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Space Resources to Stop Global Warming: a Planetary Sunshade

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ABSTRACT

A planetary sunshade is a space megastructure at Sun-Earth Lagrange 1 that stops global warming by blocking a fraction of the Sun's light from reaching earth. Climate change and the possibility of the climate crisis escalating to catastrophe makes a geoengineered future easily imaginable. Space resource development and the ongoing launch revolution make it possible to consider building a planetary sunshade from space resources in the foreseeable future. The technology required to actualize the sunshade is already under development, as are international policy frameworks. We propose a modular architecture for a planetary sunshade that revitalizes the O'Neillian dream while restoring Earth's climate and producing terawatts of power in cislunar space – catalyzing an in-space industrial economy.

I. INTRODUCTION

The planetary sunshade is a space-based solution to climate change (Figure 1). A thin-film megastructure at Sun-Earth Lagrange 1 (SEL-1), it stops global warming by blocking a small fraction of sunlight from reaching Earth. The scale is immense, but there are feasible routes to construction using space resources and launch vehicles in development. If constructed, the planetary sunshade would be a demand-driver accelerating the development of in-space industrial capabilities with funding from governments whose primary problems are caused by global warming. It would catalyze technology and infrastructure for building space megastructures and create new space industrial capabilities that would make expanding humanity throughout the solar system a straightforward endeavor. We believe that constructing a planetary sunshade is feasible in this century, an argument that rests on the acceptance of three underlying trends.

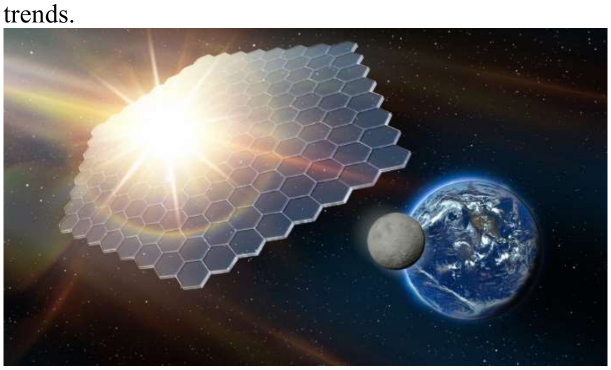

Fig. 1: A planetary sunshade at SEL-1

The first trend is climate change. Humanity's carbon emissions are unsustainable, and we believe that continuation of the fossil fuel economy will bring devastating climate outcomes. Future governments will be faced with immediate existential problems from a worsening climate, and they will act to stabilize it. Geoengineering will move from a fringe idea to a popular mandate. The planetary sunshade provides space-based geoengineering, and the degree to which the climate crisis escalates toward catastrophe will determine the need for building it.

Second, space resources are plentiful and the technology to work with them is at hand. Governments and companies alike are beginning to appreciate that scaling and sustaining a presence in space will require working with raw materials found beyond Earth's gravity well. Developing these resources and technologies is currently constrained by lack of demand. The planetary sunshade allows us to connect the foreseeable global demand for a solution to the climate crisis with a potential supply of near limitless space resources on an otherwise impossible scale.

The third trend is that the launch revolution is here, with the expectation that at least one next-generation heavy launch system will be able to achieve its design goals. The SpaceX Starship may soon be able to land 100 tonnes on the lunar surface, with potentially 1,000 Starships in active service for SpaceX's Mars fleet (Elon Musk on Twitter, 16 January 2020, https://twitter.com/elonmusk/status/1217989066181898240). Just a fraction of that fleet's capability could support creation of a cislunar industrial base at the scale needed to produce the sunshade. The development rate for lunar industry can be very fast with rapid and frequent flights to the Moon, allowing quick design iterations.

It is also becoming clear that the international legal community will deliver organizations and treaties to enable and arbitrate the acceptance of prospecting and mining of space resources for the benefit of all humanity. The efforts made to pursue the planetary sunshade will accelerate the efforts from the Hague Building Blocks for the Development of an International Framework on

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Space Resource Activities [1] to a widely accepted and internationally ratified treaty, where property rights and intellectual property are respected. The planetary sunshade will uphold the legacy of international cooperation and peaceful use of outer space while adopting and promoting the principles and solutions presented in the Hague Building Blocks.

