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Space Bubbles: The Deflection of Solar Radiation Using Thin-Film Inflatable Bubble Rafts

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Abstract

Due to the urgency of climate change and our inability to reduce emissions on Earth, geoengineering is increasingly being considered a viable alternative to tackling the issue of global warming. However, most current geoengineering proposals are considered to be risky due to their intervention with the Earth's atmosphere. As a safe alternative, the MIT Senseable City Lab is exploring a solar geoengineering approach based on a large raft of thin-film spheres positioned at the Lagrangian point between the Earth and the Sun. The project takes inspiration and surpasses similar research by James Early and Roger Angel regarding deployment complexity and efficiency. In this chapter, we describe the overall approach and lay out the significant scope of research work for the next few years.

Keywords: Solar geoengineering, space sunshade, Lagrangian point, thin films

21.1 Introduction

The Senseable City Lab focuses its research on how digital technologies and real-time systems can integrate into the built environment to address the rising climate challenges. Over the years, the lab has cultivated a novel approach to urban science, considering cities as complex systems applying tools from graph theory, big data, deep learning, and network algorithms. Bringing a diverse spectrum of designers, sociologists, and architects on one side and mathematicians, natural scientists and programmers on the other has allowed us to uncover several possible paradigm shifts in shared traffic flows, energy consumption and storage, urban communication and the immediate impact of technological changes on human living [21.1]. Despite the success of these projects, one significant discovery has become clear to us: a radical reinvention of urban infrastructures, even if achieved in today's intermittent global coordination climate, is not enough to tackle the increasingly dangerous effects of climate change. As our project portfolio has evolved, so too have the updated climate predictions that have been growing more pessimistic each year against the increasingly chaotic climate summits [21.2]. If the pessimistic predictions of a drastic

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temperature hike and corresponding climate disasters were to come true by the end of the century, do we have an emergency solution?

Having built expertise in interdisciplinary collaboration and cross-cutting between disciplines, we began looking for more fundamental and impactful solutions beyond the scale of urban infrastructures—and beyond the Earth's surface altogether. State-of-the-art geoengineering emerged as an unlikely resort. The traditional schemes of deploying aerosols in the Earth's atmosphere were based on directly interfering with the complex—and still greatly underexplored—physics of the atmosphere and were chiefly irreversible as they relied on the simple release of small greenhouse gas particles into our living environment [21.3] [21.4].

In search of a simpler yet fundamental solution, we considered the opportunity to engineer beyond the Earth's atmosphere. Despite the seemingly radical and adventurous nature of the problem, the precedent of scientific inquiries into space-based geoengineering appear to be older than the international climate change movement. Already in the 1980s, J.T. Early of Lawrence Livermore National Laboratory, conceived of a thin-film solar shield. According to Early's calculations [21.5], offsetting just 1.8% of the incident radiation would be sufficient to reverse the temperature hike and return to pre-industrial temperature levels. Early envisioned the raft to be located at the Earth-Sun Lagrangian point L1, a place where the gravitational attraction from the Earth and the Sun is balanced out, and the raft could be stabilized (Figure 21.1).

While Early's papers laid the foundations for the fundamental calculations associated with a solar sunshade, the 10-trillion-dollar budget and the technical challenges associated with deploying a large screen prevented the project from being realized. This, nevertheless, paved the way for further explorations. In 2006, Roger Angel at the University of Arizona conceived of a solar sunshade that consisted of trillions of thin and light satellites (Figure 21.2),

