A Planetary Sunshade Built from Space Resources

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Global warming is the defining problem of our time. Soon the atmosphere will hold more industrial carbon than natural, and solutions to anthropogenic climate change will become one of the largest economic sectors in the coming decades. A planetary sunshade is a space megastructure at Sun-Earth Lagrange 1 (SEL-1) that can control global warming by blocking a small fraction of the energy Earth receives from the Sun. Utilization of space resources makes building a planetary sunshade feasible. We present a space resource utilization plan for building a planetary sunshade using lunar and asteroidal resources, and consider alternative solutions to an SEL-1 sunshade as a ring sunshade in Earth orbit. The planetary sunshade offers the space resources industry an opportunity to develop an attractive and exciting solution to the geoengineering problem while establishing a cislunar economy.

I. Introduction

The Intergovernmental Panel on Climate Change (IPCC) warns that the window of opportunity to hold global warming to 1.5 degrees by emissions cuts alone is rapidly closing [1]. Yet global emissions continue to rise. In the coming decades, society may face consequences it is unwilling to bear.

The science of climate change is unfortunately politicized. Here we sidestep the politicization by noting that while facts and analyses should be objective, responses involving collective action are rightly political - and you don't have to believe in the science to appreciate that there is a large and growing constituency who views climate change as a primary political issue.

The space resources community would be well served to develop concepts that speak to the political constituency for climate action, as it is larger than the political constituency for space resource development. Space solar power is one such concept, which advances the sustainable energy transition. It competes with (and complements) technologies that are desirable for this constituency, including terrestrial renewables and energy storage.

Sustainable energy does nothing to remediate the damage already locked in from existing emissions - they only prevent future damages from becoming worse. Because climate scientists and the political constituency for climate action expect severe consequences from climate change under any likely emissions scenario, it seems possible that geoengineering will be considered as a way to mitigate those consequences. Geoengineering is the deliberate large-scale intervention to control climate change. Solar radiation management (SRM) is one aspect of geoengineering that addresses global warming by reducing the amount of sunlight contacting Earth. This can be done terrestrially through solutions like aerosol injection into the atmosphere or painting large portions of the Earth white to reflect sunlight. A planetary sunshade is a space-based solution for SRM that prevents solar radiation from reaching Earth globally, rather than regionally, and exports the industrial and energy requirements off-world.

Carbon geoengineering, cleaning the atmosphere of emissions and sequestering carbon geologically, is still needed. However, carbon removal may take a very long time, and solar geoengineering will become necessary to minimize the catastrophic impacts of global warming and buy time for carbon removal. If the window of opportunity for stabilizing the climate through emissions reductions alone closes, the space launch revolution and the development of space resources will take place in the window of opportunity for solar geoengineering. We in the space resources community have the opportunity to develop an attractive and exciting concept that solves the geoengineering problem while bootstrapping a cislunar economy. And what an economy it would create, utilizing megatons of resources in deep space, and generating terawatts of power.

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We believe that this idea is transitioning from incredible to credible. The drivers on a decadal scale are that geoengineering will become more desirable as emissions continue, and that the launch revolution and the development of space resources will make the planetary sunshade feasible. SpaceX's design goals for Starship* suggest a future in which the lift capacity to drive megatonne scale space resource utilization is commercially available.

A planetary sunshade offers the ideal form of solar geoengineering. The sunshade will stabilize Earth's climate from outside the ecosphere, cooling Earth without further alteration of our atmosphere, ocean, or land use patterns. Offering far fewer deleterious effects than terrestrial geoengineering schemes, it provides a utopian vision of a future for humanity beyond Earth while safeguarding the natural environment that makes Earth irreplaceable.

During construction, while it is operating, and even after it is no longer required for climate stabilization, a planetary sunshade can also function as a space resource processing center and as a shipyard in deep space. It creates incredible demand for space resources and incrementally increases its energy production. If made of thin-film photovoltaics, it could generate civilization-transforming energy supplies. It could have a secondary purpose for data storage and processing: the sunshade could be the largest data farm and supercomputer ever built. The planetary sunshade concept articulates the bull case for a cislunar economy while generating social license for space development.

II. The Sunshade at Sun-Earth Lagrange 1

Sun-Earth Lagrange 1 (SEL-1) is the most logical place that a planetary sunshade could be stationary in the Earth-Sun reference frame. Various formulations of the concept have been explored, including sunshades in Earth orbit and at SEL-1 by Mautner, McInnes, Angel, and Sanchez in Ref. [2-5].

The amount of global cooling required depends on our future emissions as well as whether society will want to slow global warming or restore a preindustrial climate. The IPCC bases climate forecasts off of possible emissions futures entitled representative concentration pathways (RPCs), identified by their radiative forcing in W/m^2, ranging from RPC 1.9 to RPC 8.5. Because radiative forcing is a primary metric underlying IPCC forecasts, we can use these figures to derive the range of sizes for a planetary sunshade.

Radiative forcings used in climate models quantify thermal disequilibrium over the Earth's surface. In thermal equilibrium, heat in equals heat out. The two-dimensional solar flux of 1360 W/m^2 projected onto the Earth yields an average solar flux of 340 W/m^2 because a sphere's area is 4 times that of its circular projection. The range of RPCs from 1.9 W/m2 to 8.5 W/m^2 therefore corresponds to a range of 0.56% to 2.5% retained heat. To a first approximation, a planetary sunshade blocking this percentage of sunlight would restore Earth's average temperature to a preindustrial state. This is in good agreement with results from climate modeling under a reduced solar constant [6-7], and prior analysis of a 1.7% sunshade [3-5].

