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Earth Rings for Planetary Environment Control

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EARTH RINGS FOR PLANETARY ENVIRONMENT CONTROL

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ABSTRACT

This paper examines the creation of an artificial planetary ring about the Earth to shade it and reduce global warming. The ring could be composed of passive particles or controlled spacecraft with extended parasols. Using material from dangerous asteroids might also lessen the threat of asteroid impacts. A ring at 1.2-1.6 Earth radii would shade mainly the tropics, moderating climate extremes, and could counteract global warming, while making dangerous asteroids useful. It would also reduce the intensity of the radiation belts. A preliminary design of the ring is developed, and a one-dimensional climate model is used to evaluate its performance. Earth, lunar, and asteroidal material sources are compared to determine the costs of the particle ring and the spacecraft ring. Environmental concerns and effects on existing satellites in various Earth orbits are addressed. The particle ring endangers LEO satellites, is limited to cooling only, and lights the night many times as bright as the full moon. It would cost an estimated \$6-200 trillion. The ring of controlled satellites with reflectors has other attractive uses, and would cost an estimated \$125-500 billion.

INTRODUCTION

For 95% of its past, the Earth's climate has been warmer than it is now, with high sea levels and no glaciers (Butzer, 1989). This warmer environment was interrupted 570, 280, and 3 million years ago with periods of glaciation that covered temperate regions with thick ice for millions of years. At the end of the current ice age, a warmer climate could flood coastal cities, even without human-caused global warming. In addition, asteroids bombard the

Earth periodically, with impacts large enough to destroy most life on Earth. A recent world concern is the effect of industrial greenhouse gases in raising the overall global temperature, melting the polar caps, and raising sea level. Govindasamy et al., (2000) estimated that the expected doubling of CO₂ in the atmosphere over the next century will warm the Earth by about 1-4 kelvins and raise sea level by about 1 meter. Not all scientists are convinced of human-caused global warming, but the temperature will rise, regardless of human action, as the world comes out of the current ice age. Reducing solar insolation by ~1.6% should overcome a 1.75 K temperature rise. This might be accomplished by a variety of terrestrial or space systems. Teller, et al. (1997) is an excellent review of the basic physics of a whole range of climate control techniques, with first-order evaluations of their mass and cost. Table 1 summarizes these and other proposals for climate control and their parameters. They are grouped into Earth-based systems, Earth-orbit systems, and solar-orbit systems at the Earth-sun L₁ Lagrangian point.

Scattering devices or reflectors in the stratosphere would avoid the costs of space launching. Dyson and Marland (1979) proposed scattering of sunlight by SO₂ from exhaust stacks, and the eruption of Mt. Pinatubo in the Philippines demonstrated this cooling power of such aerosols in the atmosphere by lowering the Earth's temperature ~0.5 K. Brady et al. (1994) proposed cooling by adding 0.1 μm-diameter alumina particles to exhaust stacks, or by a special combustor of aluminum powder at high altitude, to loft alumina dust into the stratosphere. Teller, et al. (1997) suggested tiny hydrogen-filled balloons with diameters of 8 mm and aluminum walls 0.2 μm thick, to float at 25 km altitude and scatter sunlight.

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Table 1. Summary of Climate Control Methods

