. Red and blue curves show cases assuming spherically symmetric and Sun-facing geometry, respectively, corresponding to Figs. 2a and b. For these calculations, $\gamma_V = 30$ m^{-1} and $\epsilon = 0.95$. The green shaded area indicates typical thermal conductivities for translucent silica and organic aerogels reported in the literature [Dorcheh and Abbasi, 2008, Baetens et al., 2011, Smalyukh, 2021].

5   Volatile Loss

A third challenge to life in space is volatile loss. All materials have some permeability to atoms and small molecules, and over long timescales the vacuum of space represents an essentially permanent sink for volatile species. In the medium term, volatiles are likely to be a critical resource for any kind of life outside of planetary gravity wells, including humans [Schwartz, 2016, Ellery, 2020]. Of course,

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[2]A systematic derivation indicates that the relevant ratio is $\chi = A_b\kappa_b h_a / A_a\kappa_a h_b$, where the a and b subscripts correspond to the translucent and opaque regions, respectively. For $\chi = 20\%$, $A_b = 3A_a$, $\kappa_b = 2\kappa_a$ and $h_a = 3$ cm, for example, this would imply $h_b = 90$ cm.

volatility depends on orbital distance: H_2O is generally volatile at Earth's orbital distance and closer, but essentially non-volatile beyond 1.5 AU, while O_2 and N_2 remain in the gas phase to much larger distances. On Mars, which can be considered a semi-benign non-terrestrial environment, volatile loss is important as a local consideration, but not as a global one, given the planet's active water and CO_2 cycles.

To understand the extent of the problem, we can again consider a spherical habitat surrounded by a vacuum. If the habitat has some internal gas pressure p_i for species i, the gas flux through the habitat wall is [Baker, 2012]

$$J \approx DK \frac{p_i}{t}, \tag{5}$$

where t is the wall thickness, D is the diffusion coefficient for the wall material, and S is the solubility of species i in the wall. The product DK is usually expressed as the permeability P, with SI units of mol m^{-1} s^{-1} Pa^{-1}. The loss rate of gas to space in mol s^{-1} is $dNdt = -4\pi r^2 J$, where r is the habitat radius. Given that the total number of moles of gas is $N = p_i V/RT$ by the ideal gas law, with T temperature, V volume and R the universal gas constant, the time required to lose e^{-1} (37 %) of the partial pressure of species i in the habitat is

$$\tau \approx \frac{N}{|dN/dt|} = \frac{rt}{3RTP}. \tag{6}$$

Permeability for real materials varies widely. To give a everyday example, isoprene rubber has P values of around 150 barrer or 5×10^{-14} mol^{-1} m^{-1} s^{-1} Pa^{-1} for CO_2 at room temperature [Baker, 2012], leading to gas loss timescales from a typical balloon of thickness $t = 10^{-5}$ m and radius $r = 0.2$ m of around $\tau \sim 1.5$ hours.

Rubber has a high gas permeability at room temperature because thermal translation and rotation of polymer chains allows for transport of gas molecules through transient microcavities. In glassy polymers, this type of motion is inhibited and diffusion is decreased by 1-2 orders of magnitude. Polylactic acid (PLA), which is regarded as a relatively gas-permeable bioplastic, has O_2 permeability of around 1 barrer. Addition of nanocomposites can reduce this value by up to two orders of magnitude by increasing gas molecule diffusion pathways [Attallah et al., 2021]. The gas permeabilities of silica and calcite-based biomaterials do not appear to have been extensively studied, but based on the properties of similar non-biological compounds they would likely be lower still [Zouine et al., 2007].