At an upper limit, blocking 2.5% of the incident solar radiation requires calculating the surface area of the angular diameter equivalent planetary sunshade at SEL-1. The solar photosphere's radius is 6.96e5 km and it covers 6.8e-5 steridians, as seen from Earth. To negate radiative forcing under the worst-case scenario of RPC8.5, the sunshade needs to block 2.5% of that solid angle or cover 1.7e-6 steridians. By using the steradian equation,

$$\Omega = \frac{A}{r^2} \quad [\text{sr}] \tag{1}$$

we can solve for the upper estimate for the total area of sunshade required at SEL-1, where r is the distance from Earth to SEL-1 (1.5 million km). We solve for A:

$$A = \Omega \times r^2 \times 1{,}500{,}000^2 \quad [\text{km}^2] \tag{2}$$

The lower limit of .56% reduction in insolation (RPC1.9) results in an area of 856,816 km^2.

A sunshade at SEL-1 would thus intercept a solar flux of 1.5 to 6.9 petawatts and, if made of thin film photovoltaics at a conservative efficiency of 20%, would generate 160 to 780 terawatts. Today's total world energy supply is 17 TW. This is the stuff of Kardashev civilizations.

Solar radiation pressure on a sunshade at SEL-1 pushes the equilibrium point farther away from Earth [McInnes]. For minimal mass sunshades, this would increase the required size substantially, but as aereal density increases, the effects of solar radiation pressure decreases. A sunshade made of space resources, featuring photovoltaic power generation, large habitats, industrial facilities, and potential ballast from unused raw material would be substantially heavier than minimum mass designs and so would not be affected as substantially by this factor.

A. Analysis of Alternatives

A range of one to four million square kilometers of solar panels seems like a massive undertaking. It is, so it was necessary to see if there were alternatives to SEL-1 as, intuitively from Figure 1, an object closer to Earth would

* Elon Musk on Twitter (2020, January 16). [Tweet]. https://twitter.com/elonmusk/status/1217989066181898240

require less area. Considering that in space we are constrained by orbital dynamics, anything not at SEL-1 would have to orbit Earth.

Several options were investigated to demonstrate that SEL-1 was in fact the best, lowest mass option. One was to construct, essentially, a Dyson ring around Earth inclined to the ecliptic (23.5 degrees) at various altitudes from 1000 km (LEO) to several times the altitude of GEO. Another was, instead of creating a single sunshade at SEL-1, to put multiple smaller sunshades as a constellation in the same Lissajous type orbit with evenly staggered true anomalies.

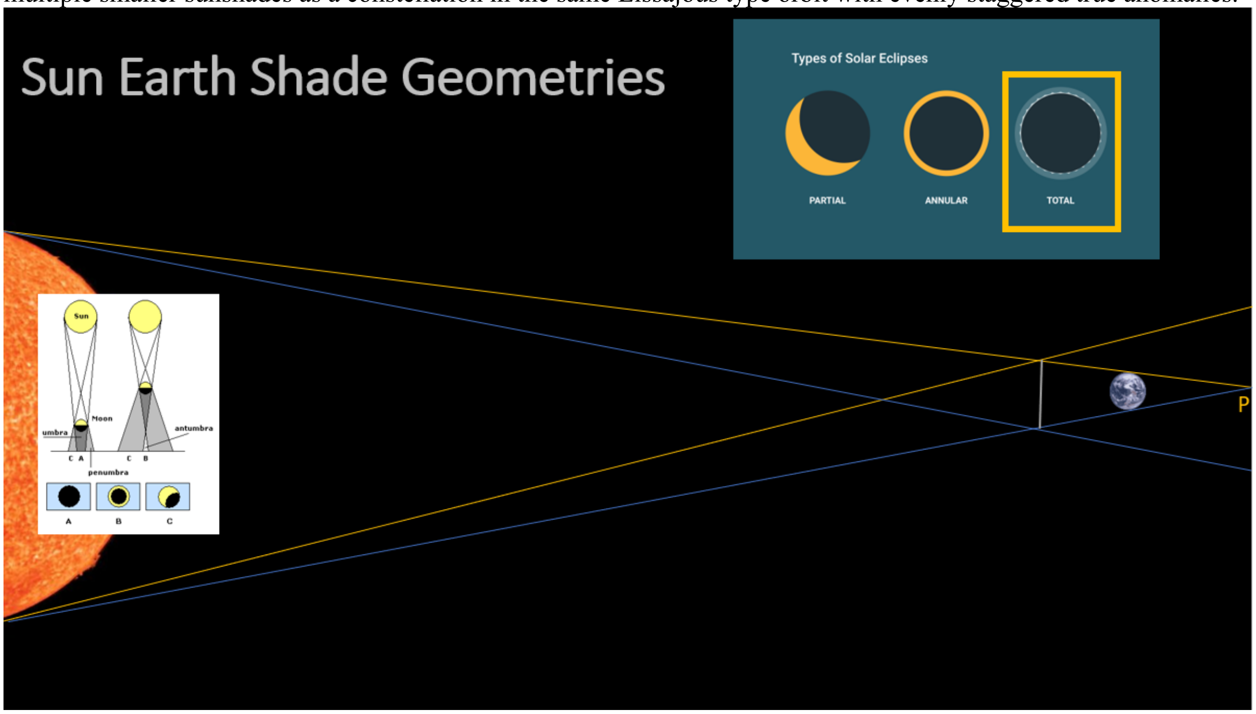

Fig. 1 Geometry of the planetary sunshade design space, not to scale. Point P is Earth's umbra-antumbra shared vertex. Placing a sunshade closer to the Sun would require, for the same angular cross section, a larger area. The vertical line depicts the cross-sectional area where a sunshade would cast a shadow on Earth. If the entire area were filled it would create a total eclipse over the entire Earth.

1. Ring Sunshade

When we initially considered the "ring sunshade" concept, we were concerned that it would adversely affect communities at the equator with permanent shading. This is not the case, with the ring inclined at the ecliptic and the Earth rotating independently; however, other problems with the solution made this concept ultimately untenable.

To size the ring sunshade, we again need to determine the surface area of the Sun obscured, this time as seen from point P, the umbra-penumbra point, to get the approximate amount of sunlight obscured across the Earth (to include the lowest 200 kilometers of the Earth's atmosphere). Point P is the point that Earth's apparent size equals the Sun's apparent size. A drawing of the geometry of a sunshade ring is seen in Figure 2.