Author	Description	Requirements	Mass, kg	Maintenance
Earth-Atmosphere Methods				
Dyson and Marland, 1979	SO ₂ from coal-fired plants	Smokestack additives		Exhaust control required
Brady, 1994	Al from rockets	Rocket design		Rocket control
Teller, et al., 1997	H ₂ -filled Al balloons	0.02 μm walls; “anti-greenhouses”	10 ⁸	Replenish as necessary
Earth Orbit Systems				
Mautner, 1991; Pearson et al., 2002	Saturn-like particle rings	R = 1.2-1.5 R _e R = 1.3-1.6 R _e	3.4x10 ¹¹ 2.1x10 ¹⁴ 2.3x10 ¹²	Replenish as necessary
NAS, 1992	Orbiting mirrors in random LEO orbits	55,000 mirrors, A = 100 km ²		Uncontrolled; collisions, debris
Pearson et al., 2002	Controlled spacecraft	50,000 to 5 million spacecraft	5x10 ⁹	Active control
Solar Orbit Systems				
Early, 1989; Mautner, 1991	L ₁ lunar glass from mass driver	D = 2000 km, 10 μm thick	10 ¹¹	Active control
Mautner and Parks, 1990	L ₁ thin-films	31,000 solar sails, 3x10 ¹² m ² each	5x10 ¹⁴	Active control
Hudson, 1991	L ₁ parasol			Active control
Teller, et al., 1997	L ₁ metallic scattering	D = 638 km T = 600 angstroms	3.4x10 ⁶	Active control
McInnes, 2002	L ₁ metallic reflector	D = 3648 km	4x10 ¹¹	Active control
Other Concepts				
Korycansky et al., 2001	Move Earth using Kuiper-belt-objects	150-km object; One encounter every 6000 years	10 ¹⁹	Actively moved, low delta-V
Criswell, 1985	Lower sun’s mass to slow brightening	Remove plasma from magnetic poles	2x10 ²⁸	Continual spacecraft ops

In Earth-orbit-based systems, Mautner (1991) proposed a thin film like a belt around the Earth, and rings of grains. The National Academy of Sciences (1992) proposed 55,000 orbiting mirrors of 100 km² area each, aligned horizontally, but in random orbits. The current paper describes both a particle ring and a ring of controlled satellites.

For solar orbit systems, Early (1989) proposed placing a shield at the sun-Earth L₁ Lagrangian point, about 1.5 million kilometers sunward from the Earth, as a ~10¹¹-kg refractor composed of lunar glass. Mautner and Parks (1990)

proposed thin-film solar sails at L₁, and Hudson (1991) proposed a ~10¹¹-kg opaque thin film at L₁. Teller et al. (1997) proposed a ~10⁶-kg small-angle metallic scatterer at L₁, and McInnes (2002) proposed a metallic reflector.

Other, more ambitious schemes include the proposal by Korycansky et al. (2001) to move the Earth to a more distant solar orbit, and by Criswell (1985) to remove material from the sun’s poles, lowering its mass, extending its stay on the main sequence, and thereby postponing the red-giant phase by billions of years. From a different perspective, Fawcett and Boslough

(2002) suggested that grazing asteroid impacts have created temporary debris rings that cooled the Earth for 10^5 years. They find fossil evidence for such a ring associated with an asteroid impact 33.5 million years ago (although not with the dinosaur-killer of 65 million years ago); another temporary ring may have caused the period of heavy glaciation about 570 million years ago.

The Fawcett and Boslough climate modeling results show that such rings could drastically lower the planetary temperatures. Muller and MacDonald (1987) even proposed that past ice ages were caused by a ring of dust in the Earth's orbital plane. The meteorological community is developing improved climate models that could be useful in detailed analyses of the climate effects of these systems (Watts, 1997). There has been at least one study looking at the economic effects of global warming on the U.S. economy (National Assessment Synthesis Team, 2001).

ARTIFICIAL EARTH RINGS

This paper proposes to create an artificial ring about the Earth to reduce solar insolation. An equatorial ring location was chosen from the standpoint of stability and reduced perturbations. We describe two different options: a ring of passive particles, derived from the Earth, moon, or asteroids, and a ring of attitude-controlled spacecraft with large, thin-film reflectors. The optimum ring size, location, and material properties are addressed, using a climate model to determine the desired reduction in insolation. Ring materials and cost of emplacement are evaluated, and methods are discussed for controlling ring deterioration from particle loss due to air drag and ring spreading or from satellite malfunctions.