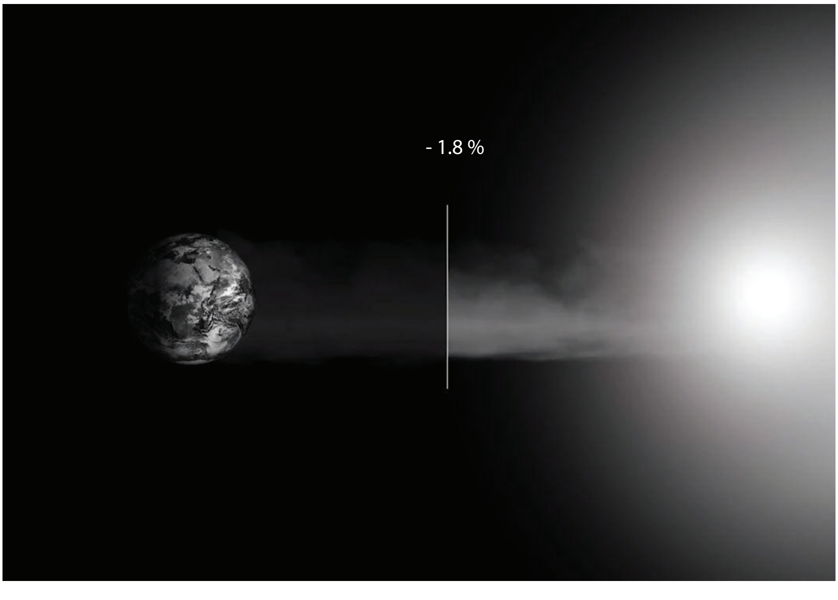

Figure 21.1 A schematic diagram representing the impact of a sunshade, placed so as to offset (or block) 1.8% of incident solar radiation at Earth. The scale of the Sun and the distances are diminished for clarity of concept, and the sunshade is located at the Earth-Sun L1 point.

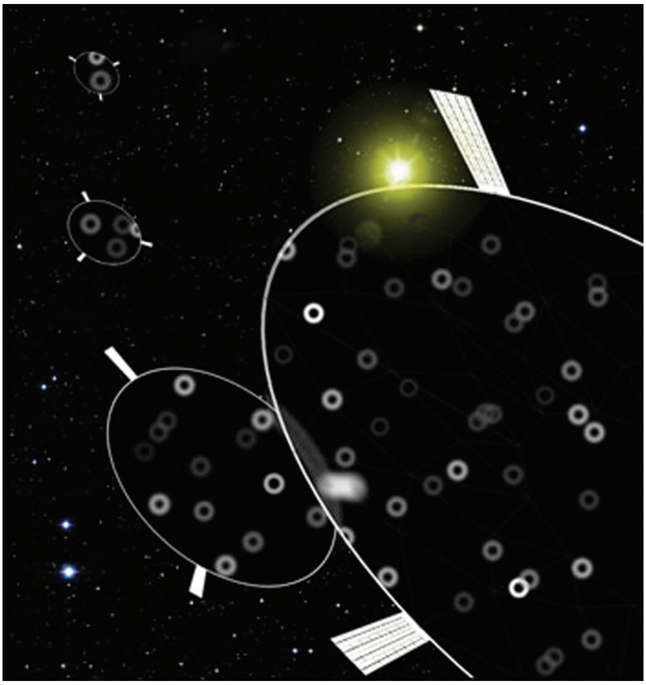

Figure 21.2 Schematic image of satellite components in the sunshield proposed by Roger Angel [21.6]. Each transparent filament would be about 60-cm across, with 10-cm protruding fins allowing for energy gathering and position adjustment. Each disk would act like a small lens and focus a small amount of solar radiation away from the Earth. (Image courtesy of Roger Angel and Steward Observatory, University of Arizona).

each carrying a thin fragment of a large shield [21.6]. The proposal involved assembling the small robots and dispatching them to the Lagrangian point, which still posed a challenging technical problem and involved a bloating budget of several trillion dollars.

21.2 A Bubble Sunshade

At MIT, we decided to revisit Angel's idea and brainstormed a fundamentally simple and lightweight solution for the task of balancing thin reflective films in space, abstracting from the cumbersome satellite assemblies or large supporting frames. We have found the solution in the simplest and most fundamental geometrical volume: a sphere. Across a wide scale of natural systems, a fluid spherical film—more familiar to us as a "bubble"—is capable of stabilizing itself at the smallest possible thickness due to surface tension and Marangoni effects. A thin film within a bubble can thus achieve the optimal thickness of a few nanometers without the relatively heavy mechanical support infrastructure. A swarm of trillions of liquid bubbles can outperform a trillion separate satellites in terms of mass, cost, and deployment complexity.

To make this concept work, we had to think about how to make such "bubbles" work in outer space—i.e., at zero atmospheric pressure and near-zero atmospheric temperature with aggressive solar radiation flux incident on the surface. A basic look at phase diagrams for water [21.7] shows that it evaporates at low pressures unless cooled down significantly.