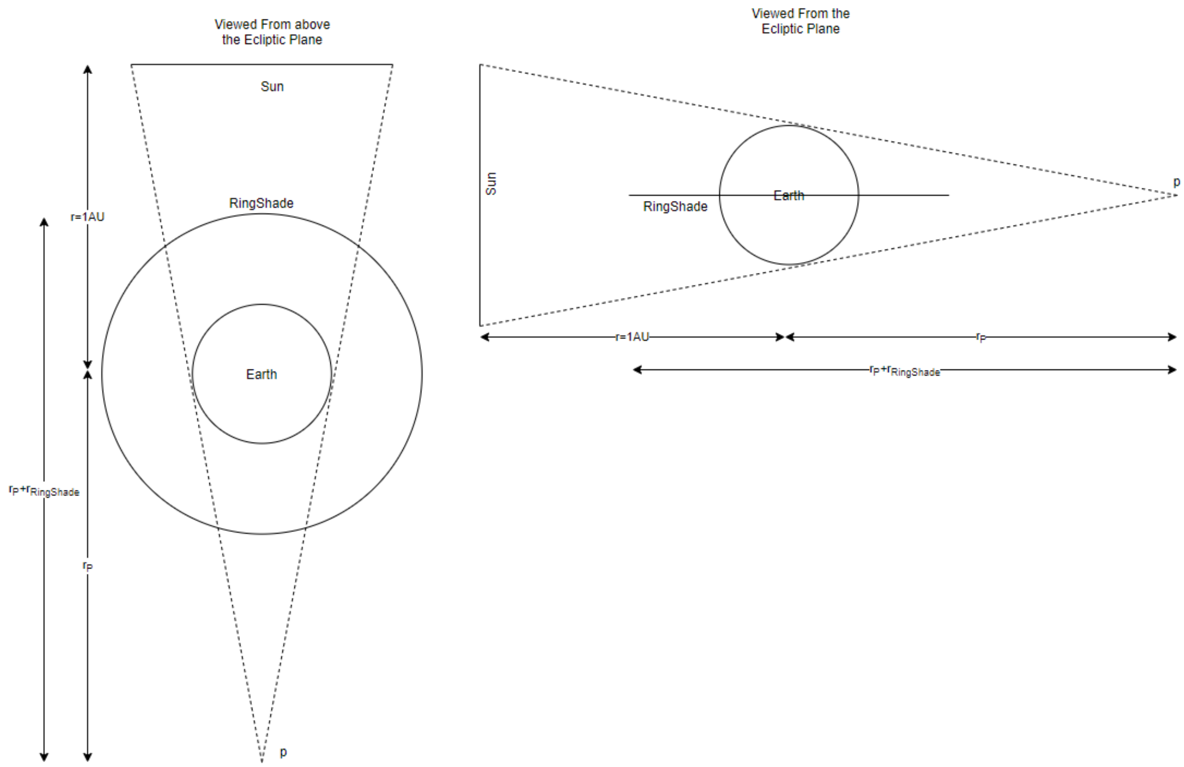

Fig. 2 Geometry of a sunshade ring, viewed from above the ecliptic, and from the ecliptic, not to scale.

This distance from Earth's center to point P, r_p, can be solved for with Equation 1 by setting the angular cross section of the Sun to the angular cross section of the Earth:

$$\Omega_{Sun} = \Omega_{Earth} = \frac{A_{Sun}}{(r_{AU}+r_p)^2} = \frac{A_{Earth}}{{r_p}^2} \tag{3}$$

Rearranging for r_p, we get:

$$(A_{Sun} - A_{Earth})r_p^2 - A_{Earth}r_{AU}r_p - A_{Earth}r_{AU}^2 = 0 \tag{4}$$

Solving the quadratic equation for r_P, we find the length of Earth's umbra to be ≅ 1,420,000 km.

To determine the height and corresponding cross section of the ring that functionally shades the Earth at an altitude, r_{ring}, we have to solve for the area again defined by 1.7e-6 [sr] to meet RPC8.5 or 3.8e-7 [sr] for RPC1.9. From point P, the approximate distance to the ring that is shadowing the sun is the sum of r_P, the radius of the Earth, and the altitude of the ring. Table 1 depicts resulting sizing estimates and rough order of magnitude mass of the rings. The resulting masses and areas are plotted in Figures 3 and 4.