Inhibition of volatile escape would be most easily achieved by the same part of the habitat wall responsible for maintaining the pressure differential necessary to stabilize liquid water. For a 1-cm thick layer with permeability 0.1 barrer, a habitat of radius 10 m and internal temperature 288 K would have $\tau = 13,000$ y. This timescale shows how long it takes to decrease the internal *partial pressure* of a given molecule, so a habitat ecosystem that rapidly transformed volatiles such as CO_2 and O_2 into higher mean molecular mass molecules would inhibit total mass loss further. Additional volatile loss pathways include macroscopic effects due to cracks or defects in the wall material, and, in more autonomous living habitats, use of volatiles for specific purposes such as propulsion and attitude control.

6   Radiation, Free Energy and Nutrients

Other aspects of the space environment present additional obstacles to habitability, although none appear insurmountable. Radiation levels vary widely across the solar system, and at some locations and times are a major hazard to humans [Chancellor et al., 2014], but are unlikely to prevent habitability for microbial life [Dartnell, 2011]. Shortwave ultraviolet solar radiation, especially below 325 nm, is damaging to DNA, proteins and other biomolecules, but it is easily blocked by UV-absorbing materials such as amorphous silica, which plays a role in decreasing UV fluxes in silicified biofilms and stromatolites today, reduced iron and substrates that scatter short wavelength light [Phoenix et al., 2006]. Some of these UV absorbing substrates, such as reduced iron, preferentially absorb the UV radiation, allowing through visible light required for photosynthesis [Cockell and Raven, 2004].

Access to sufficient free energy in the form of solar photons is unlikely to be an obstacle. Growth of Arctic algae under ice occurs at light levels as low as 0.17 μmol photons m^{-2} s^{-1} ($\sim$ 0.04 W m^{-2}) [Hancke et al., 2018]. Rapid growth of many common cyanobacterial and green algal photosynths in the laboratory can be achieved at 2-5 W m^{-2}. For comparison, the received solar flux at the orbit of Jupiter is about 50 W m^{-2}. Key nutrients are readily accessible on many asteroids and comets, particularly at orbital distances beyond Earth, where small bodies tend to contain higher abundances of volatile

species. Growth of microbial life on a carbonaceous chondrite substrate has recently been demonstrated in a laboratory setting [Waajen et al., 2022]. Indeed, in general a range of primordial rocky materials, such as ultramafic rocks or chondritic material in contact with liquid water, will provide biologically accessible CHNOPS elements [Cockell et al., 2021].

Long-term, an additional consideration is the ability of a closed-loop ecosystem to process waste products such as recalcitrant organic matter and to sustain internal redox gradients. On Earth today, most organic material is oxidized in the oceans, but a small amount sinks to the seafloor, where it is eventually thermolyzed in Earth's interior following subduction [Berner, 2004]. Absent such extremes of temperature, a fully closed-loop ecosystem in space would require some internal compartmentalization and specialist biota capable of breaking down such waste products [e.g., De Gonzalo et al., 2016].

7 Scale and Location

On Earth, the size of unicellular organisms is limited by factors such as diffusion rates of O_2 and nutrients into the cell membrane, and waste products out (Fig. 1). The factors that limit the scale of larger organisms are varied and complex, but frequently also emerge from limitations on the chemical transport or diffusion of elements and molecules required for life. The largest relevant scale for terrestrial biota is of course the size of the planet itself.

For a habitat in an airless environment, the ratio of volume to surface area sets the timescale for loss of volatiles (Section 5), which favors larger sizes. However, if photosynthesis is the main source of chemical energy, and liquid H_2O is the dominant solvent in the habitat interior, the region of productivity will be limited to a euphotic layer of a few tens of meters, beyond which visible light is fully absorbed and photosynthetic primary production is inhibited. The width of this photic zone will depend on how much the habitat wall attenuates visible light, as well as any impurities in the interior that can scatter and/or absorb light. However, as the last few sections have made clear, habitat wall thicknesses on the order of several centimeters are adequate for regulating pressure, temperature and volatile loss, while simultaneously allowing transmission of more than enough visible light for photosynthesis.