We considered a multi-stage workflow where a bubble is produced at a sufficiently high pressure and temperature where the material can remain fluid. Subsequently, it is instantly frozen and lowered to near-zero temperature. As it is frozen, the remaining pressure is dropped to zero to prevent the collapse or explosion of the film due to gas pressure. When the film is frozen at zero pressure and zero temperature, the sphere can be deployed in outer space. To prove the concept, we conducted a series of lab experiments with water-based bubbles. We first produced a bubble at a low pressure, instantly froze it with liquid nitrogen or dry ice, and lowered the pressure further. After rounds of collapsed films, cracks due to pressure jumps, and cooling failures, we were able to see a "bubble" deployed in the near-space conditions.

While fully automating and tuning this process will require further investigations, it is clear that producing frozen bubbles in space delivers many logistical advantages. A much lower surface-to-mass ratio that does not require frame supports will significantly reduce the total material used, the payload, the cost, and deployment time. Furthermore, relying on just the liquid material means the bubble can be produced *in situ*. Instead of propelling individual robots from Earth, a compact, compressed molten fluid solution could be delivered via magnetic launchers or elevators to Earth's orbit and transported to the Earth-Sun Lagrangian point, where liquid portions will be transformed into frozen spheres. This will further save transportation space, cost, and time and scale the deployment by several orders of magnitude.

The most important advantage of this method is its full reversibility. Because of the unstable equilibrium of the L1 point, an active system for space-keeping will be necessary for guaranteeing the correct number of spheres are in place. Therefore, by acting on the stabilization system, the exact number of spheres and the overall raft shape can be easily tuned (Figure 21.3). Moreover, as space debris (see Chapter 25) will likely destroy the thin frozen spheres over time, the replenishment rate for the production of new ones can be modified and controlled.

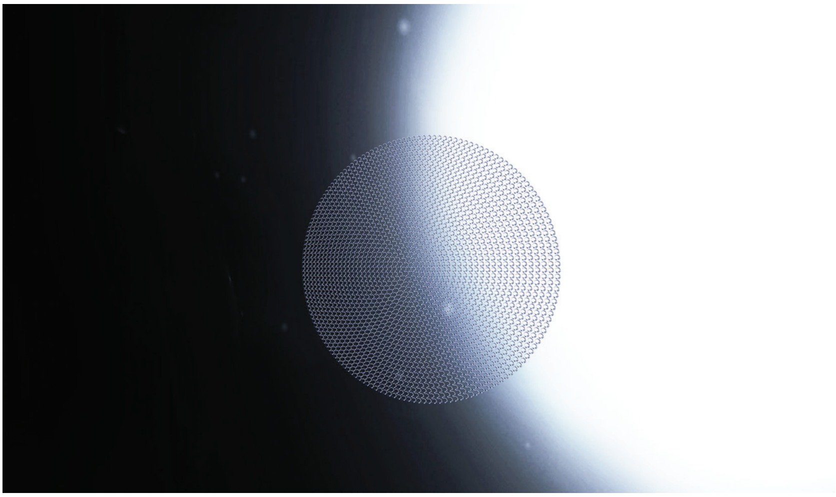

Figure 21.3 A schematic representation of a bubble raft acting as a sunshade. The relative size of an individual bubble is exaggerated for clarity of representation.

21.3 Future Developments

As we are looking ahead to deliver a basic production prototype, several significant engineering challenges remain. As of this writing, we have launched an investigation into polymer materials for the bubbles that will reflect enough solar radiation, and allow the bubble to be inflatable within convenient pressure and temperature range. We have also launched other investigations regarding the shading capacity of a bubble raft, the stabilization of the bubbles, and the exact estimates of mass and cost. We have also started the construction of an automated device for producing individual bubbles on a CubeSat mission.

Beyond the purely technical challenges associated with the prototype, the project will necessitate broader discussions of the potential impact on the atmosphere and the environment. Despite the affordable reversibility of the project, it will only come to fruition if the side effects are carefully considered and ruled out. Beyond that, the project will require significant cooperation between the public, private entities, corporations, and governments, and an intergovernmental policy coordinating a fraction of GDP to be spent on this mega venture.