Sunshade Ring Sizing Table													
Altitude Regime	LEO				MEO	GEO	Beyond GEO						
Altitude [km]	500	2500	7500	10000	18000	36000	72000	108000	144000	180000	216000	252000	288000
Distance From Ring to Point P [km] R_{SP} = Rp+Re+Alt	1,428,156.07	1,430,156.07	1,435,156.07	1,437,656.07	1,445,656.07	1,463,656.07	1,499,656.07	1,535,656.07	1,571,656.07	1,607,656.07	1,643,656.07	1,679,656.07	1,715,656.07
Full sr Cross-sectional Area at altitude [km^2] $A_{RingAlt} = \sqrt{((R_{SP})*5.8e-5)}$	11,776.99	11,793.48	11,834.72	11,855.33	11,921.30	12,069.74	12,366.60	12,663.47	12,960.34	13,257.20	13,554.07	13,850.93	14,147.80
Apparent Width of Sun at Altitude [km] $W_{AS} = \sqrt{(A_{RingAlt}/\pi)}$	122.45	122.54	122.75	122.86	123.20	123.97	125.48	126.98	128.46	129.92	131.37	132.80	134.21
Required area for RPC 8.5 [km^2] $A_{8.5}=\sqrt{(R_{SP}*1.7e-6)}$	1,862.11	1,864.71	1,871.23	1,874.49	1,884.92	1,908.39	1,955.33	2,002.27	2,049.21	2,096.15	2,143.09	2,190.03	2,236.96
Required Height for RPC 8.5 [km] $H_{8.5} = W_{AS}/A_{8.5}$	15.20660057	15.21724456	15.24382202	15.25709339	15.29948441	15.39443742	15.58260774	15.76853273	15.9522909	16.13395628	16.3135988	16.49128455	16.66707612
Required area for RPC 1.9 [km^2] $A_{1.9}=\sqrt{(R_{SP}*3.8e-7)}$	881.31	882.54	885.63	887.17	892.11	903.22	925.43	947.65	969.86	992.08	1,014.29	1,036.51	1,058.72
Required Height for RPC 1.9 [km] $H_{1.9} = W_{AS}/A_{1.9}$	7.197076976	7.202114632	7.214693383	7.220974541	7.241037634	7.2859776	7.375036049	7.463031814	7.550002053	7.635981806	7.721004162	7.80510041	7.888300168
Total Area of Ring for RPC 8.5 [km^2] $A_{Total8.5} = 2\pi(R_E+Alt)*H_{8.5}$	657,177.68	848,863.21	1,329,244.57	1,570,059.68	2,343,457.98	4,099,072.01	7,673,878.89	11,332,198.39	15,072,581.05	18,893,643.19	22,794,062.38	26,772,573.25	30,827,963.72
Total Area of Ring for RPC 1.9 [km^2] $A_{Total1.9} = 2\pi(R_E+Alt)*H_{1.9}$	311,033.25	401,755.40	629,113.36	743,087.87	1,109,126.75	1,940,034.96	3,631,942.38	5,363,375.18	7,133,647.36	8,942,104.04	10,788,119.33	12,671,094.35	14,590,455.43
Volume for RPC 8.5 [m^3] micron Thickness	657,177.68	848,863.21	1,329,244.57	1,570,059.68	2,343,457.98	4,099,072.01	7,673,878.89	11,332,198.39	15,072,581.05	18,893,643.19	22,794,062.38	26,772,573.25	30,827,963.72
Volume for RPC 8.5 [m^3] milimeter Thickness	6.57E+08	8.49E+08	1.33E+09	1.57E+09	2.34E+09	4.10E+09	7.67E+09	1.13E+10	1.51E+10	1.89E+10	2.28E+10	2.68E+10	3.08E+10
Volume for RPC 1.9 [m^3] micron Thickness	3.11E+05	4.02E+05	6.29E+05	7.43E+05	1.11E+06	1.94E+06	3.63E+06	5.36E+06	7.13E+06	8.94E+06	1.08E+07	1.27E+07	1.46E+07
Volume for RPC 1.9 [m^3] milimeter Thickness	3.11E+08	4.02E+08	6.29E+08	7.43E+08	1.11E+09	1.94E+09	3.63E+09	5.36E+09	7.13E+09	8.94E+09	1.08E+10	1.27E+10	1.46E+10
Mass for RPC 8.5 [tonnes], micron ρ=3,000 kg/m^3	1.97E+09	2.55E+09	3.99E+09	4.71E+09	7.03E+09	1.23E+10	2.30E+10	3.40E+10	4.52E+10	5.67E+10	6.84E+10	8.03E+10	9.25E+10
Mass for RPC 8.5 [tonnes], milimeter ρ=3,000 kg/m^3	1.97E+12	2.55E+12	3.99E+12	4.71E+12	7.03E+12	1.23E+13	2.30E+13	3.40E+13	4.52E+13	5.67E+13	6.84E+13	8.03E+13	9.25E+13
Mass for RPC 1.9 [tonnes], micron ρ=3,000 kg/m^3	9.33E+08	1.21E+09	1.89E+09	2.23E+09	3.33E+09	5.82E+09	1.09E+10	1.61E+10	2.14E+10	2.68E+10	3.24E+10	3.80E+10	4.38E+10
Mass for RPC 1.9 [tonnes], milimeter ρ=3,000 kg/m^3	9.33E+11	1.21E+12	1.89E+12	2.23E+12	3.33E+12	5.82E+12	1.09E+13	1.61E+13	2.14E+13	2.68E+13	3.24E+13	3.80E+13	4.38E+13

Table 1 Sunshade ring sizing table

It should be noted that most sizing options for the ring sunshade are larger than the estimate for the planetary sunshade at SEL-1. As a final consideration, the length of the umbra of these structures is shorter than their altitude. They would not totally eclipse the Sun until an observer is within 1500 km of them; however, the structures would be visible to observers on the Earth's surface and block significant amounts of light for observers directly below them, leading to regionally differentiated climate problems. The shadow of a ring inclined to the ecliptic will always fall below the Tropic of Cancer and the Tropic of Capricorn. As viewed from the equator during the summer solstice, the lowest LEO ring would cover 67% of the width of the Sun for an extended period of time. At MEO, this would be reduced to 10%, and to 5% at GEO. Even if such a large structure at the lowest LEO altitude we considered were deemed acceptable, the climate consequences could be unacceptable. An altitude below 1700 km results in a total eclipse of the Sun.

A ring sunshade below GEO should further be considered untenable because the delta-v requirements to bring space resources down the gravity well would approach that of Earth launched material. Finally, the threat of a Kessler syndrome should not be ignored. An engineering failure, sabotage, or a meteorite impact to a sunshade below GEO could lead to catastrophic results. It would be irresponsible for this reason alone.

At four times the altitude of GEO, the percentage of the sun covered is reduced to 1%, as seen from the equator on the summer solstice. At nearly halfway to the Moon, with a two-week period, the threat of a Kessler syndrome is much lower, and an argument could be made for building a fragmented or modular structure instead of building a ring structure. The equivalent area distributed across the plane of the ecliptic would still need to range from 7 million km^2 for RPC1.9 to 15 million km^2 for RPC8.5. But here, if the inclination relative to the ecliptic remains within +/- 1.33 degrees then the shading could be distributed north and south of the tropics, avoiding the other issues with a lower than GEO ring sunshade.