For habitats on the surface of a planet or moon, thermal transients are an additional consideration. For example, on the Moon, which has a night duration of $\tau_{night} \sim 30$ days, a habitat would require volume $V \sim \tau_{night}\sigma T_{eq}^4/c_p\rho\Delta T = 13.7$ m^3 to limit the temperature drop ΔT to 10 K, given $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}, specific heat capacity $c_p \sim 4200$ J kg^{-1} K^{-1}, internal density $\rho \sim 1000$ kg m^{-3} and habitat external equilibrium temperature $T_{eq} \sim 250$ K. Active or semi-passive thermal control techniques could lower this value, at the cost of additional system complexity.

Given all these considerations, habitat volumes of order 10 m^3 and wall thicknesses of order 0.01 to 0.1 m probably represent a reasonable optimum. In any specific scenario, the exact balance would dependent on wall permeability, internal light extinction rates, physical properties of the wall material, and other factors. Finally, the potential for local wall failure to compromise the habitat might favor redundancy in the form of internal subdivisions.

Regarding location, two key factors are access to life-essential elements and solar distance. Of these, the latter sets the amount of greenhouse warming required to maintain internal liquid water. These two factors are in tension, as outside of Earth's gravity well, locations where volatiles (especially C, H and N of the biologically important CHNOPS elements) accumulate tend to be those where temperatures are lowest. Locations that are relatively accessible from Earth include polar regions on the Moon and near-Earth volatile-rich asteroids such as 101955 Bennu [Hamilton et al., 2019]. An intermediate case between Earth and these targets is Mars, which can be classed as a semi-benign environment, with an atmospheric source of CO_2 and abundant near-surface H_2O deposits at high and mid-latitudes [Morgan et al., 2021]. At greater distances, the asteroid belt and Jovian and Saturnian moons possess abundant volatiles, but solar flux is so low that efficient passive thermal control would be needed to maintain habitable temperatures (Fig. 3).

8 Maintenance and Growth

So far, we have deliberately focused on the basic physical requirements for life in space to keep the discussion as concrete as possible. It should be emphasized that biologically generated habitats for simple life would have many benefits for humans in space even if they were *not* completely self-sustaining. Nonetheless, a fully closed system capable of regeneration and growth is apparently not prohibited by any physical or chemical constraints, and is therefore interesting to consider a little further.

Regardless of the composition of habitat walls, they will inevitably degrade over time due to UV irradiation, micrometeorite bombardment, and other effects. To maintain steady state or achieve growth, regeneration is therefore required. Efficient recycling of old wall material will be an essential part of this process. Biological approaches for recycling of bioplastics are already well-developed on Earth, and further advances in synthetic biology will only widen the range of biogenic materials that can be processed [Rosenboom et al., 2022].

In the least autonomous approach, microbial cultures or plants could be used to create the feedstocks for their own habitat wall material, and then additional processing could occur separately via industrial methods as required. The specific choices of organisms and wall materials in a real application would require detailed study, but amorphous silica, as well as organic polymers such as cellulose, agarose, and lignin, can all be produced by existing photosynthetic life on Earth today.

A more autonomous living space habitat would be able to grow its own wall material, just as plant cells regenerate their own walls on the micrometer scale. Wall material could either be created internally and then transported to the outer boundary, or directly synthesized *in situ*. The gradient in temperature and pressure that habitat walls would need to maintain makes this an interesting but likely tractable materials science problem that we leave for future study. Finally, to grow, a living habitat also requires the ability to absorb new material. In the most straightforward scenario, nutrients could be processed externally and then added, but a more autonomous habitat would have the ability to absorb new material itself, e.g., through engulfment. This could include the processing of local regolith material and extraction of the required elements.

9 Silicon and life

Until now, we have focused the discussion on carbon-based life, as this allows a more concrete consideration of requirements. Another type of life that has been proposed to operate in a space environment is a self-replicating 'machine' [Freitas Jr, 1980, Borgue and Hein, 2021]. In this concept, an autonomous spacecraft capable of propulsion, remote sensing and power generation creates copies of itself, allowing further exploration, potentially without limit. Such a system would be classed as alive according to most useful definitions of the term [e.g., Walker and Davies, 2013].