The plan for the next few years is to develop and test a prototype pipeline for producing bubbles in outer space. A small device that can inflate a thin-film sphere from a liquid solution, freeze it and release it in a vacuum will be deployed on an orbital satellite to explore the robustness of the workflow and the longevity of individual bubbles in outer space. Once the prototype is successful, we will begin efforts to scale up the production. At the same time, we intend to involve a broader scientific community to study further the environmental impacts of the solution as well as the international collaboration required to fund and secure the project.

Broadly, the scope of research for the next several years will involve the following six topics:

1. **Material and mass density:** A fundamental phase in this project is selecting the right material and technology to fabricate and maintain thin-film spheres in outer space conditions. In our preliminary experiments, we succeeded in inflating a thin-film bubble at a pressure of 0.0028 atm and maintaining it at around -50 °C (to approximate space conditions of zero pressure and near-zero temperature). Further research will investigate the use of other types of low vapor-pressure materials to rapidly inflate and assemble bubble rafts (including silicon-based melts and graphene-reinforced ionic liquids, which have ultra-low vapor pressures and relatively low densities); key design metrics include the viscous, interfacial thermal properties of the bubble formers during inflation as well as the optical and structural properties of the bubble rafts when exposed to sun radiation. We will also study whether a bubble-based shield is mass-efficient compared to other proposed shading solutions.
2. **Position and stabilization of the raft:** While at the L1 Lagrangian point, gravitational forces from the Earth and the Sun cancel each other out, a wide and thin bubble raft would be significantly exposed to solar radiation pressure, suggesting that the optimal location should be identified slightly closer

to the Sun. An active stabilization mechanism is needed and will have to be designed, preferably through geometry modification.

3. **Shading capacity:** Previous geoengineering research suggests that to reverse the effects of climate change, incoming solar radiation should be reduced by 1.8% [21.5], even if smaller percentages would be enough for supplementing global warming mitigation initiatives on Earth [21.8]. A solar radiation reflection model will be built and used to determine the optical properties of the bubble raft. In contrast, a deeper analysis with climate models will identify the desired solar radiation reduction fraction.
4. **Space production and delivery:** A significant advantage of a bubble raft is the possibility of *in-situ* assembly using space-based fabrication methods. The coordination of the process of delivery, raw material transfer, inflation and the coordination of the resulting bubble rafts will be studied. Moreover, novel ways of shipping the material from Earth will be investigated.
5. **Maintenance and reversibility:** If a bubble raft is no longer needed, sheets of thin spheres are easy to destroy by breaking their surface equilibrium and collapsing them from their metastable equilibrium point to a lower energy configuration. This minimizes debris compared to other proposed approaches and makes it safer and more resilient in case of impacts with other objects. Maintaining such a fragile shield is a challenge, and an effective replenishment rate will be studied to ensure the shield maintains its size, together with strategies to guarantee a smooth end-of-life transition.
6. **Impact on Earth's climate and ecosystem:** Despite the remote location from Earth's atmosphere, some studies suggest that complex phenomena may arise on Earth's climate due to the reduction of solar radiation, such as the weakening of extratropical storm tracks [21.9]. This aspect will be further investigated with different solar radiation reduction fractions. Furthermore, a phase-out approach will be designed to avoid the Earth's ecosystem shock of a sudden termination of the geoengineering program when it will no longer be needed.
7. **Public policy implications:** How to maximize synergies between emission cuts and solar geoengineering is a public policy problem that needs careful investigation. Moreover, research will be done on the following topics: how to overcome political opposition and political fear; how to avoid what has been referred to as the "moral hazard" [21.10]; how to make the project economically sustainable; how to open-source the solution design for a widespread engagement.

As of this writing, the project is at its infancy and will take significant resources and effort going forward. Yet, this is an issue of unprecedented urgency, significant world scale and complicated scientific implementations. While space-based solutions should not substitute current climate mitigation and adaptation strategies, which will be the only valuable solutions in the long end, we believe that advancing feasibility of a solar shield to the next level could constitute a supplementary plan for a low-carbon transition on Earth—and in any case help us make more informed decisions in the years to come should geoengineering approaches become urgent. Together, through interdisciplinary and international cooperation, we can tackle the crisis and potentially resolve the most significant issue of humankind.

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