Earth Ring Concept

Our baseline concept is to create an Earth ring in equatorial orbit, similar to Saturn's B ring, but closer. The concept is shown in Figure 1. We looked at radii between 1.2 and 1.8 R_e . The ring can be composed of particles or of individual spacecraft, and is characterized by its radial extent and by its density, or opacity. This low-altitude ring shades the tropics primarily,

providing maximum effectiveness in cooling the warmest parts of our planet. The shadow oscillates like a sine wave over the Earth, from a minimum line over the equator at the equinoxes to a maximum shading area in the winter tropical zone at the solstice, which is the time represented in Figure 1. This amplifies seasonal effects, just as Saturn's rings do (Smith, 1981).

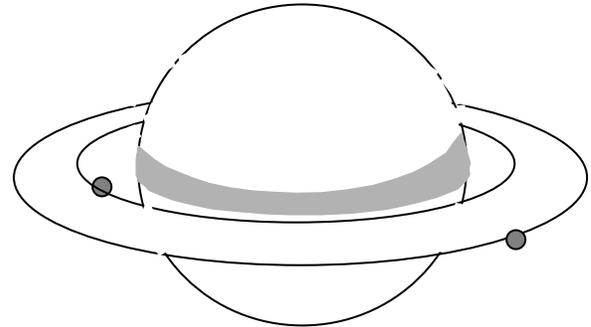
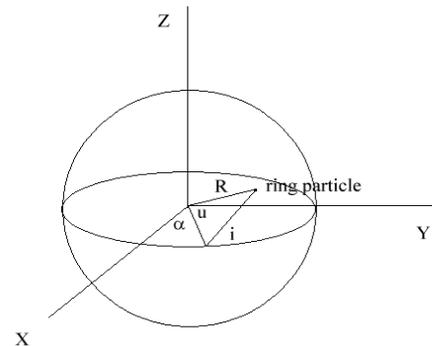


Figure 1. Earth Ring Concept, $R \sim 1.3-1.7 R_e$, With Shepherding Satellites

Ring Shadow

To allow for the climatic effects of the ring shadow, the shadow area and position must be calculated. Refer to Figure 2 for this derivation.



Sun

Figure 2. Calculation of Ring Shadow Area

The area of the ring shadow in the YZ plane (blocked sunlight area):

$$A = RH (u_2 - u_1) \sin \beta,$$

where R is the ring radius, H is the width of the ring ($H \ll R$), $\sin \beta = \sin i \sin \alpha$, i is the inclination of the ring plane, and u_1 and u_2 are solutions to the equation

$$Y^2 + Z^2 = R_E^2$$

where R_E is the Earth radius, and

$$\begin{aligned} Y &= R \cos u \sin \alpha + R \sin u \cos i \cos \alpha, \\ Z &= R \sin u \sin i. \end{aligned}$$

The equation for u can be re-written as

$$\begin{aligned} &\sin 2u \sin 2\alpha \cos i + \cos 2u (\sin^2 \alpha - \cos^2 i \cos^2 \alpha - \sin^2 i) \\ &= 2R_E^2/R^2 - (\sin^2 \alpha + \cos^2 i \cos^2 \alpha + \sin^2 i) \end{aligned}$$

or

$$\cos (2u - \varphi) = [2R_E^2/R^2 - (\sin^2 \alpha + \cos^2 i \cos^2 \alpha + \sin^2 i)] / D,$$

where

$$D = [(\sin 2\alpha \cos i)^2 + (\sin^2 \alpha - \cos^2 i \cos^2 \alpha - \sin^2 i)^2]^{1/2}$$

$$\varphi = \arctan [(\sin 2\alpha \cos i) / (\sin^2 \alpha - \cos^2 i \cos^2 \alpha - \sin^2 i)]$$

Now, it appears that

$$u_2 - u_1 = \arccos \{ [2R_E^2/R^2 - (\sin^2 \alpha + \cos^2 i \cos^2 \alpha + \sin^2 i)] / D \}$$

and the shaded area is

$$A = RH \sin i \sin \alpha \arccos \{ [2R_E^2/R^2 - (\sin^2 \alpha + \cos^2 i \cos^2 \alpha + \sin^2 i)] / D \}. \quad (1)$$

If the ring is not narrow, Equation (1) must be integrated over the range of R, assuming $H = dR$. This area is then calculated for each of the latitude bands for input to the climate model.

