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DYSON DOTS

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ABSTRACT

No study of coping with climate change is complete without considering geoengineering. We propose placing a large (300K – 1M km^2) lightsail(s) in a radiation-levitated non-Keplerian orbit just sunward of the Sun-Earth Lagrange-1 point. The purpose of this syncretic concept is twofold: (I) As a parasol, it would reduce insolation on Earth by at least one-quarter of a percent, same as that which caused 1.8°C drop during the "Little Ice Age" (~1550-1850), and same as the IPCC Third Report's mid-range value for global warming by 2050. Lowering temperature will reduce the atmosphere's water vapor content, which should reverse the increasing frequency and severity of storms, likewise reducing the damage accompanying climate change. The sail would utilize the very photons it diverts from us to maintain its position without expensive fuel. (II) As a photovoltaic power station, the sail could displace about 300 EJ/a (~100 trillion kWh/yr) of fossil-fired electricity for its creators, roughly the entire global demand forecast by 2050, in turn displacing most carbon burners from the terrestrial grid, providing revenue from clean energy sales to pay for the scheme. This approach to geoengineering is linear, scalable, incremental ("pay-as-you-go"), customizable, minimally intrusive, and above all, reversible. If a Tellurian spacefaring civilization built lightsails to fuel its exponential growth, then eventually there might be enough of them to have a detectable effect on Sol's apparent luminosity as seen from far away, similar to the eponymous Dyson Sphere. For this reason, we tagged our concept with the moniker "Dyson Dot".

Keywords: geoengineering; global warming; Lagrangian point; non-Keplerian; photovoltaic solar sail; radiation-levitated orbit

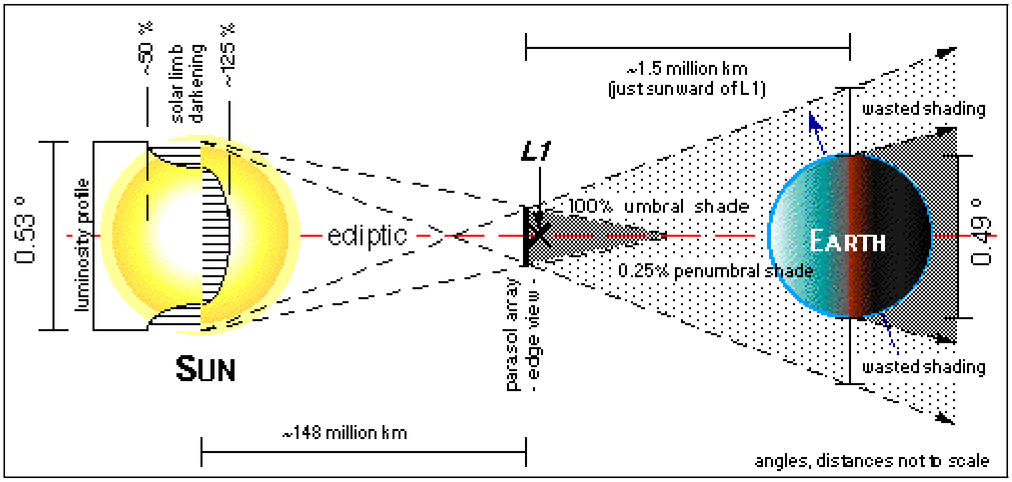

Fig. 1. Schematic of Dyson Dot (edge-on view) in non-Keplerian orbit inferior to Sun-Earth L1

INTRODUCTION

Water means life, and we live on a water world. Ultimately, climate change is about water also: too much water where it is not supposed to be or when; not enough water where or when it is supposed to be; plus drying soils, changing habitats and ocean currents, and rising sea levels over the next century. Warm air holds much more water than cool air, and when it is released, weather events tend to be much more violent and concentrated toward the extreme ends of the probability distribution. As the saying goes, climate is the weather one expects, while weather is the precipitation one gets, therefore climate change means *getting the unexpected*. Since the IPCC's *Fourth Report* in 2007, it has become clear that a certain amount of global warming is already "dialed in". Therefore coping with climate change means *managing the unavoidable*, while *avoiding the unmanageable*.