II. CLIMATE CHANGE

Climate change is already here and, while complex, it is dominated by global warming through radiative forcing from greenhouse gasses. Global warming occurs when Earth's energy budget – energy entering into Earth's ecosphere versus energy out – becomes unbalanced and the system retains more heat than it rejects into space. This is mainly caused by increasing carbon in Earth's atmosphere, which acts as a warm blanket around the planet and increases the amount of heat retained. Radiative forcing expresses this energy imbalance; it is a primary metric for climate forecasts. The Intergovernmental Panel on Climate Change (IPCC) uses a range of Representative Concentration Pathways (RCPs) to model future emissions, named for their radiative forcings in W/m^2. These modeled scenarios range from RCP1.9, which may no longer be achievable, to RCP8.5, which represents catastrophic climate change [2]. By blocking sunlight, the planetary sunshade counteracts radiative forcing, returning Earth's energy balance to equilibrium.

The effects of the planetary sunshade are distinct from those of sustainable energy, which only eliminates carbon emissions to reduce the rise in radiative forcing. Sustainable energy on Earth is required to stop making the problem worse, but it does nothing to stop or reverse the already accumulated damage. The sunshade is a form of solar geoengineering, a technique of reducing solar heating on Earth to counteract global warming. In a world where the impact of global warming is already felt, geoengineering is the only alternative to suffering escalating damages as the climate crisis worsens.

The amount of geoengineering required depends on our future emissions as well as whether society will want to slow global warming or restore a pre-industrial climate. Government action will eventually be forced as a result of historical government inaction because climate change simply gets worse as action is delayed. The IPCC recognized the Paris Accords as our last opportunity to avert catastrophic climate change by emissions reduction alone. We are failing spectacularly at this goal [2]. Emissions are not reducing but increasing. The window of opportunity to avert catastrophic climate change is almost closed. As that window closes, we must contemplate geoengineering. To be clear, geoengineering is no substitute for sustainable energy – it is required to remediate the consequences of unsustainable energy.

We have become used to a world in which government action on climate is impossible, but every year that the status quo remains in place ratchets up the eventual consequences of climate change. Meanwhile, climate action is a generational issue, with younger people who expect to live longer making it a primary political issue. As the consequences of climate change manifest and a climate aware demographic comes to dominate the electorate, governments will be motivated to act. The planetary sunshade allows space industrialization to be part of the solution to this problem.

III. SUNSHADE CONCEPT

The planetary sunshade concept has been explored over thirty years, most notably by Colin McInnes at the University of Glasgow [3] and Roger Angel at the University of Arizona [4]. Its efficacy in controlling climate has been modelled [5,6], and orbital control laws based on solar radiation pressure have been developed for station-keeping and orbital control around SEL-1 [6]. Besides our own recent work [7], we are unaware of any progress on the concept since 2015; since then, the trends discussed above have made the concept relevant for more serious consideration.

The sunshade is a physical structure, located between the Earth and the Sun. It evenly shades the Earth and, since it stops incoming energy before it reaches the atmosphere, balances Earth's energy budget without negatively impacting the atmosphere or oceans. Controllable as a solar sail, the effects of the sunshade are also fully reversible; it can be easily and incrementally moved out of the path of incoming sunlight once Earth's atmosphere is returned to its preindustrial carbon level.

The required size of the sunshade would vary based on future emissions and climate goals, but far exceeds that of any credibly proposed space architectures and places it on par with terrestrial megastructures, such as China's Three Gorges Dam. Even using the full capabilities of the cheapest, most rapidly reusable heavy launch vehicle currently under development – SpaceX's Starship – launching a planetary sunshade from Earth would require nearly 100 years to emplace, cost hundreds of billions of dollars in launch costs alone, and further damage Earth's environment through mining and launch activities. Fortunately, all the materials needed to construct the sunshade are available in cislunar space.

The Moon, Earth's closest celestial neighbor, will likely be the first source of space resources. The lunar surface is rich in minerals such as silicates and metal oxides that can produce structural materials and oxygen. The lunar poles also contain water that can be transformed into propellant via electrolysis to fuel a cislunar transportation network. Near Earth objects (NEOs) also provide a variety of resources, including water, metal ores, platinum-group metals, and organic compounds. Although technologies for prospecting and mining NEOs are not as developed as equivalent lunar options, asteroidal resources will eventually replace Earth-launched materials and components and allow for a complete space-based supply chain.