One-Dimensional Climate Model

The average insolation over a 24-hour period at specific latitudes and solar declinations (Sellers, 1965) is given by:

$$I = (S/\pi) (T \sin \varphi \sin \delta + \cos \varphi \cos \delta \sin T),$$

where all angles are in radians, and δ = solar declination, φ = latitude, T = half-day length in radians, S = solar constant, and $T = \cos^{-1}(-\tan \varphi \tan \delta)$.

The insolation value at the equator for the equinox, $T = \pi / 2$, $\sin T = 1$, so $I = S/\pi$, as expected. The Earth ring shading was modeled and used to calculate the insolation values for each latitude band for input into a global climate prediction model, shown in Figure 3.

The one-dimensional climate model of McGuffie and Henderson-Sellers (1996) was used. The model begins with the solar constant, 1370 W/m² outside the atmosphere, and develops the insolation values for 10-degree latitude zones in terms of a sunlight weight from the formula above. An initial temperature and albedo are chosen for each latitude zone. This model takes the average insolation in latitude bands and applies these inputs to a simplified energy balance model of the Earth's climate system; the result is a set of average temperatures for the latitude band, and a resulting overall planetary temperature. The model allows for changes in albedo due to the formation of ice and snow, and uses an iterative calculation in an Excel spreadsheet to perform the analysis in 50 integration steps. This kind of model does not show altitude variations in temperature, nor does it take into account ocean currents or other second-order effects. However, it does show the latitude dependency of the temperatures resulting from various ring configurations, as well as the global results. The model can also be modified to show the seasonal effects, giving results for winter and summer temperatures as functions of the ring parameters.

The iteration in Figure 3 uses the nominal solar constant (SC) of 1370 W/m² outside the atmosphere, applies the geometry to produce the sunlight weight for each zone, and through the iterative process (two steps are shown) gives the zonal temperatures. These are averaged by the zonal areas to produce the current predicted global mean temperature, 14.87 C.

particle diameters. Aerodynamic, plasma, and Poynting-Robertson drag reduce the ring orbital diameter, but the rate is inversely proportional to particle size; consequently long-lived rings must have particles neither too big nor too small. Natural rings seem to be generally kept in place by shepherding moons located just beyond the ring edges (Smith, 1981).

To estimate the orbital lifetime of a particle, we may use the following approximate formula:

$$T = V H_a \rho_m D / (3 \mu \rho_a), \quad (2)$$

where T is the orbital lifetime, V is the orbital velocity in the initial orbit, H_a is the scale height of the atmosphere in the initial orbit, ρ_m = particle density, D = particle diameter, μ = Earth's gravity constant, $398,603 \text{ km}^3/\text{sec}^2$, and ρ_a = air density in the initial orbit.

As an example, assuming $H_a = 100 \text{ km}$ and $\rho_a = 1.5 \times 10^{-15} \text{ kg/m}^3$ at an altitude of 1000 km , we get an estimate of $T = 23 \text{ days}$ for $D = 10^{-6} \text{ m}$, $\rho_m = 5000 \text{ kg/m}^3$. This means that a particle has to be 16 microns in diameter to survive 1 year when initially placed in a 1000 km orbit, and it has to be 1.6 mm to survive 100 years .

The totals for N particles of the same size are as follows. The total shading area is:

$$S = G_c N \pi D^2 / 4,$$

where G_c is some geometry coefficient, depending on the orbit parameters and over-shading of the particles.