Another study utilizing a ring as a planetary sunshade exclusively analyzed out to three Earth radii [2]. Mautner noted that these ring sunshades would have orbital dynamic issues, which have only been partly addressed by more recent research into solar sailing, such as Halo orbits and Lyapunov orbits as described by Heiligers in Ref. [8]. Heiligers' solutions would be appropriate for modular, distributed structures beyond GEO, and for demonstration missions prior to departure to SEL-1.

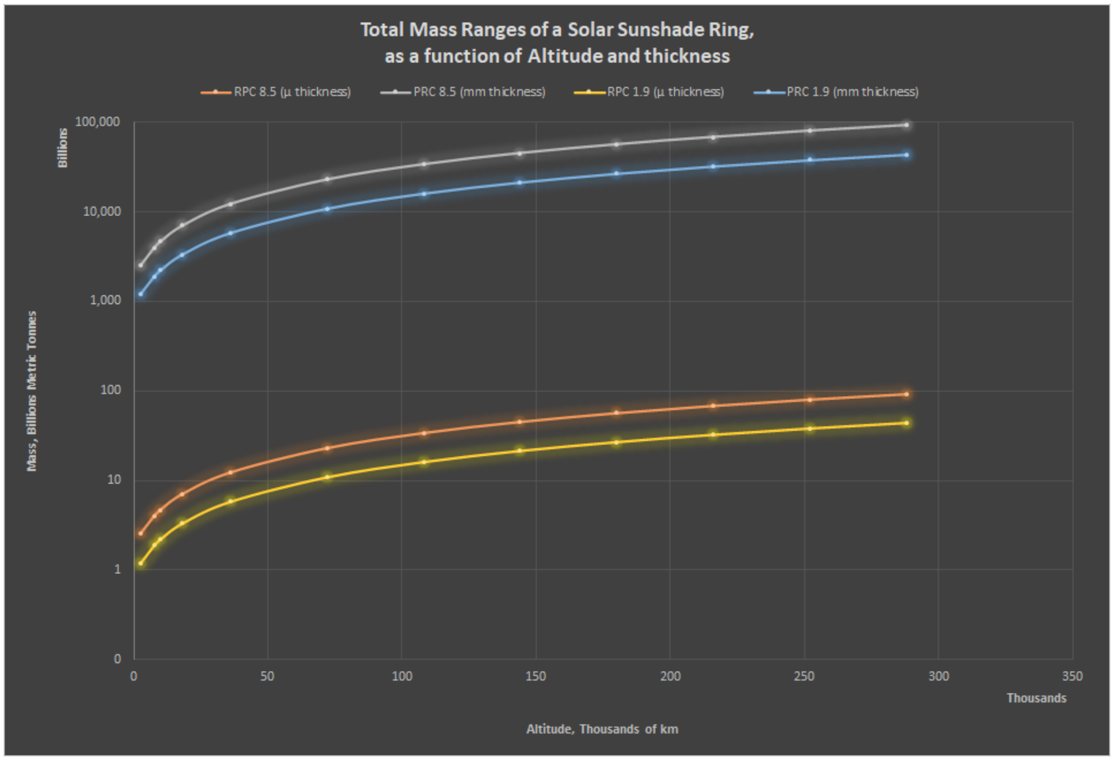

Fig. 3 Total mass ranges of a sunshade ring. Thickness requirements outweigh area requirements by three orders of magnitude.

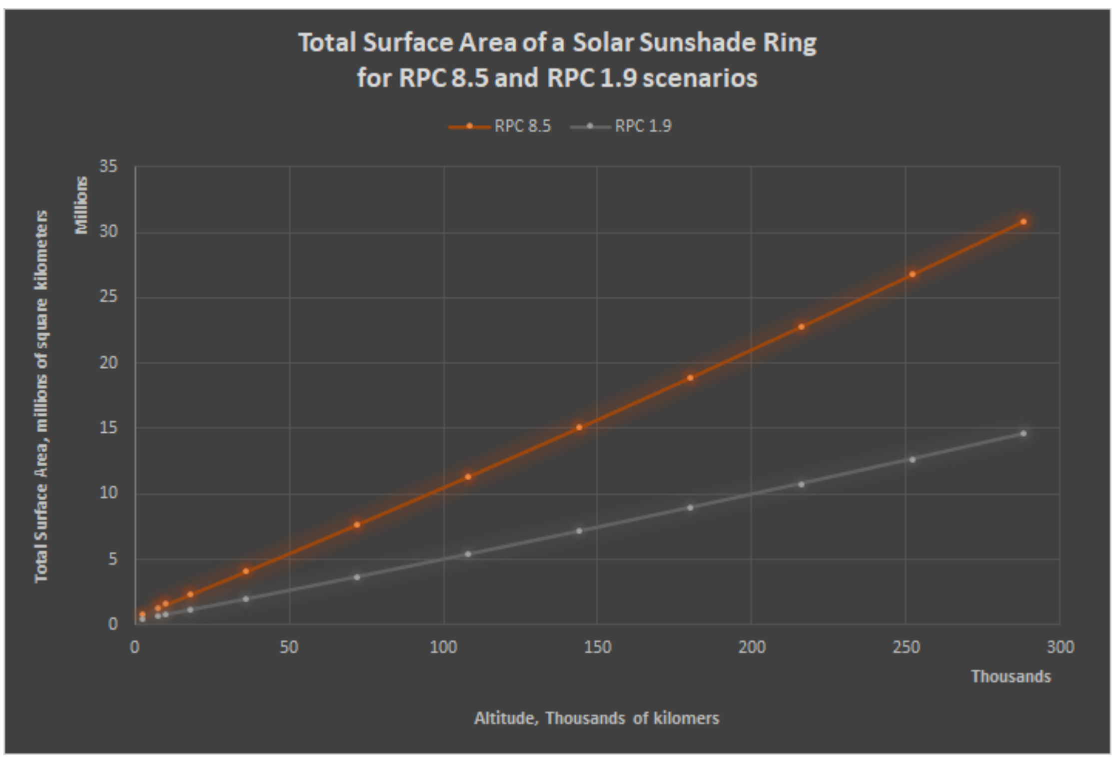

Fig. 4 Total surface area of a sunshade ring for RPC 8.5 and RPC 1.9 scenarios. Surface area roughly doubles between the climate forecast extremes.