IV. SUNSHADE ARCHITECTURE

The required area of the planetary sunshade is between 856,816 and 3,825,075 km^2, which is based on IPCC RCPs [7]. An incremental and exponential growth architecture is needed to make such a large structure. A modular design (Figure 2) allows the construction of individual 1,039 km^2 hexagons, made of thin-film photovoltaics, to be assembled into 'islands' at SEL-1. Each island would be composed of 169 hexagons and have a total surface area of 175,630 km^2. This size is smaller than required to accomplish likely climate goals but large enough to have a measurable effect. Several islands orbiting in a sunshade archipelago around SEL-1 would allow scalability to changing climate and would let competing nations or groups of nations work separately toward a common goal. The mass of the structure varies depending on the thickness and material composition of the film and the addition of structural supports and capabilities such as human habitats and manufacturing facilities. For the film alone, we estimated a wide mass range between 525 kilotonnes and 525 megatonnes for each island. All of this mass can be sourced from the Moon and NEOs.

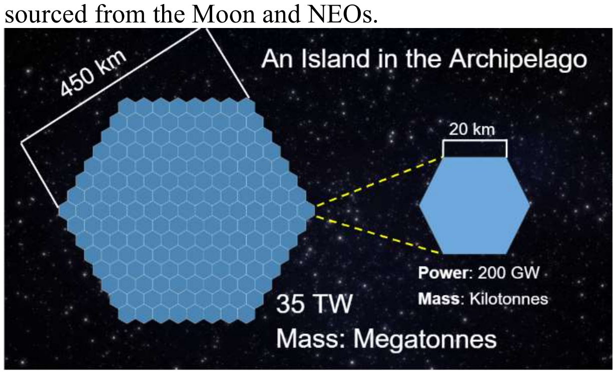

Fig. 2: Planetary sunshade island, composed of 169 20-km hexagons. Five to 22 islands would be required to restore preindustrial average temperatures under RCP1.9 and RCP8.5, respectively.

An incremental manufacturing and assembly approach allows future space construction initiatives to scale up or down to meet the climate change goals. As carbon is removed from the atmosphere, individual sections or islands can be removed from their positions by solar sailing and repurposed at other locations.

This also allows construction speed to scale exponentially; power generated by each sunshade module can support the construction of subsequent modules. If manufacturing equipment is flown to SEL-1 or manufactured onsite at a compounding rate and raw materials are delivered to SEL-1 at a compounding rate, the requirements for exponential growth will be met. A sunshade archipelago at SEL-1 would intercept a solar flux of 1.1 to 5.2 petawatts and, if made of thin film photovoltaics at an efficiency of 20%, would generate 160 to 780 terawatts, with each island contributing 35 terawatts. Today's total world energy supply is 17 terawatts. A planetary sunshade is the stuff of Kardashev civilizations.

An archipelago of five to twenty-two islands would be required to meet the 0.56% to 2.5% reduction in insolation needed to restore preindustrial temperatures under IPCC RCPs. Figure 3 depicts how this might look to an observer from Earth. Venus's transit of the Sun in 2012 is shown as a visual comparison.

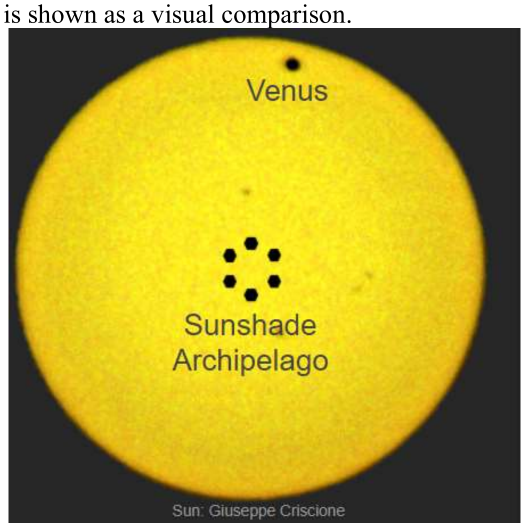

Fig. 3: A six island sunshade archipelago compared to the 2012 Venus transit as seen from Earth. This sunshade configuration would exceed the RCP1.9 climate forecast for a 0.56% reduction in total insolation.

Venus's transit resulted in a reduction of total solar irradiation from the Sun's normal 1361.25 W/m^2 to 1359.85 W/m^2 at maximum (Figure 4), a 0.1% reduction in solar irradiation [8]. The transit of Venus, much like an eclipse, is only viewable with special glasses or camera filters; likewise, the sunshade archipelago will only be visible to the protected eye as a series of small black spots.