The total mass is

$$M = N \rho_m \pi D^3 / 6, \quad (3)$$

and therefore,

$$M/S = \rho_m D / (1.5 G_c), \quad (4)$$

or

$$\rho_m D = 1.5 G_c M/S.$$

After substituting the expression into the formula for the orbital lifetime, we obtain

$$T = V H_a G_c (M/S) / (2 \mu \rho_a),$$

or

$$M = 2 T S \mu \rho_a / (G_c V H_a) \quad (5)$$

This is a useful formula because it does not include any details of the ring composition, particle size or density. It can be interpreted as a minimum ring mass required to provide a given shading area for a given period of time. The minimum is reached when the sizes of all particles in the ring are optimized for the given orbital lifetime. The formula says that the minimum ring mass is proportional to the orbital lifetime, shading area and the air density at the ring altitude (assuming it is narrow). If there is an altitude where $\rho_a/(G_c V)$ is minimum, this will be the optimum position of the ring, providing a minimum ring mass for any given lifetime and shading area.

If we ignore the over-shading of the particles, then the geometry coefficient is roughly

$$G_c = \arcsin(R_e / \bar{R})/\pi,$$

where R_e is the Earth radius and \bar{R} is the ring mean radius. If we assume that the air density ρ_a drops exponentially with a scale height of $H_a \ll R$, then the ratio ρ_a/G_c will not have a minimum. This means that the minimum mass of the ring will decrease with the ring radius because the optimum particle size will drop.

Thus, the best positioning of the ring must be a result of considering the trade-offs: large particles are ineffective because of low S/M ratios. Small particles are more effective, but they must be placed far enough to provide a reasonable lifetime. Also, for micron size particles, solar pressure will significantly deform orbits. Small particle collisions will produce even finer particles, which quickly drop out of the main ring and infest low orbits.

Particle Heating and Re-Radiation

Assume spherical (or randomly-shaped and randomly-oriented) particles that are far enough apart that particle-to-particle heating and shading can be neglected, compared to their effects on the Earth and vice versa. First it is

necessary to estimate the view factor of the Earth from the particle. If the orbit radius of the particle is $R = R_r/R_e$, then from Carroll (1997), the view factor is:

$$F = (1 - \sqrt{1 - (1/R)^2}) / 2$$

For $R = 1.3, 1.5,$ and $1.7,$ the view factors are 0.18, 0.13, and 0.10.

For dark particles, most of the sunlight striking them is absorbed and re-radiated as long-wave radiation. The Earth's absorptance for this is higher (~ 0.95) than it is in the visible (~ 0.65). And this radiation is re-radiated isotropically, rather than preferentially sunward, as albedo radiation would be. That gives it a better chance of reaching the Earth, since the sunlit side faces away from the Earth rather than toward it during most of the sunlit period. On the other hand, most long-wave radiation is intercepted higher than shortwave radiation is (no "greenhouse effect" comes into play). Let us guess that it reduces the surface heating effect from 0.95 to 0.65. That would suggest that long-wave radiation has a net effect comparable to shortwave radiation.

Next, let's analyze sunlit and eclipsed particle cases separately. This is relevant for both small particles and thin films, because they will heat up or cool down quickly compared to the orbit period. Any energy carryover would simply have the effect of reducing daytime temperatures and increasing nighttime temperatures, rather than changing the net energy balance. For the daytime case, the long-wave effect caused by the energy intercepted by a black particle should reduce the shading by 0.10 to 0.18. But keep in mind that the illuminated particle count is much higher than the count of particles that actually cast a shadow on the Earth: about 3 times larger for $R = 1.5,$ and by smaller and larger amounts for $R = 1.3$ and $1.7.$ This suggests that long-wave radiation from the particle may reduce the shadowing impact by $\sim 40\%.$