There are three elements to global warming: The first, which most people think of, is greenhouse gases (GHG) in the atmosphere, e.g., water vapor, carbon dioxide (CO_2), methane (CH_4), plus other minor ones. The second element is heat and light continuously coming in from the Sun, also known as "the radiative forcing function". The third is how much incoming energy is immediately reflected, or *albedo*. Dark surfaces (e.g., water) absorb energy; light ones (e.g., ice) reflect it. Sunlight directly warms our planet because our atmosphere is transparent to the predominant wavelengths of solar radiation: visible light. But GHGs in our air partly block the IR re-radiating from the warmed surface, trapping some heat. This greenhouse effect keeps the overall planet warm (even at night) making it possible for life to exist. Without a blanket of GHGs, plus lots of that truly amazing substance, liquid water, to moderate temperature extremes, Earth would be a cold, inhospitable place.

Humanity's efforts are currently focused (unsuccessfully) on reducing the GHGs (principally CO_2) being emitted to the atmosphere, mainly via (ineffective) top-down attempts to limit the consumption of carbonaceous fossil fuels. Conservation, recycling, more efficiency, altered lifestyles, and new low-carbon sources of energy are all needed to reduce our GHG emissions. But so far, all that these tactics have achieved is reducing the *rate* of emission *growth*, and not even that in most places. Absolute consumption of fuel, and concomitant emissions and concentration [CO_2] in the atmosphere), continues to rise dramatically. To avoid the worst effects of climate change, humanity needs to do more than merely reduce growth; we must bring down the absolute amount of these gases in the atmosphere to levels below those of the last century. However, with more people entering the global middle class, and their commensurate use of more energy, it does not seem we will be able to stop global warming. We certainly will not be able to conserve our way back to pre-20th-century [CO_2] -- not without declining to pre-XX living standards at any rate. Who would willingly accept that? Who would enforce it?

If we cannot eliminate the causes of climate change, then is there anything we can do to mitigate it? What if we could reduce the overall amount of sunlight hitting Earth so that global atmospheric temperatures and weather patterns can return to what we consider normal? What if we were to build a large sunshade in space allowing Earth to cool off, thus buying time to do the really hard thing: changing our behavior and attitudes?

1. GEOENGINEERING, OR, A MODEST PROPOSAL

Geoengineering, or planetary engineering, is the application of technology for the purpose of influencing the properties of a planet on a global scale. No study of coping with climate change is complete without considering geoengineering. Leveraging Tsiolkovsky's and Tsander's 1920s idea to use mirrors in space for propulsion, Glaser's 1970s study of solar power satellites, and Forward's 1990s concept of "statites", we propose placing a large mirrored-solar sail in a radiation-levitated non-Keplerian orbit just sunward of the Sun-Earth L1 point. Building, placing, and controlling a 300,000-1,000,000 km^2 lightsail, massing tens of millions of tonnes, would be greatest engineering project yet tackled by the human race, but the challenge of worldwide climate change is also great. The purpose of this syncretic concept, which we tagged with the moniker "Dyson Dots", is twofold:

(I) A 300,000 km^2 parasol would reduce insolation on Earth by at least one-quarter of a percent, same as that which caused the 1.8°C drop during the "Little Ice Age" (~1550-1850 AD), and same as the IPCC's (*Third Report*) mid-range value for global warming by 2050. (Values in the *Fourth Report* went up.) Lowering temperature will reduce the atmosphere's water vapor content, which should reverse the increasing frequency and severity of storms, likewise limiting the damage from climate change. We forecast the burden of damage related to climate change to rise from 0.1% of global product now to 1% by 2100. The expected present value of the sum of these casualties over the coming century is on the close order of $100 trillion, discounted to 2010 dollars. Avoiding this damage compared to business-as-usual is likely worth more than the cost of the parasol.

(II) As a 300,000 km^2 power station covered on its sunny side with photovoltaics (PV), beaming that energy to Earth via maser (*m*icrowave l*aser*), the shield could offset ~300 EJ/a (~90 trillion kWh) of electricity. This is roughly the same as forecast global demand by 2050, which in turn would displace most carbon burners from the terrestrial grid. Also, to maintain its position without continual shipments of expensive rocket fuel, the sail would utilize the light pressure imparted by very photons it diverts from us, an elegant bonus.