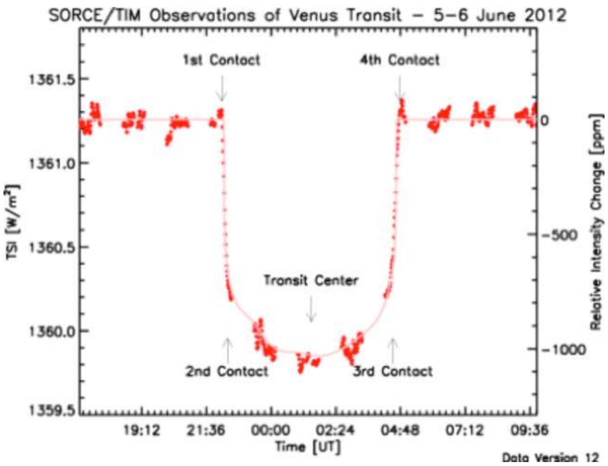

Fig. 4: Solar Radiation and Climate Experiment (SORCE) Total Irradiance Monitor (TIM) recording of the total solar irradiance reduction over the course of the 2012 Venus Transition [8]

While the primary function of a planetary sunshade is to stabilize Earth's climate, it is far from the only function it could have. Energy production is necessary for construction on this scale and would remain a useful asset after the sunshade is complete. With each island in the archipelago generating more energy than today's total terrestrial supply, the energy supply necessary for Kardashev-scale endeavors becomes readily available in deep space. Power could be beamed to Earth to supplement terrestrial power generation, perhaps to drive direct air capture and carbon sequestration to more rapidly restore the climate to a state where space-based stabilization is not required; in that eventuality, the sunshade could be sailed to a different orbit where it does not shade Earth, and continue to be used for its secondary purposes. The aperture size and power available on a sunshade island could host incredible telescopes and a space domain awareness system cataloging everything of interest in cislunar space and around the ecliptic, including asteroids or objects that could one day threaten Earth. The energy could also be used for computational purposes to produce a giant server farm in the sky. While this may sound fantastical, progress in artificial intelligence has historically required exponential increases in compute power, and the apparent end of Moore's law implies that improvement in artificial intelligence may be limited by the availability of terrestrial server farms in the foreseeable future. The compute cost of creating improved algorithms is much greater than the cost of deploying them, so the ten-second latency between Earth and SEL-1 may not be prohibitive.

During its construction, the sunshade also brings into being an enormous manufacturing capacity at SEL-1, capable of utilizing the sunshade's power to create still more megastructures. The same logistical chain that brings lunar and asteroidal resources for sunshade construction could deliver resources for building infrastructure to distribute across the solar system. Given developments in propulsion technology that could generate thrust from waste material of construction, the developed photovoltaic manufacturing capacity could produce power systems capable of accelerating large Mars cyclers that could ease mass emigration to a new planet, and to power ships for exploration and settlement throughout the solar system.

At the scale of a planetary sunshade, the required logistics and energy flows dull arguments against bringing humans into space. When operating on the scale of megatonnes and gigawatts, and with continual resupply of machines and raw materials, it is relatively simple to support a human crew to manage the sophisticated machines doing the actual construction. The history of industrialization is one of humans utilizing ever more advanced machines to build ever larger and more complicated creations. Even if it were possible to develop space megastructures without human labor, there is an existential imperative for most people to work, and for some to work and live on the frontiers of human expansion. People will want to live and work on the sunshade during its construction and during its operation. A habitat would be expected on each island of the sunshade archipelago, at first consisting of crewed ships from Earth, soon tethered to each other and spun up for artificial gravity, then perhaps connected into a hub-and-spoke network with radiation shielding made from space resources, and evolving finally into an enclosed and permanent habitat.

With all these pieces in place, the sunshade archipelago becomes much more than just a climate stabilization device. Situated at the edge of Earth's gravity well, SEL-1 is a favorable location in the energy landscape of deep space for a logistical hub connecting cislunar space with the greater solar system. With developed infrastructure, including effectively unlimited energy and a very large construction and potentially shipbuilding capacity, the islands of the sunshade archipelago become natural spaceport cities capable of self-sustaining economies hosting deep-space heavy industry and facilitating transport throughout the solar system.

V. TECHNOLOGY MATURATION

In keeping with the architectural theme of harnessing compounding improvements to drive exponential growth, the technology necessary to build a planetary sunshade will be the result of continuously compounding improvements in space resource utilization and manufacturing.

