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Solar radiation management with a tethered sun shield

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This paper presents an approach to Solar Radiation Management (SRM) using a tethered solar shield at the modified gravitational L1 Lagrange point. Unlike previous proposals, which were constrained by the McInnes bound on shield surface density, our proposed configuration with a counterweight toward the Sun circumvents this limitation and potentially reduces the total mass by orders of magnitude. Furthermore, only 1% of the total weight must come from Earth, with ballast from lunar dust or asteroids serving as the remainder. This approach could lead to a significant cost reduction and potentially be more effective than previous space-based SRM strategies.

solar radiation management | sun shield | climate change

Climate change is a looming threat to the way of life for a significant fraction of humanity (1). As "greenhouse gases" such as CO_2 and methane increase in the atmosphere, it retains a larger fraction of solar energy (2, 3). Solar radiation management (SRM) is a geoengineering approach (4, 5) that aims to reduce the amount of solar radiation absorbed by the Earth to mitigate the effects of climate change. Two strategies proposed for SRM involve adding dust or chemicals to the Earth's atmosphere to increase the reflected fraction of sunlight (6–8) or reduce the incoming radiation from space with solar shades (9–12) or dust (13).

Despite the potential of SRM to mitigate the effects of climate change, it has faced criticism e.g., ref. 14. Nevertheless, given the severity of the problem, any avenue that might lead to the partial mitigation of a catastrophe should be investigated. Since modifying the Earth's atmosphere appears riskier, we focus on space-based SRM strategies next.

One of the biggest hurdles for proposals aimed at blocking a small fraction of sunlight from space is weight. In space, weight translates into unrealistic costs. The preferred location for a sunshade is beyond the L1 Lagrange point toward the Sun, where the solar radiation pressure and gravity of the Earth and the Sun are in balance. Advances in light materials, such as graphene, could produce extremely light solar shades, similar to solar sails (15). These could be lifted into space at a relatively modest cost. Unfortunately, any such structure is subject to the McInnes bound (16): the balance of the gravitational forces and solar radiation pressure sets a minimum weight or, equivalently, a minimum surface density for a shade to be in equilibrium beyond the L1 point. The minimum surface density required is orders of magnitude above that of graphene, making a significant cost reduction infeasible with this emerging technology.

The gravitating mass of a shield must be inside the L1 point, while the efficiency of a shield increases toward the Earth. Dropping the constraint that the two are in the same location, this paper proposes a configuration to overcome the McInnes bound: a tethered sun shield with a counterweight toward the Sun. The total weight of our proposed shield can be significantly lower than the McInnes bound. Moreover, only the shield structure weighing 1% of the total must come from Earth. Lunar dust or material from asteroids can serve as ballast. Therefore, the needed work (potential difference times mass) and thus the cost can be many orders of magnitude below the McInnes limit. As such, our solution offers a promising avenue to address the challenges of climate change.

In the next section, we sketch out our proposed configuration and provide an approximate calculation demonstrating how it circumvents the McInnes bound. The final section summarizes the results and discusses some of the caveats.

Sun Shields

Tetherless Shields. The L1 Lagrange point is about 1.5×10^6 km from Earth, which is 1% of the Earth–Sun distance. It is a preferred location to park satellites since the Sun and Earth's gravity are balanced. It is also a natural place for a sun shield (9). Note that the L1 point is weakly unstable along the Sun–Earth axis and stable in the perpendicular plane.

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For a solar screen, the solar radiation pressure will modify the point where all the forces are in balance (9). The lighter the screen, the closer the balance point shifts from L1 toward the Sun. The following equation determines the equilibrium orbital radius r:

$$r\omega = \frac{GM_\odot}{r^2} - \frac{GM_\oplus}{(r_\oplus - r)^2} - \frac{L_\odot}{4\pi r^2 c\sigma}, \qquad [1]$$

where $M_\odot$ and $M_\oplus$ are the mass of the Sun and the Earth, respectively, $r_\oplus$ is the distance of the Earth from the Sun (1AU), $L_\odot$ is the solar luminosity, and σ is the surface density of the shield. G is the gravitational constant, and c is the speed of light. Since the radiation pressure has the same $1/r^2$ dependence as gravity, far from the L1 point, it no longer helps to get closer to the Sun. We can generalize the above equation for the possible range of optical properties of the shield by replacing σ with an effective surface density σ/Q. In our notation, $Q = 0, 1$, and 2 correspond to full transparency, perfect absorption, and perfect reflection, respectively. Consequently, there is an asymptotic minimum surface density for a shield (*Top* dots on Fig. 1), while the density diverges at the L1 point itself. The lowest surface density from the standard configuration is 4 to 6 orders higher than the lightest graphene material envisioned for solar sails (15).