Avoiding the damage of climate change (insured or not) would provide the value, while clean energy sales could provide the cash flow to pay for the scheme – there is plenty of potential. The world's electricity grid alone is worth ~$16 trillion today (average overnight capital cost of $4/watt, ~4 terawatts total generating capacity, 40-year useful life). Demand for electricity, the highest, most useful form of energy, is growing faster than any other. Tens of trillions of dollars are already programmed to maintain or replace the grid over the next four decades, and petroleum is already the largest industry on Earth, $3-5 trillion per year, depending on crude oil prices.

2. NON-KEPLERIAN ORBITS, OR, LOCATION, LOCATION, AND LOCATION

Gravity keeps our feet on the ground, satellites in orbit overhead, and Earth revolving around the Sun. The Sun's immense mass pulls on Earth -- but for our motion in orbit around it, we would fall in. Earth likewise tugs on the Sun. There is a orbiting point in space at which the pull of Earth's gravity one way exactly equals the Sun's the other way. It is called the Sun-Earth *Lagrange*-1 point (SEL1), and is much closer to Earth than the Sun, due to our much smaller mass. The term honors Italian mathematician Giuseppe-Luigi, Count of Lagrange, who in the 18th century worked out the physics to describe the behavior of celestial objects at these points.

If you want to see SEL1, go outside during the daytime and look up (wearing proper eye protection) at the center of the Sun. It is right there, only 1,500,000 km away (about four times farther than the Moon). But while Luna moves against the background of fixed stars over a month, the SELI point will always be directly between Earth and the Sun. Therefore, an object placed there will always block some of the sunlight that would otherwise hit Earth. This effect is occultation, not an eclipse. Unless the object at SEL1 is thousands of km in diameter, the dark part (*umbra*) of a shadow from there cannot reach Earth -- only the dim outer *penumbra* stretches that far.

Not all shade is equal: see in Figure 1 that a sunshade parked right on the Sun-Earth line intercepts a higher quality of light than one parked off-axis. This phenomenon, which varies by a factor of 2.5 or so, is called *solar limb darkening*, and is one of the components of shading efficiency. One can observe something similar in an ordinary light bulb -- the edge of the bulb appears dimmer than the center no matter where one stands.

Although the Lagrangians are called "points", they are in fact *spatial regions* of metastability (L1, L2, L3) or true stability (L4, L5). For example. the region of metastability centered around SELl point in Figure 1 is shaped like a sausage lying about 800,000 km along the orbit (i.e., perpendicular to the page). The region's transverse dimensions (i.e., up-and-down, and left-to-right on the page) are approximately 200,000 km each. Thus the Sun-Earth L1 region contains roughly 30 quadrillion cubic kilometers of space, within an order of the 200-quadrillion km^3 volume of cislunar space in the Earth-Moon system. However, for purposes of shading sunlight on Earth, the "sweet spot" is a lot smaller, less than 1 percent of the region.

A similar technique could be applied to *raise* the global temperature as well, because sometimes ice ages happen, too. In principle, these methods could be applied to any other planet, anywhere. The L1 regions for the Sun-Jupiter or Sun-Saturn ordered pairs are much larger than the SEL1 – in fact, far greater extent than the gas giants or even Sol himself. These regions could host mirror-sails in large numbers – *vast*.

3. PARASOLS IN SPACE

If we want to cut down the amount of solar radiation hitting a planet with as little effort as possible, then the object must have maximum surface area for minimum mass. It must block a lot of light yet not be too heavy to launch. Fortunately, a technology exists today that might be up to the job: solar sails.