Based on examination of these alternatives, it appears that a sunshade at SEL-1 is the best option.

III. Sunshade Architecture

Having determined that a planetary sunshade should be constructed at SEL-1, we can begin discussing an architectural concept to build it. Because the range of emissions forecasts varies over an approximately fivefold range in radiative forcing, the size of the required sunshade is unknowable at this time. Furthering uncertainty is the unknown degree of climate remediation that will be desired in the future; options less than restoration of a preindustrial climate may be desired, requiring a smaller sunshade**.**

Accordingly, we propose a sunshade design that is significantly smaller than that required to fully reverse global warming, but large enough to have a substantial effect on the climate and to adequately capture the scale of the endeavor. It is of modular construction, so that reasonably constructable components could be fabricated anywhere in cislunar space and assembled at SEL-1 into a larger sunshade. Our architecture concept is shown in Figure 5, a sunshade composed of 169 20km-sided hexagonal solar panels, which each have a surface area of 1,039 km^2. The sunshade has a total surface area of 175,630 km^2. Multiple such sunshades could be constructed, perhaps by individual nations working separately toward a common climate goal, with each sunshade functioning as an island in a sunshade archipelago.

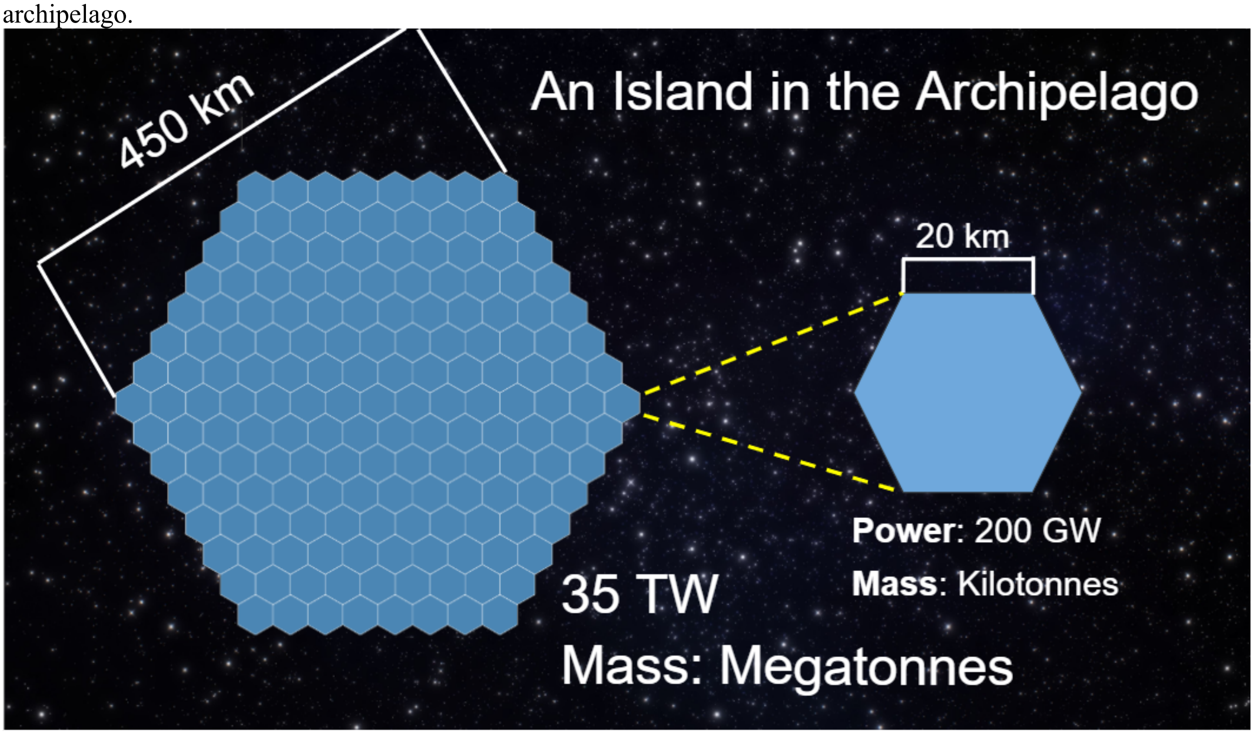

Fig. 5 Planetary sunshade island, composed of 169 20km hexagons. Five to 22 islands would be required to restore preindustrial average temperatures under RCP1.9 and RCP8.5, respectively.

One feature of an SEL-1 sunshade is that it is both scalable due to its modularity, and controllable as a solar sail. With a modular design, the proposed archipelago can be scaled up or down to meet geoengineering goals. When a sunshade is no longer needed, it can be flown away from SEL-1 deliberately, or rendered nonfunctional by ceasing to maintain the minimal station-keeping delta-v budget. Any orbit about SEL-1 is a Lissajous orbit, orbiting above and below the ecliptic, and can survive for extended periods of time with solar radiation pressure station-keeping. A sunshade could then survive at SEL-1 so long as the materials the sunshade are made of survive.

A thin filmed megastructure without significant additional structures (omitting mining and processing facilities) could have a wide range of average thickness, between a micron and a millimeter. As the majority of the sunshade's materials will be either mined from the Moon or directly from asteroids, we assume the average density of the planetary sunshade will be at the lower end of the density of an ordinary chondrite (3,000 kg/m^3). This establishes the range of volume and mass of one island as between $1.75e^5$ and $1.75e^8$ m^3 and 525 kilotonnes and 525 megatonnes (a significant mass range!). The majority of this mass can be sourced from the Moon and ordinary chondrite asteroids (the most common asteroid), as described in the next section.

If an island includes a toroidal habitat for living and manufacturing in space, such as a single toroid as proposed in NASA's 1975 Space Settlements [9], an additional 200 kt would be needed per toroid. These toroids can be combined to create banded toroidal settlements as well, scaling linearly, depending upon the population needs of the settlement. If all 700+kt of mass were sourced from Earth, this would be a wasteful undertaking, when instead we could use that mass budget to build a resource economy in space.