To calculate the mass of a shield that achieves a certain amount of reduction, we must consider the efficiency as it changes with distance r and the corresponding shield radius R. The simplest approximation comes from the solid angle of the shield as viewed from Earth (17),

$$R = R_\odot \frac{r_\oplus - r}{r_\oplus}\sqrt{\frac{\Delta S}{S}}, \qquad [2]$$

where $R_\odot$ is the radius of the Sun, and $\Delta S/S$ is the targeted decrease of the solar flux. For a standard goal of reduction of $\Delta S/S \simeq 1.7\%$, there is a minimum mass c.f., refs. 12, 16, and 17, and Fig. 2. The optimal configuration is about 2.4 Mkm from the Earth toward the Sun. The minimum mass is a few hundred Mton. We aim to find an alternative arrangement for lighter shields to exploit available technology such as graphene.

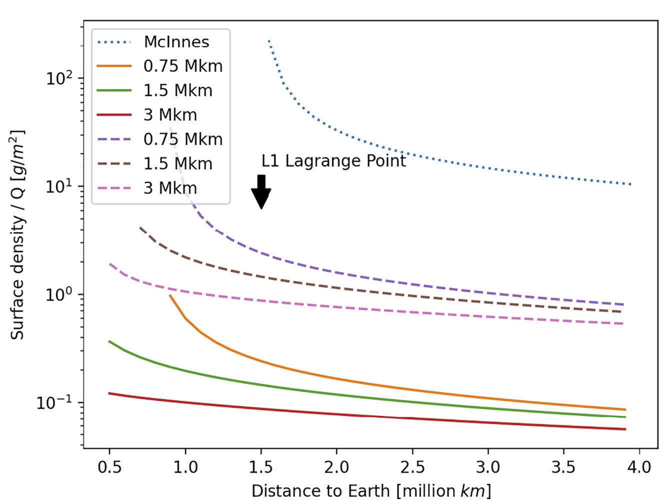

Fig. 1. Surface density as a function of shield distance to Earth. Q characterizes the reflective properties of the shield. The dots show the solution of Eq. **1**, and the dashes and solid lines correspond to shield counterweight ratios of 10 and 100, respectively. The two series of curves show tether lengths of 0.75 Mkm, 1.5 Mkm, and 3 Mkm from *Top* to *Bottom*. An arrow marks the distance of the L1 point. The fiducial graphene surface density 8.6×10^{-4} g/m^2 with reflectivity $Q = 1.99999$ from ref. 15 is about two orders of magnitude below the lowest curve on the figure.

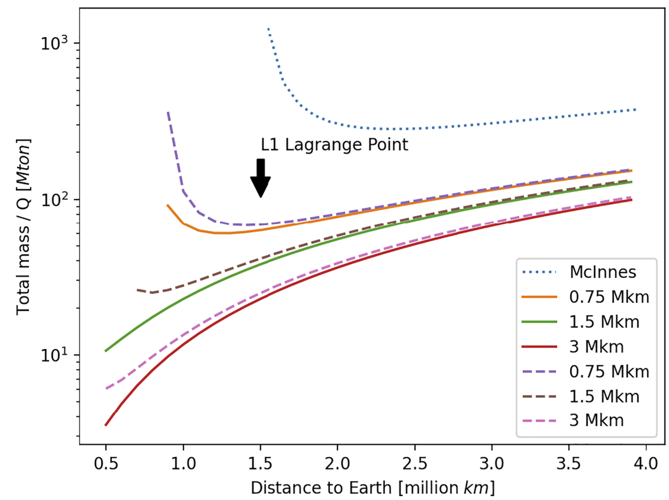

Fig. 2. Total mass as a function of shield distance to Earth for the fiducial $\Delta S/S = 1.7\%$ solar radiation reduction. Q characterizes the reflective properties of the shield. The dots show the solution of Eq. **1**, and the dashes and solid lines correspond to shield counterweight ratios of 10 and 100, respectively. The two series of curves show tether lengths of 0.75 Mkm, 1.5 Mkm, and 3 Mkm from *Top* to *Bottom*. Higher mass ratios would yield marginal gain. An arrow marks the distance of the L1 point.

A Tethered Shield Concept. We modify the standard shield balancing gravity and the solar radiation pressure at a modified Lagrange point as envisioned by ref. 9. We attach a lightweight tether to the shield with a counterbalance mass placed toward the Sun. For the generalization of Eq. **1**, we neglect the weight of the tether. We assume two parameters: α is the ratio of the counterweight to the shield mass, while r_c is the length of the tether to the counterweight. The equation for balance is now the following:

$$\begin{aligned}\alpha(2r - r_c)\omega = & GM_\odot\left(\frac{1}{r^2} + \frac{\alpha}{(r-r_c)^2}\right) \\ & - GM_\oplus\left(\frac{1}{(r_\oplus - r)^2} + \frac{\alpha}{(r_\oplus - r + r_c)^2}\right) \\ & - \frac{L_\odot}{4\pi r^2 c\sigma}.\end{aligned} \qquad [3]$$

As before, σ represents the effective surface density σ/Q. The dashes and solid lines on Fig. 1 show the results for $\alpha = 10, 100$, respectively. The two series of curves correspond to $r_c = 0.75$ Mkm, 1.5 Mkm, and 3 Mkm from *Top* to *Bottom*. For our tethered configurations, the surface density diverges way inside the L1 point for shield positions (while the counterweight is still outside the L1 point). We stop solving the equation at $r_\oplus - r = 0.5$ Mkm to keep the shield safely outside the Moon's orbit $r_\circ \simeq 0.384$ Mkm. Note that the Moon's gravity is negligible at the level of our approximations.