A solar sail is just what its name implies: a sail that propels itself using sunlight. Sunlight has no rest mass, but it does have momentum. When light is reflected from an object, the light imparts some of its momentum to that object, just like one billiard ball hitting another. The momentum of a photon is very, very small. But in space, without air and wind and in situations where the pull of gravity from Earth or Sun is also small, the tiny push from sunlight can be a significant factor in making a spacecraft move. If the spacecraft has a large, lightweight, and highly reflective sail attached, it can maneuver just about anywhere in the inner solar system without fuel, using only reflected sunlight to propel it. But parasols will not be solar sails in the traditional sense. There will be some big differences. Solar sails for geoengineering can be very heavy compared to solar sails used to transport cargo around the solar system. They will not have a payload; in a sense they *are* the payload. Since they will not be hauling designated freight, we can make them any size we want based on ease of fabrication and other factors. For our purposes we do not really care if we have a million small sails a kilometer square each or a single great sail of a million square kilometers. It is the optical properties which are critical, and will vary a lot depending on the particular engineering solution chosen. They do not have to be totally reflective mirrors, or totally absorptive blackbodies. Different parts may be mirrored, or black, or diffractive, even transparent, or some combination. Rather than a one-shot cargo mission. they will be built for longevity. They must endure the harsh conditions of interplanetary space, withstand high radiation fields and continual assaults by the solar wind (or even the occasional solar storm), and tolerate occasional punctures by micrometeoroids.

The sails will need to have sensors, controls and even some onboard intelligence. To remain precisely at the SELl point, they must vary the thrust resulting from solar radiation to counter forces that would pull them off-station. Because many thousands or possibly millions of solar sails will be cruising along in orbit in proximity to one another (much like a giant school of fish) they will also have to be social, i.e., their sensors will observe their neighbors as well as the primary and the satellite, and they will maneuver to avoid crashes or other conflicts such as cutting off a neighbor's light. They will have the means to receive and execute instructions from their builders and operators. We will want them to move out of position if the temperature on Earth drops too much.

To distinguish these rather specialized solar sails from ones intended for propelling spacecraft, we have coined the term "Dyson Dot". It is a deliberate allusion to the eponymous Dyson Sphere proposed by Freeman Dyson as a system of orbiting space facilities which completely encompasses a star, capturing its entire output. In contrast, our Dyson Dot would manipulate only a tiny fraction of a star's light shining on one of its planets (ours).

A typical solar sail needs a mass:area ratio about 10-20 grams per square meter (g/m^2) to be useful. Our Dyson Dots can be that light or they can be much heavier, up to 1 kg/m^2 if necessary. Lighter Dyson Dots will have greater acceleration due to light pressure, which requires that they be positioned somewhat closer to the Sun -- perhaps 1.5 million km sunward of the Ll point. If it was heavier or less shiny, it could be set closer to L1. To understand why, consider again the physics of the Ll point. In conjunction with centripetal acceleration due to its orbital motion, the planet's mass accelerates any object at Ll exactly opposite to the acceleration caused by the Sun's gravity. From the point of view of the object, this in effect reduces the mass of the Sun, allowing the object to have a solar-orbital period *while at L1* exactly equal to that of the planet further out. But with a solar sail we now have a fourth acceleration to work with – the result of photons hitting and/or reflecting from the sail. This fourth acceleration, *which can be varied and controlled*, adds to the effect of the planet's gravity on the Dot, in effect moving the equilibrium point sunward from the usual L1 point. (For completeness, we note that the effect of solar wind is three orders of magnitude smaller, and Luna will impart a periodic, but predictable, disturbance.)

Not only would these sails block light like a lady's parasol, they could use some of that light for station-keeping thrust rather than conventional reaction mass squirted from an engine. Sunlight in space is effectively free, unlike rocket fuel shipped up from Earth or somewhere else, which would get expensive over the long run. With photovoltaics on their bright side, the sails could easily make enough electricity for their onboard computers and other equipment. Furthermore, there is no reason why they might not generate a surplus over their own modest power requirements -- perhaps a very large surplus.

4. HOW MUCH IS ENOUGH? OR, A MIRRORED MAUNDER MINIMUM

Dyson Dots can be put slightly sunward of the SEL1, but how much sunlight do we need to stop? This seemingly simple question does not have a simple answer. Depending on future energy policies, and on various global and solar cycles, we may need to either artificially cool down, or at some point, even warm up our planet.

To begin to bound the problem, we recall that the sunspot cycle shut down for unknown reasons between the mid-16th and 17th centuries. Astronomers estimate that a quarter-percent (0.25%) reduction in the Sol's energy output accompanied this event, and refer to the period as the *Maunder minimum*. Historians call it "the Little Ice Age". Chronicles tell that the Thames River in England froze for the first time in recorded history; sea ice cut off Iceland from Europe; crops failed. Parish records show European population growth stalled. Tycho Brahe recorded winter temperatures 2.7° Fahrenheit (1.8°C) below average during the last two decades of XVI.