IV. Space Resources Utilization Plan for the Planetary Sunshade

When the Sunshade concept was initially conceived, the plan was to build it on Earth from ultra-lightweight thin film materials. One proposed sunshade architecture [4] is composed of millions of 'flyers,' each one meter in diameter and weighing about one gram, made of refractive screens constructed on Earth. The total mass of the system is a minimal 20M tonnes. Assuming SpaceX achieves their stated Starship design and cost goals (100 tonnes to LEO for $2M per launch), a sunshade mass of 20M tonnes would require 200,000 Starship launches, totalling $400B in launch costs alone. Once in LEO, the flyers would still require propulsion to SEL-1. If sunshade launches monopolized the entire capability of the Starship fleet (1,000 ships each launching three times per day), it would take over 66 years to launch the mass needed. Extracting, processing, and manufacturing the raw materials on Earth would also contribute to terrestrial pollution and exhaust products from Starship's methane engines would further add to Earth's atmospheric carbon burden; neither of these outcomes is desirable for an initiative that aims to preserve Earth's environment. Fortunately, all the resources required to construct the sunshade exist in cislunar space.

The planetary sunshade represents the ultimate bull case for the establishment of a cislunar economy based on space resources. There are three elements to a space resource utilization plan:

1. economically extractable resources;
2. technologies to extract, process, and deliver the resources, and;
3. customers willing to pay for it.

A. Resources

The resources present in cislunar space are vast and varied. The simplest and most abundant resource in space is sunlight. At 1AU from the Sun, 1360 W/m^2 of solar irradiance is available to provide energy to power spacecraft, extraction and processing equipment, and manufacturing facilities. Location in space is also a type of resource. LEO is a very useful location for staging propellant refueling activities and performing technology demonstrations. Lagrange points, both in the Sun-Earth system and the Earth-Moon system, provide stable locations for deep-space manufacturing and, in the case of SEL-1, the location for the sunshade itself. The characteristics of deep space itself can also be favorable for manufacturing. Hard vacuum, microgravity, and the coldness of space are all resources to be used in various types of manufacturing, from vacuum deposition to the growth of perfect crystals.

The first physical resources from space will likely be sourced from the Moon. As our closest celestial neighbor, the Moon has been studied extensively by orbiting spacecraft, rovers and landers from several countries, impactors into the poles, and the astronauts of the Apollo missions. Civil space agencies around the world are studying the Moon and its resources to advance their human exploration goals, either as a stop on the way to Mars or as a destination unto itself. Lunar rocks and regolith are rich in silicates and metal oxides [10]. Minerals can be extracted from the rocks and used to make glass, titanium, aluminum, iron, and other structural materials. Oxygen and other volatiles can be separated out and used for crew life support, propellant, and extraction and manufacturing processes. KREEP soil is also a source of rare Earth elements, which will be useful in producing space-based electronics. The permanently shadowed regions (PSRs) of lunar poles also contain up to 30%wt water ice [11]; in addition to use for crew life support, water can be electrolyzed to produce hydrogen and oxygen for propellant.

The resources from near-Earth objects (NEOs) are more varied than those on the Moon, although they are not as well understood. There are potentially hundreds of millions of NEOs, varying in size from a few meters to more than one kilometer in diameter. There are several benefits to extracting resources from NEOs compared with the Moon. First, is the relative location of NEOs. The energy (delta-v) to reach NEOs and send materials back to be manufactured is relatively low; the energy required to move them to SEL-1 is substantially less than that to move them down Earth's gravity well. There may be an additional temporal advantage to SEL-1; its non-Keplerian orbital period may provide more frequent synodic opportunities for capturing sunward NEOs (Atiras). SEL-1 is also a safe place to move and 'park' asteroids for subsequent processing. An asteroid parked at SEL-1 would provide a steady, nearby source of materials for sunshade production, and its stable orbital location is easy to maintain with little station-keeping; it is also an orbit where the asteroid would pose little threat to Earth.

The second benefit is the composition of the asteroids themselves. Carbonaceous chondrite asteroids, the most common type of NEO, contain hydrated minerals, which can provide water for propellant or life support. They also contain hydrocarbons and organic compounds, which are not common on the Moon. Less common are stony asteroids, which are a mix of silicates, sulfides, and metals. The rarest type of NEOs are metallic asteroids, which contain large quantities of pure metals as well platinum-group metals such as rubidium and platinum [12]. Due to their varied material composition and convenient access to SEL-1, asteroidal resources will prove a valuable complement to lunar materials. However, our understanding of NEOs is limited compared to the Moon. Prospecting asteroids is more challenging than prospecting the Moon, which has been studied by orbiting spacecraft, landers, rovers, and human astronauts. Simply finding viable asteroids, which are typically small and dark, is difficult, and determining their composition to a high degree of accuracy could require expensive ground-truth missions. However, due to their abundance and variety of resources, NEOs will be a viable source of resources in the later stages of sunshade production.

Due to the scale of the planetary sunshade, any and all resources from cislunar space could be used in its construction. Metals, such as aluminum, iron, and titanium, could be used to produce structural members. Silicon will be used to produce photovoltaics, glass, and electronic components. Water can serve many functions, including as life support and radiation shielding for human crews and propellant for in-space transportation. Even "space junk," such as defunct spacecraft and spent upper stages, can be harvested for electronics and other components. Islands within the sunshade archipelago may be built by different entities and made from different materials, increasing the variety of profitable resources. The materials and design of the sunshade is also likely to evolve during construction. The sunshade may initially require Earth-supplied components that are phased out as off-Earth resource extraction and manufacturing is established. Resources that initially come from the Moon may be later supplied from asteroids as the supply chain extends further out from Earth.