In addition to this, the particles provide a small heating effect at night, by intercepting and re-radiating back to Earth a small fraction of the

outgoing radiation. The average blackbody temperature of the night side of the Earth is probably ~ 240 K. With Earth view factors of 0.10 to 0.18, the particles will absorb and return to the Earth a long-wave radiation of 2-6 W/m^2 of particle surface, or 8-24 W/m^2 of "daytime shadow area." If the particles are in circular orbit, the time spent in this mode (shadowed by Earth) should be the same that the particles spend shadowing Earth, so the reduction in net cooling due to night-time re-radiation back to Earth should be 0.6 to 2% of the shading effect. Hence daytime re-radiation towards Earth should be far more important than night-time re-radiation towards Earth. It appears to reduce the net effectiveness of shading by roughly 40%.

Particle Ring Design Requirements

Now let us design two conceptual particle rings and compare them. To overcome a doubling of the carbon dioxide in the atmosphere over the next century, a cooling of about 1.75 K is required, which can be achieved with about a 1.6% reduction in insolation. We choose one ring extending from $R = 1.2$ to $1.5 R_e,$ and the other from $R = 1.3$ to $1.6 R_e.$ For 1.6% insolation reduction, the required opacity is 0.356, as viewed normal to the ring. Figure 5 shows the climate effects. The lower ring has a much greater effect in the 0-10° latitude band, and less in the other latitude bands. This will moderate the climate extremes, but as we shall see later, it requires much more mass.

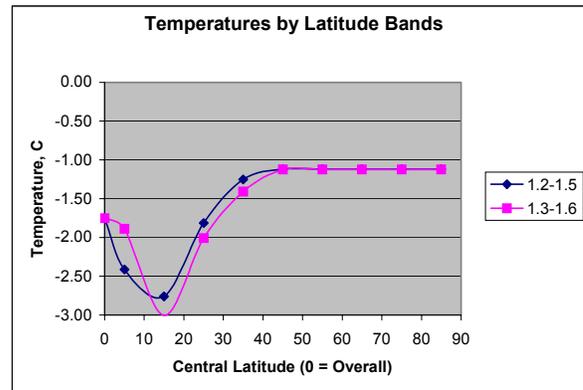


Figure 5. Temperature Reductions from Two Broad Earth Rings

We can calculate the lifetimes of particles from Equation 2. The ring should have a lifetime of about 1000 years, to cover the expected era of fossil fuel burning. For rocks of average density of 2700 kg/m^3 , the particle sizes required are:

R	1.2	1.3	1.4	1.5	1.6
D	4.3 mm	54 μ	1 μ	1 μ	1 μ

Because particles smaller than 1 micron may be swept out by non-gravitational effects, that diameter is used as the lower limit. For a lifetime of 1000 years, the lower ring edge, $R = 1.2$, must have particles 4.3 mm in diameter, ranging down to 1μ . Integrating Equation 2 over this range gives an average diameter of 5.2×10^{-4} m. Similarly, the upper ring particles, $R = 1.3-1.6$, range from 54 microns to 1 micron, with an average diameter of 4.7 microns. From Equation 4, the lower ring mass is 2.1×10^{14} kg, and the upper ring mass is 2.3×10^{12} kg, (only 1% as much), allowing for a 40% reduction in efficiency from particle heating and re-radiation. The ring mass is seen to be strongly determined by the largest particles.

Particle Ring Side Effects

This revolutionary system will have planet-wide effects as the intended result. In addition, there will be unwanted or unexpected side effects that must be dealt with. The rings will reflect sunlight onto the twilight and night portion of the Earth during the summertime of each hemisphere, providing additional evening illumination, extending twilight, and reducing the need for city and highway lighting. The total nighttime illumination at 45° latitude will be that of a dozen full moons at midnight and 48 full moons at 9 pm and 3 am. At sunset at 30° latitude, it will arch like a silver rainbow across the southern sky, spanning 11 to 26 degrees altitude maximum at due south, and shining with the equivalent of 22 full moons. This will significantly reduce nighttime lighting requirements, by extending twilight and eliminating complete darkness. It may also have adverse effects on animals, especially nocturnal ones, and on plant growth. The ring will shade the “winter” portion of the tropics, enhancing the annual temperature differential there without

directly deepening the winter in the temperate and polar regions.