This topic has been discussed elsewhere, so not too much will be added here. However, it seems clear that the majority of the self-replicating probe ideas are significantly more complex than the living habitats for carbon-based life we have discussed here. Much of this complexity stems from a focus on achieving full self-replicability, as well as the need to rely on semiconductors for power generation and information processing. In the modern semiconductor industry, temperatures of > 1000 K are required for carbothermal reduction, which is the first step in conversion of SiO_2 to monocrystalline quartz for semiconductor production [Lee et al., 1977]. Additional steps, particularly the microfabrication process, require highly controlled, sterile conditions, which in turn require sophisticated quality control and verification capabilities.

The information storage and replication abilities of carbon-based life, while messy and imperfect, might be closer to the kind of system required for autonomous operation in space. Interestingly, given how useful silicate compounds are for control of temperature, pressure and UV radiation (Sections 3 and 4), carbon-based life is also likely to be dependent on silicon for its survival in an extraterrestrial environment. Although life on Earth does not use silicon as a backbone element within its key macromolecules (hence the epithet 'carbon-based'), it does manipulate and use silicon, primarily in the form of silica (SiO_2), as a structural material. Silica is manipulated to form spicules within sponges [Holzhüter et al., 2005], phytoliths in plants [Katz, 2015], and the outer casings of diatoms (frustules). These template-directed structures could be manipulated artificially via nanotechnology [Neethirajan et al., 2009], raising the possibility that carbon-based biochemistry might enable the construction of silicon-based materials and machines in the future.

10 Discussion

In this article, we have argued that simple organisms could be fully capable of creating the materials necessary for their own survival in a space environment. It is entirely possible that we have underestimated some technical difficulties. However, our aim has been simply to show that there are *no obvious physical or chemical limitations* to the self-sustained existence of simple carbon-based life in space.

Further research in this area could have benefits for multiple fields. The synthetic biology community has already made a strong case for the use of biotechnology to support humans in space [Nangle et al., 2020, Berliner et al., 2021, Averesch et al., 2023], and the arguments presented here strengthen this case further. The potential benefits to astrobiology of further research on this topic are also high, because it would help to expand thinking beyond the current intense focus on Earth-like environments. The physical processes we consider here, although guided by the requirements of terrestrial biology, are essentially agnostic about the detailed biochemical architecture of life. Furthermore, the general principles we consider could be applied with other boundary conditions, such as liquid ammonia as a biochemical solvent. Thus, we propose that a physics-based consideration of habitability can led to new agnostic means of quantifying habitability and detecting life.

The question of how to detect non-technological life that is not bound to the gravity wells of planets, but instead enclosed in the sorts of structures we describe here, would be an interesting topic for future research. Research on the homeostasis of extraterrestrial living habitats would open up a complementary avenue of investigation. For example, it could allow further evaluation of whether habitable spaces could be maintained by life on distant or free-floating planets [Abbot and Switzer, 2011, Wordsworth, 2012], and what sort of other natural or artificial structures could allow life to exist in interplanetary and interstellar space.

Finally, the ideas discussed here can be contrasted with the concept of terraforming. Most frequently proposed for Mars, terraforming is defined as global modification of the climate via industrial technology in order to create conditions suitable for Earth-like life [McKay et al., 1991]. It is controversial and would be phenomenally resource-intensive, as it involves global, irreversible modification of an entire planet. In contrast, biologically generated habitats would pose no more of an environmental concern than any human mission. Indeed, as has been noted elsewhere [Santomartino et al., 2023], given the effectiveness of biological systems at recycling waste materials, adaptive biology may offer the *most* sustainable and environmentally sound way to support the long-term presence of humans and other complex life beyond Earth in the future.