A reduction of this close order in the radiative forcing function would be necessary to offset global warming. (*Nota bene*: while this approach could adjust the average global temperature, it would not address other environmental issues associated with the continued burning of fossil fuels, such as acidification of the oceans.)

At this writing. it appears that the gross parameters of an array of sails will vary by a factor of roughly 3: from 300,000 km^2 (about the size of the state of Arizona) with a mass of 10-20 million tonnes at the low end, to about 900,000 km^2 (somewhat greater than the entire West Coast of the United States) and 50-60 million tonnes at the upper end. For example, using reasonable middle values for the parasol parameters -- 50 percent albedo, mass 53 g/m^2, position 2.1 million km from Earth -- we would need almost 700,000 km^2 of sunshade area, i.e., 37 million metric tons, to achieve a reduction of 0.25 percent in the solar constant. (This sounds like a lot, but for perspective bear in mind that the United States alone burns about one billion tonnes of coal, and another billion tonnes of oil and gas, every year. One supertanker of the many hauling crude around the world's oceans weighs about half a million tons fully loaded; and 37 megatonnes is just 3 days' supply of crude oil.) If each Dyson Dot has an area of 10 km^2, then our array would consist of 70,000 units. In the grand scheme of things, 37 million tonnes is not so much. For example, it is the mass of a small stony-iron asteroid a mere 300 meters across -- a class of rock so minor that we have not seriously looked for it yet.

The schematic on the first page illustrates why no stable sunshade can project exactly the right-sized shadow spot (same diameter as the Earth). Some shade is unavoidably wasted due to the geometry of the Sun-Earth L1 system. This component of shading efficiency is maximized at 82 percent right at L1, as shown. Any sunshade made of a nonmagical material will have to cruise somewhat inside of SEL1. The brighter the mirror, the further inside SEL1 it must go, and paradoxically the greater its overall mass and cost, and the less efficient the total project gets. Any real solution will be an optimization-tradeoff among multiple values and constraints.

For cooling Earth, it does not matter how the Dyson Dot reflect solar radiation just as long as it is prevented from getting here. Some 1400 megawatts of raw sunlight passes through each and every square kilometer at Earth orbit. If 20% of this flow is converted to electricity at 10% efficiency, we get 28 megawatts of power per square kilometer of sail. We will have over 700,000 km^2 of solar sail to work with. If this power was beamed back to Earth via maser, allowing for 80% loss along the way (transmission, reception, rectifying, and inversion to grid), our Dyson Dots would still out-produce 10,000 gigawatt-class nuclear power plants, and with 100% capacity factor. One hour of sunshine falling on the bright side of Earth is about the same as the primary energy budget of the entire human race today (~500 EJ/a). If even a small part of the sunpower that Dyson Dots capture is transformed to electricity, it would be enough to provide for all the people in this world, with plenty left over. Moving polluting power generation offworld would be a good thing, and benefit the biosphere. Terrestrial carbon burners, and even "nukes", waste two-thirds of their fuel's energy due to basic thermodynamic inefficiency.

Another intriguing possibility is to selectively filter wavelengths of light falling on Earth with the Dot, such as enriching the red-orange and purple ends of the color spectrum which are beneficial to growing plants.

A large factory on the moon could make Dots with lunar materials and then launch them to SEL1, or a large railgun on Earth could shoot a carrier to SEL1 to deploy Dots. An asteroid could be caught, mated with a robo-factory, unfurl a sail, and move itself to SEL1, making Dyson Dots along the way using the asteroid itself as raw material and reaction mass. Wherever they will be, the factories would be busy for some time. Deploying the example above over 10 years means handling about 10,000 tonnes of Dot stuff a day. Even after achieving the goal, Dots would still have to be replaced as they fail.