The launch revolution and modern industry are pushing space technology iteration and maturation quicker than ever before. It is becoming cheaper and faster to test out ideas in space, promising researchers and engineers around the world the ability to push the envelope of in-space resource utilization (ISRU) systems. Across the field, there is active development in systems that prospect and refine asteroids and lunar regolith into feedstock, reusable cislunar transportation architectures, and actual in-space manufacturing systems. While no space resources system has collected, processed, and manufactured a final good, the maturation process is already well underway.

Some of the core technologies required for sunshade construction include collecting and refining lunar or asteroidal resources into products used in construction, efficient cislunar transportation, and scalable in-space manufacturing of large structures. The Colorado School of Mines has established the Center for Space Resources and the world's first graduate program in the field [9], of which the authors are students. Here, an interdisciplinary approach is being brought to bear on all aspects of the space resource science, technology, value, and policy chains.

ISRU technologies are being developed by private companies, academia, and civil space agencies. Scalable lunar infrastructure concepts are currently being studied, including some that provide power across large portions of the lunar poles [10,11] and that collect and refine resources in difficult to reach places on the Moon [12,13]. As lunar resources are utilized for the sunshade, expansive lunar infrastructure will be required. Such an ISRU process would collect and refine metals from the regolith, manufacture components from that metal feedstock, and propel it into orbit via lunar-derived propellant and perhaps a mass driver for transport to SEL-1 for final assembly, thus creating a railroad from the Moon.

Asteroid processing technologies are also in development. TransAstra is actively developing a scalable architecture that can collect, process, and transport water-bearing asteroids. As part of the first ever NASA Innovative Advanced Concepts (NIAC) Phase III grant [14], TransAstra aims to demonstrate an in-orbit system that will directly extract water from asteroid simulant while in low-Earth orbit. The much larger Queen Bee concept would be able to collect and return several thousand tonnes of water ice to cislunar space per two-year mission. This amount is still tiny in terms of the sunshade, but shows technology that may work and scale to meet demand.

Made In Space is actively developing integrated in-space manufacturing capabilities. They have multiple manufacturing development systems aboard the International Space Station (ISS), including systems to manufacture optical fibers, crystals, ceramic structures, and small plastic components. Beyond these demonstration units, Made In Space has released concepts able to build large scale structures, such as industrial truss beams, directly in orbit.

The ultimate goal of sunshade construction will require extensive infrastructure across cislunar space, including on the Moon's surface and multiple near-Earth asteroids. Many of the ideas for this have been around for decades, yet concrete work is being done today to advance these concepts. Even with the rapid development enabled by the launch revolution, processing speeds of the early systems will be slow. However, continual refinement and expansion can compound year after year if the demand can be generated, enabling production rates required to construct the sunshade.

This technology maturation is enabled by our third trend, which is the accelerating launch revolution. The technical breakthrough represented by Starship's launch capacity design goal of 100 megatonnes per year may seem incredible but the organization behind it is credible, attracts unlimited capital, and is existentially dedicated to achieving the goal. Once these capabilities are demonstrated, other launch organizations will be driven to match or complement them.

Starship and other reusable heavy launch vehicles would allow regular freight service not just to LEO but to an industrial park on the Moon, where the poles offer a constrained geography featuring continual access to sunlight and volatiles in permanently shadowed craters; the lunar poles offer the nearest source of extraterrestrial propellant. Rapid and regular transportation can create a railroad to the Moon, accelerating lunar industrial development, with transport of workers and equipment on a continual basis.

Technological improvement comes fastest with iteration, and having humans and robots working together, with fabrication, repair facilities, and other centralized infrastructure, will make the lunar poles a fast technology and resource development site. We see a world in which you can just fly something to space and try it or bring your engineering team to the Moon and work the problem on site. The launch revolution will make the Moon a factory, a mine, and a gas station. Progress in space, which we have been conditioned by scarce launch capacity to believe is slow, will become fast.

The construction of a planetary sunshade will create enough demand for space resources to drive this capacity building cycle very quickly. Indeed, cislunar industrial development would be an ideal demand driver for Starship's capability – after all, launch opportunities to Mars occur only every 26 months.

VI. SPACE POLICY CHALLENGES AND OPPORTUNITIES

Many of the larger and, therefore, more costly space missions have been enabled through international

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collaboration and the drawing together of funds and resources; the chief example of this is the International Space Station. The planetary sunshade, a megastructure requiring in-space assembly, can reasonably be envisaged to be no exception to this trend. International support for such a venture is key as well as the accompanying policy framework required to enable the development of the planetary sunshade.