11   Code availability

Code to reproduce Figure 3 is available to reviewers on request. On publication, it will be made available open-source at *https://github.com/wordsworthgroup/space_habitability*.

References

D. S. Abbot and E. R. Switzer. The Steppenwolf: A proposal for a habitable planet in interstellar space. *The Astrophysical Journal Letters*, 735(2):L27, 2011.

C. W. Arnscheidt, R. D. Wordsworth, and F. Ding. Atmospheric evolution on low-gravity waterworlds. *The Astrophysical Journal*, 881(1):60, 2019.

O. A. Attallah, M. Mojicevic, E. L. Garcia, M. Azeem, Y. Chen, S. Asmawi, and M. Brenan F. Macro and micro routes to high performance bioplastics: Bioplastic biodegradability and mechanical and barrier properties. *Polymers*, 13(13):2155, 2021.

N. J. H. Averesch, A. J. Berliner, S. N. Nangle, S. Zezulka, G. L. Vengerova, D. Ho, C. A. Casale, B. A. E. Lehner, J. E. Snyder, K. B. Clark, et al. Microbial biomanufacturing for space-exploration: What to take and when to make. *Nature Communications*, 14(1):2311, 2023.

R. Baetens, B. P. Jelle, and A. Gustavsen. Aerogel insulation for building applications: A state-of-the-art review. *Energy and Buildings*, 43(4):761–769, 2011.

R. A. Baker. *Membrane Transport Theory*, chapter 2, pages 15–96. John Wiley & Sons, Ltd, 2012.

A. J. Berliner, J. M. Hilzinger, A. J. Abel, M. J. McNulty, G. Makrygiorgos, N. J. H. Averesch, S. Sen Gupta, A. Benvenuti, D. F. Caddell, S. Cestellos-Blanco, et al. Towards a biomanufactory on Mars. *Frontiers in Astronomy and Space Sciences*, 8:711550, 2021.

R. A. Berner. *The Phanerozoic Carbon Cycle: CO_2 and O_2*. Oxford University Press, 2004.

O. Borgue and A. M. Hein. Near-term self-replicating probes — A concept design. *Acta Astronautica*, 187:546–556, 2021.

R. Caps and J. Fricke. Infrared radiative heat transfer in highly transparent silica aerogel. *Solar Energy*, 36(4):361–364, 1986.

M. H. Carr, M. J. S. Belton, C. R. Chapman, M. E. Davies, P. Geissler, R. Greenberg, A. S. McEwen, B. R. Tufts, R. Greeley, R. Sullivan, et al. Evidence for a subsurface ocean on Europa. *Nature*, 391 (6665):363–365, 1998.

J. C. Chancellor, G. B. I. Scott, and J. P. Sutton. Space radiation: The number one risk to astronaut health beyond low earth orbit. *Life*, 4(3):491–510, 2014.

G. Church. Picogram-Scale Interstellar Probes via Bioinspired Engineering. *Astrobiology*, 22(12):1452–1458, 2022.

C. S. Cockell and J. A. Raven. Zones of photosynthetic potential on Mars and the early Earth. *Icarus*, 169(2):300–310, 2004.

C. S. Cockell, R. Wordsworth, N. Whiteford, and P. M. Higgins. Minimum units of habitability and their abundance in the Universe. *Astrobiology*, 21(4):481–489, 2021.

T. W. Cronin. On the choice of average solar zenith angle. *Journal of the Atmospheric Sciences*, 71(8): 2994–3003, 2014.

G. C. C. Damant. Storage of oxygen in the bladders of the seaweed Ascophyllum nodosum and their adaptation to hydrostatic pressure. *Journal of Experimental Biology*, 14(2):198–209, 1937.

L. R. Dartnell. Ionizing radiation and life. *Astrobiology*, 11(6):551–582, 2011.

G. De Gonzalo, D. I. Colpa, M. H. M. Habib, and M. W. Fraaije. Bacterial enzymes involved in lignin degradation. *Journal of Biotechnology*, 236:110–119, 2016.