SEL1 is way up beyond this deep gravity well we live in, and our existing technology is grossly unequal to the task of lofting such large payloads into space. Chemical rockets are too expensive to implement this solution. At a current launch cost of $20,000/kg, the Dot above would cost $750 trillion (gross world product for 15 years) just for the ride into low Earth orbit (LEO). Only a truly advanced spacefaring civilization using energy on an unprecedented scale could execute this project. However, proposed solutions to global warming -- including doing nothing which is always an option in human affairs -- are also very expensive or painful. Reducing CO_2 emissions in the developed world to 80 percent of the 1990 level could cost $50 trillion. Bringing the developing world up to our standard of living while lowering their CO_2 emissions could easily cost an order of magnitude more. Perhaps becoming an advanced space-faring civilization would be the cheaper alternative after all.

5. DYSON DOTS AND ASTEROID DEFENSE

Since the discovery in the 1980s of the true cause of the dinosaurs' demise, humanity has been made increasingly aware of the chaotic and violent nature of the solar system. Small resources are being devoted to the problem of surveying and characterizing the threat of bolides from space (both asteroids and comets). Much more is needed. While Dyson Dots in the configuration we imagine will not be able to directly deal with errant rocks the size of cities, merely building the Dots provides a development path of mutually reinforcing capabilities. Asteroids, of the metallic and carbonaceous chondrite variety, will likely be a source of building materials for the Dots, much more cost-effective than simply hauling megatonnes of mass out of Earth's deep gravity well. Therefore, a robust asteroid prospecting and mining program in support of building Dots will necessarily yield a great deal of information about the distribution and behavior of asteroids (and comets), which is directly applicable to the problem of defense and a trove for science to mine. And *vice versa*: a search/survey program motivated by defense or science, will be useful to the prospectors and miners. Whatever their motives, more eyes in space would be an absolute good, and no doubt will yield serendipitous scientific discoveries. They always do.

6. THE INTERSTELLAR PERSPECTIVE

Imagine, in the interest of other worlds, other places, we wanted to reduce the solar radiation hitting our neighbor Venus to Earth-normal levels (as opposed to the venuforming of Terra which seems to be going on right now). We would need to block about half (48% exactly) of the incoming sunlight, which can be done using Dyson Dots located at the Sun-Venus L1 point. But the level of effort would be several orders greater than that required to cope with global warming right here on *terra firma*. We recognize that the terraforming of Venus would involve much more than just adjusting its solar constant, but that task would be an essential part of the overall effort. If we were terraforming Mars instead, we would do just the opposite – double the Martian insolation with extra light from off-axis Dots. Projects like this could take millennia without quasi-magical methods like self-replicating nanotechnology. Nevertheless, how much would a second home in this Solar System be worth to the human race? Survival trumps ordinary economic calculus.

Given the Copernican Principle, none of these considerations are unique to our home system. Physical laws are the same for everybody. It is reasonable to suppose that intelligent beings elsewhere may apply techniques we would recognize. If a race were interested in terraforming a planet, solar sails would be a useful technique. Dyson Dots as described here can *convert* a *solar constant* into a *solar variable*, and to modify the color of light hitting the target planet. They can catch light from their star for energy, and reap their stellar wind for matter. Can we deploy this tool in time to make a difference in global warming here? Certainly not without cheap and reliable access to space, nor without the national or international will to do great things. It is clear that building and using Dyson Dots would be the biggest engineering project yet attempted by the human race, but also the doing of it would create a set of mutually reinforcing capabilities, each of them valuable, perhaps even indispensable, to a spacefaring civilization. Solving the climate change problem here on Earth may be just the thing to bootstrap the human race to a new plane of existence.

Although we may find the project too daunting right now, other beings in other solar systems may have done it already. Perhaps researchers at the Search for Extraterrestrial Intelligence (SETI) should look for the occasional flash from distant Dyson Dots. They are designed to reflect a lot of energy. A school of mirrors at the L1 point pairing a jovian planet and central star in some other system would have much greater diameter than the gas giant or star itself. This bright source would appear to wax/wane by many magnitudes, yet be synchronized with the orbital period. The reflection would display rhythm but due to the non-Keplerian nature of sails' orbits, the observed motion would seem funny somehow. If the instruments doing the observing were sensitive enough, this anomaly might be visible at interstellar range to outsiders like us. They may not want to talk to us, but it would somehow be comforting to know that other beings are making themselves comfortable on distant worlds.

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