B. Technologies

The planetary sunshade is a space resource megaproject and utilizes the entire space resource technology stack at a scale otherwise unlikely to be economically feasible. The sunshade is an "all of the above" use case for cislunar space resources, and therefore it also requires an "all of the above" approach to the technologies used to extract, process, transport, and manufacture those resources.

The first technologies to be matured will be resource extraction and in-space manufacturing of thin film photovoltaics. These technologies represent both ends of the space resource logistics chain: initial resource extraction and final structural manufacturing. Both of these technology areas are currently in development within academia, civil space agencies such as NASA and ESA, and by private companies. Maturing these technologies will require technology demonstrations such as small-scale resource extraction from the surface of the Moon and LEO photovoltaic manufacturing using Earth-launched materials. As these early technologies develop, they will flow towards the middle of the logistics chain. Resource extraction will lead to resource processing (for example, water extraction will lead to water purification and electrolysis to produce hydrogen and oxygen), and manufacturing will begin to use space resources rather than terrestrial. As resource extraction, processing, and manufacturing ramp up to operational levels, cislunar logistics will be required to transport materials from their point of origin to SEL-1 for manufacturing. Establishing cislunar logistics will require technologies such as orbital refueling from propellant depots, development of tugs to move materials through space, launch capacity from the lunar surface (whether using chemical propellants or something new like a mass driver), and the implementation of a traffic control network to track and communicate with assets throughout cislunar space, and the corresponding space domain awareness. Once manufacturing at SEL-1 is established using lunar resources and the demand for materiel increases, asteroidal resources could be brought online using technologies such as asteroid bagging, optical mining, or asteroid redirection. Enabling the development of all these space technologies will be improvements in heavy launch from Earth. Frequent, inexpensive launch from Earth will enable rapid design iteration and implementation of technologies across the space resource value chain.

C. Customer

Climate change is not a new problem for humanity. We have known for decades that increasing carbon in the atmosphere will cause an imbalance in Earth's energy budget, leading to global warming. However, humanity has thus far been unable to even slow the pace at which we add carbon to the atmosphere, much less begin the lengthy process of removing carbon. Clearly, global warming is a problem in need of a viable solution. Likewise, the idea of in-space resource utilization to achieve commercial and exploration goals is not new. The idea has been around for decades, and yet we have never successfully extracted a resource from space for use in space (apart from solar energy used to power spacecraft). The reason for this is because, with the laudable exceptions of United Launch Alliance and NASA (though so far not at a price sufficient to make a market), no customer has emerged to buy space resources on the scale needed to justify the huge investments necessary to develop the technology to find, extract, and process these resources. Space resource utilization is a solution that has yet to be applied to the right problem. The planetary sunshade marries the problem (global warming) to the solution (space resources) in a way that benefits both the Earth and the establishment of a cislunar economy. The customers for the planetary sunshade will be the customers for space resources.

The customers for the planetary sunshade are everyone on Earth who will be impacted by global warming: in short, everyone on Earth. World governments, under pressure from citizens concerned about climate change, will take action to fund the development of climate change solutions. This may seem impossible today, but the fact of today's inaction simply escalates the climate crisis, with thermodynamic inevitability; at some point, the impossible will become inevitable.

V. Conclusion

With all of humanity the customer of the planetary sunshade and governments funding it by fiat the planetary sunshade becomes an achievable solution to climate change without introducing terrestrial side effects.

Governments should fund space resource prospecting, extraction, processing, and manufacturing efforts that contribute to the goal of establishing individual hexagonal shades within the next decade, with an exponential mindset towards resolving climate change in near real time. As the climate crisis escalates, the world will find the consequences intolerable. A planetary sunshade and habitat constructed from space resources connects humanity's need for a stabilized climate and ecological restoration of Earth with a future in space, beyond the limits to terrestrial growth.

References

[1] Emissions Gap Report 2019. (2019). UNEP - UN Environment Programme. https://www.unenvironment.org/resources/emissions-gap-report-2019

[2] Mautner, Michael Noah. "A space-based solar screen against climatic warming." Journal of the British Interplanetary Society44 (1991): 135.

[3] McInnes, Colin R. "Minimum mass solar shield for terrestrial climate control." JBIS 55 (2002): 307-311.

[4] Angel, Roger. "Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1)." Proceedings of the National Academy of Sciences 103.46 (2006): 17184-17189.

[5] Sánchez, Joan-Pau, and Colin R. McInnes. "Optimal sunshade configurations for space-based geoengineering near the Sun-Earth L 1 Point." Plos one 10.8 (2015): e0136648.

[6] Govindasamy B, Caldeira K. Geoengineering Earth's radiation balance to mitigate CO2-induced climate change. Geophysical Research Letters. 2000; 27(14):2141–4.

[7] Irvine P. et al., Halving warming with idealized solar geoengineering moderates key climate hazards. Nature Climate Change, 2019.

[8] Heiligers, J. Hiddink, S. Noomen, R. and MInnes, C. R. (2015). Solar sail Lyapunov and Halo orbits in the Earth–Moon three-body problem. Acta Astronautica. Volume 116, November-December 2015 Pages 25-35. https://www.sciencedirect.com/science/article/abs/pii/S0094576515002295

[9] Johnson, Richard D., and Charles H. Holbrow, eds. Space settlements: A design study. Vol. 413. Scientific and Technical Information Office, National Aeronautics and Space Administration, 1977.

[10] Heiken, G., Vaniman, D., French, B. M., & Schmitt, J. (1991). Lunar Sourcebook: A User's Guide to the Moon (1st ed.). Cambridge University Press.

[11] Li, S., Lucey, P. G., Milliken, R. E., Hayne, P. O., Fisher, E., Williams, J.-P., Hurley, D. M., & Elphic, R. C. (2018). Direct evidence of surface exposed water ice in the lunar polar regions. Proceedings of the National Academy of Sciences, 115(36), 8907–8912. https://doi.org/10.1073/pnas.1802345115.

[12] Rossi, A. P., & Gasselt, V. S. (2017). Planetary Geology (Springer Praxis Books) (1st ed. 2018 ed.).