A. S. Dorcheh and M. H. Abbasi. Silica aerogel; synthesis, properties and characterization. *Journal of materials processing technology*, 199(1-3):10–26, 2008.

F. Dyson. *Disturbing the Universe*. Basic Books; Sloan Foundation Science Series, 1979.

A. Ellery. Sustainable in-situ resource utilization on the Moon. *Planetary and Space Science*, 184:104870, 2020.

R. A. Freitas Jr. A self-reproducing interstellar probe. *Journal of the British Interplanetary Society*, 33 (7):251–64, 1980.

B. J. Goodno and J. M. Gere. *Mechanics of Materials*. Cengage Learning, 2020.

V. E. Hamilton, A. A. Simon, P. R. Christensen, D. C. Reuter, B. E. Clark, M. A. Barucci, N. E. Bowles, W. V. Boynton, J. R. Brucato, E. A. Cloutis, et al. Evidence for widespread hydrated minerals on asteroid (101955) Bennu. *Nature Astronomy*, 3(4):332–340, 2019.

K. Hancke, L. C. Lund-Hansen, M. L. Lamare, S. Højlund Pedersen, M. D. King, P. Andersen, and B. K. Sorrell. Extreme low light requirement for algae growth underneath sea ice: A case study from Station Nord, NE Greenland. *Journal of Geophysical Research: Oceans*, 123(2):985–1000, 2018.

V. Hernández, D. Ibarra, J. F. Triana, B. Martínez-Soto, M. Faúndez, D. A. Vasco, L. Gordillo, F. Herrera, C. García-Herrera, and A. Garmulewicz. Agar biopolymer films for biodegradable packaging: A reference dataset for exploring the limits of mechanical performance. *Materials*, 15(11):3954, 2022.

G. Holzhüter, K. Lakshminarayanan, and T. Gerber. Silica structure in the spicules of the sponge Suberites domuncula. *Analytical and Bioanalytical Chemistry*, 382:1121–1126, 2005.

B. M. Jakosky. Atmospheric loss to space and the history of water on Mars. *Annual Review of Earth and Planetary Sciences*, 49:71–93, 2021.

J. F. Kasting, R. Kopparapu, R. M. Ramirez, and C. E. Harman. Remote life-detection criteria, habitable zone boundaries, and the frequency of Earth-like planets around M and late K stars. *Proceedings of the National Academy of Sciences*, 111(35):12641–12646, 2014.

O. Katz. Silica phytoliths in angiosperms: Phylogeny and early evolutionary history. *New Phytologist*, 208(3):642–646, 2015.

J. G. Lee, P. D. Miller, and I. B. Cutler. Carbothermal reduction of silica. *Reactivity of Solids*, pages 707–711, 1977.

L. Li and C. Ortiz. Pervasive nanoscale deformation twinning as a catalyst for efficient energy dissipation in a bioceramic armour. *Nature Materials*, 13(5):501–507, 2014.

C. P. McKay and H. D. Smith. Possibilities for methanogenic life in liquid methane on the surface of Titan. *Icarus*, 178(1):274–276, 2005.

C. P. McKay, O. B. Toon, and J. F. Kasting. Making Mars habitable. *Nature*, 352(6335):489–496, 1991.

G. A. Morgan, N. E. Putzig, M. R. Perry, H. G. Sizemore, A. M. Bramson, E. I. Petersen, Z. M. Bain, D. M. H. Baker, M. Mastrogiuseppe, R. H. Hoover, et al. Availability of subsurface water-ice resources in the northern mid-latitudes of Mars. *Nature Astronomy*, 5(3):230–236, 2021.