Recent developments in space policy are an encouraging first step towards the fulfillment of such an initiative. The planetary sunshade requires ISRU, which is in keeping with the establishment of the Artemis Accords. The Accords seek to find a common basis through which countries can extract and utilize space resources. In addition, increasing governmental support across the globe for commercial actors in space will promote the kind of ecosystem that will enable fully commercial heavy lift launchers, such as Starship, that are essential to this effort. Should space policy continue to evolve along its current trajectory, it can be expected that by the time all the necessary technological developments reach maturation stage, space policy will also be prepared to enable in-space mining and assembly of megastructures.

It is expected that building such a megastructure in space will raise questions, particularly regarding UNOOSA's Long Term Sustainability guidelines. However, the development of the planetary sunshade could be expected to follow COSPAR's Planetary Protection Policy and efforts to include sustainability principles from the design phase.

In order to pass the legal test, the planetary sunshade must adhere to the domestic laws of the launching countries that will bring it about and their international treaty obligations. The body of law regulating space activities is limited to four widely accepted treaties and the Moon Agreement, which is not widely accepted. Last year, the Hague published Building Blocks for the Development of an International Framework on Space Resource Activities (HBB), which we applaud, and believe has the potential to create an international body that would provide arbitration and deconfliction services similar to those provided by the International Telecommunications Union (ITU). Significant detail needs to be worked out, but the HBB framework and the principles promoted therein reflect the spirit of the 1967 Outer Space Treaty (OST): that space is a domain for peaceful use for the benefit of all humankind. Collectively, this reduces risk for companies involved in all aspects of the design and construction of the planetary sunshade, for investors funding those companies, and for countries wary of each other's true intentions. The International Space Station presents a legal precedent for collaboration in space, as fifteen nations were involved in the initial intergovernmental agreements (IGA) -- each member nation signed onto the 1998 IGA. This framework established a three-tier legal framework: at the top was the IGA, supported by memoranda of understanding, and implementing arrangements, established as needed [15]. A similar framework could be used by countries and organizations involved in the planetary sunshade.

Ultimately, the planetary sunshade and global warming will be a forcing function for the international adoption of a space resource treaty. We fully support the framework and principles proposed by the Hague Working Group. The planetary sunshade need not be an entirely altruistic endeavor; governments will see benefit through global thermal stabilization for their own citizens and the prevention of climate change based wars (such as, arguably the Syrian civil war), mass migration caused by climate change, or the potential destabilization caused by terrestrial geoengineering (where weather control causes regional versus global mitigation, or through unintended extra-border effects). Space resource companies throughout the value chain will be able to create value and wealth in unexpected ways outside of the planetary sunshade through advances in prospecting, mining, processing, and manufacturing products in space for the sunshade project itself, but also in solving problems for supporting economies and industries. Having an orderly and lawful space econosphere will provide unexpected benefits to people on Earth. The establishment of clear and limited property rights will enable the promotion of talent to create wealth and find new solutions to the inevitable problems that occur while trying to implement the planetary sunshade project.

VII. REVIVING THE O'NEILLIAN DREAM

Space exploration has always been fueled by dreams. In a more idealistic era, the O'Neillian dream of cislunar development was built around creating utopian space habitats for humans to live and work in, beyond the limits to terrestrial growth. The visions featured ecological spaces, rendered in a palate of cool blues and greens like a recreated Earth.

This dream has been largely dormant in the first twenty years of the 21st century. One reason is that technical and economic drivers did not develop to sustain the dream. Another, however, is that dystopian visions of our future have come to dominate our culture, and space exploration is represented by founding a 'Planet B' on Mars. Rendered in reds and blacks, the dream of humans struggling against a majestic but unforgiving planet has captured the spacefaring imagination.

There is ample room for both visions, and indeed they are complementary, but to articulate an ecologically utopian case for space development requires addressing the ecological crisis of the anthropocene: climate change. The planetary sunshade does that directly, connecting the dream of expanding into space to the imperative of protecting and restoring Earth's environment.

With an overarching ecological motivation, the building blocks leading to a planetary sunshade take on a green hue, with industrial development no longer degrading the environment but instead protecting and sustaining it. Seemingly intractable problems in the world of today exist because of the past century's tension between industry and ecology. If we take responsibility for the anthropocene, the next century can be built on a foundation of green industry, expansion into space, and ecological preservation.

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