Using Eq. **2**, we can calculate the total mass for our solution. For larger tether sizes, the minimum point would be closer than 0.5 Mkm. Nevertheless, we can achieve up to two orders of magnitude reduction at that point compared to the McInnes bound. We note that $\alpha \simeq 100$ is close to saturating the mass limit, although the fraction of the screen itself could be lowered further. Moreover, according to Fig. 1, the required surface density is still several orders above the surface density of graphene, leaving plenty of weight for the support structure of the shield.

For these approximate calculations, we neglected the weight of the tether. Assuming a tensile strength 130 GPa, the mass of the most extended tether at $r_\oplus - r = 0.5$ Mkm for $\alpha = 100$ is of order 10 kTon, a negligible fraction of the approximately 3.5 Mton total weight of the structure.

1. Summary and Discussion

A tethered sun shield yields up to two orders of magnitude of total mass reduction over the McInnes bound. The shield will likely be manufactured on Earth, about 1% of the total mass (and this fraction could even be lowered in principle). Moondust or asteroids can supply the rest for the counterweight. Therefore, only about 35 kTon (or less) needs to be transported from Earth. Using available material in space will result in significant cost savings, similar to the proposal of ref. 13. However, our structure is permanent and controllable compared to the $\simeq 10^{10}$kg dust at L1 that has to be continuously resupplied.

This conceptual paper aims at an order of magnitude estimate. We used Eq. **2** instead of a more accurate ray tracing (17). Furthermore, we neglected engineering details, such as placing and keeping the structure in orbit, contingencies for a breaking tether, etc. Next, we speculate about some of these issues qualitatively.

While simulations suggest that about 1 to 2% of irradiation must be shielded to counteract greenhouse effects causing global warming (4), a more cautious approach would use historical data. During the "little ice age," the total output of the Sun lowered by about 0.24% (18), while the global temperature decreased by about 0.5 to 0.6 °C. Therefore, a gradual approach with multiple components achieving 0.24% or less and expanding further after verification will be safer. Since the shield mass scales linearly with the desired solar flux reduction, Fig. 2 trivially rescales for any goal distinct from our fiducial 1.7%.

Given the nonlinearity and unpredictability of geoengineering, a modular and reversible approach is optimal. Thus, several smaller shields are preferable over a single shield, even for the initial subgoal. Each shield could open up in a petal configuration when placed near its orbit and connected to a structure holding the tether and the counterweight. A slow opening allows the gradual filling of the counterweight with lunar dust or asteroid material.

Any structure in L1 is mildly unstable along the Sun–Earth axis requiring active control. Manipulating the length of the tether is an opportunity for orbit maintenance without fuel. The counterweight should use solar-powered winches to lengthen or shorten the tethers to counteract the Moon's and solar wind's destabilizing effects. If several shields rotating around the L1 point connect to the same counterweight, changing incidence angles with several tethers achieves active control of the synchronized rotation to avoid tangling.

The shield has enough weight to wreak havoc if it accidentally crashes on Earth. If multiple tethers hold the shield, breaking one or two would not create an accident. When down to two tethers, the shield automatically turns away from the solar radiation (like a sail when the rigging breaks), and the counterweight pulls the structure safely toward the Sun. The structure would be lost in the worst case, but the security threat to Earth is negligible.

The main technological hurdle to implementing a tethered solar shield is the existence of sufficiently robust tethers. The technology is identical to space elevators, although an order of magnitude longer tether is needed. The rest of the required technologies will be available soon. Present-day technology could produce the graphene shield needed, although the cost would be high. Graphene cost is about $\$100/\text{m}^2$ today, but if the current trends continue, it could become $\$1/\text{m}^2$ in a decade. NASA expects launch costs to go down to "$10's per kg"; therefore, launching the 35 kTon for the shield itself, about twice in orbit today, appears achievable soon. A permanent Moon base and/or asteroid orbit manipulation can supply the ballast material for the counterweight at a reasonable cost. Sustained R&D must start now to produce an engineering solution in time as an insurance policy: A tethered shield can always be deployed if other efforts to mitigate climate change fail.

Depending on the parallel and intertwined development of graphene, tether, and orbital technologies, a tethered shield might initially be faster and cheaper to realize than a heavier structure satisfying the McInnes bound. Nevertheless, the latter might eventually serve as a solar energy source for Earth or solar system exploration.

Data, Materials, and Software Availability. All study data are included in the main text.

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