S. N. Nangle, M. Y. Wolfson, L. Hartsough, N. J. Ma, C. E. Mason, M. Merighi, V. Nathan, P. A. Silver, M. Simon, J. Swett, D. B. Thompson, and M. Ziesack. The case for biotech on Mars. *Nature Biotechnology*, 38(4):401–407, 2020.

S. Neethirajan, R. Gordon, and L. Wang. Potential of silica bodies (phytoliths) for nanotechnology. *Trends in Biotechnology*, 27(8):461–467, 2009.

V. R. Phoenix, P. C. Bennett, A. S. Engel, S. W. Tyler, and F. G. Ferris. Chilean high-altitude hot-spring sinters: A model system for UV screening mechanisms by early Precambrian cyanobacteria. *Geobiology*, 4(1):15–28, 2006.

R. T. Pierrehumbert. *Principles of Planetary Climate*. Cambridge University Press, 2010.

J.-G. Rosenboom, R. Langer, and G. Traverso. Bioplastics for a circular economy. *Nature Reviews Materials*, 7(2):117–137, 2022.

C. Sagan. *Comet*. Ballantine Books, 1997.

C. Sagan and E. E. Salpeter. Particles, environments and possible ecologies in the Jovian atmosphere. *NASA Technical Report No. NASA-CR-148170*, 1976.

R. Santomartino, N. J. H. Averesch, M. Bhuiyan, C. S. Cockell, J. Colangelo, Y. Gumulya, B. Lehner, I. Lopez-Ayala, S. McMahon, A. Mohanty, et al. Toward sustainable space exploration: A roadmap for harnessing the power of microorganisms. *Nature Communications*, 14(1):1391, 2023.

J. S. J. Schwartz. Near-Earth water sources: Ethics and fairness. *Advances in Space Research*, 58(3): 402–407, 2016.

S. Seager, J. J. Petkowski, P. Gao, W. Bains, N. C. Bryan, S. Ranjan, and J. Greaves. The Venusian lower atmosphere haze as a depot for desiccated microbial life: A proposed life cycle for persistence of the Venusian aerial biosphere. *Astrobiology*, 21(10):1206–1223, 2021.

N. N. Shi, C.-C. Tsai, F. Camino, G. D. Bernard, N. Yu, and R. Wehner. Keeping cool: Enhanced optical reflection and radiative heat dissipation in Saharan silver ants. *Science*, 349(6245):298–301, 2015.

I. I. Smalyukh. Thermal management by engineering the alignment of nanocellulose. *Advanced Materials*, 33(28):2001228, 2021.

K. E. Tsiolkovsky. *Speculation Between Earth and Sky*. Isd-vo AN-SSR, 1895.

C. Verseux. Bacterial growth at low pressure: A short review. *Frontiers in Astronomy and Space Sciences*, 7:30, 2020.

A. C. Waajen, R. Prescott, and C. S. Cockell. Meteorites as food source on early earth: Growth, selection, and inhibition of a microbial community on a carbonaceous chondrite. *Astrobiology*, 22(5):495–508, 2022.

J. Wadsworth and C. S. Cockell. Perchlorates on Mars enhance the bacteriocidal effects of UV light. *Scientific Reports*, 7(1):4662, 2017.

S. I. Walker and P. C. W. Davies. The algorithmic origins of life. *Journal of the Royal Society Interface*, 10(79):20120869, 2013.

R. Wordsworth. Transient conditions for biogenesis on low-mass exoplanets with escaping hydrogen atmospheres. *Icarus*, 219(1):267–273, 2012.

R. Wordsworth, L. Kerber, and C. Cockell. Enabling Martian habitability with silica aerogel via the solid-state greenhouse effect. *Nature Astronomy*, 3(10):898–903, 2019.

A. Zouine, O. Dersch, G. Walter, and F. Rauch. Diffusivity and solubility of water in silica glass in the temperature range 23–200 °C. *Physics and Chemistry of Glasses-European Journal of Glass Science and Technology Part B*, 48(2):85–91, 2007.