The Earth ring will extend into the Van Allen radiation belts, and absorb the charged particles trapped in the belts. This will lower the intensity of the radiation belts, and reduce the radiation experienced by spacecraft and humans venturing beyond LEO. The ring will also reflect radio waves, acting as an artificial ionosphere for international communication.

The particle ring particles have limited lifetimes in LEO, and there will be a continual loss of material from the lower edge. Even a ring with a million-year lifetime will lose 10^{-6} of its mass per year—about 2.3 million kg per year raining down and impacting all LEO satellites as they cross the equator twice each orbit. This means that a particle ring must have a shepherding object at its lower edge to catch these particles, or they will destroy all LEO satellites. The shepherd needs to have a diameter equal to the thickness of the ring. Saturn’s rings are estimated to be 40-1100 meters thick, and the ring thickness scales with the orbital velocity (Burns, 1981). Earth rings, at one-third the velocity, would be ~15-400 meters thick.

A 1-km shepherding asteroid at 2700 kg/m^3 would have a mass of 1.4×10^{11} kg, just 6% of the total ring mass. A shepherding satellite could be much lower in mass. In addition to shepherding the ring particles, it could remove the ring if its orbit were gradually raised past the ring. Also, a pair of shepherding satellites, at the top and the bottom, could create the ring and catch the stray ring particles, continually replenishing the ring.

Without shepherding, an alternative solution would be to make the ring out of random pieces of a very thin tape or film, e.g., 1 cm pieces of 0.01 mm thickness, as suggested by Mautner (1991). These pieces will provide high S/M ratios, like a film of the same thickness, but the number of pieces will be orders of magnitude less than the number of particles, the ring can be much more uniform, and the pollution of low orbit will be many orders of magnitude less than with unshepherded dust particles.

Particle Ring Development Scenario

A natural Earth ring could be formed by simply bringing small asteroids into the desired orbits and letting collisions provide the ring material. The asteroids would be retrieved over decades by emplacing propulsion systems on them, and bringing them into Earth orbit at the outer and inner radii of the planned particle ring. These shepherding asteroids could also act as a source of additional ring material to replace material lost by diffusion. They would be processed for their raw materials, and the tailings would be tailored to the proper diameters to form a long-lived ring. The remnants of the two asteroids then become the shepherds that prevent ring spreading and loss of ring material.

The lower shepherd, with a sufficient diameter so that it is wider than the thickness of the ring, will prevent the constant loss of ring material from the lower edge, with its resultant sandblasting of LEO satellites. Similarly, the upper shepherd will prevent ring particles from spreading into higher orbits, where the particles could interfere with GEO satellites. To provide ring shepherding with less mass, the shepherding moons might be replaced by spacecraft with large areas to catch the decaying or spreading ring particles. The relative velocities of the particles leaving the rings will be very low, so there will be no structural difficulty in withstanding the forces.

CONTROLLED SPACECRAFT RING

Spacecraft Ring Design Requirements

Without shepherding, the particle ring would produce additional meteoroid intensity for LEO satellites, and would be more difficult to remove if it has unexpected deleterious effects. An alternative approach is to create a ring of controlled reflecting spacecraft in LEO. Putting spacecraft with multiple reflectors, or parasols, in a few dedicated orbits is more organized and easier for other spacecraft to navigate. The concept is based on the use of lightweight spacecraft using electrodynamic tethers and thin-film reflectors, which could be solar arrays (Pearson et al., 2001). These satellites have maneuvering capability (from electrodynamic forces on conductors in the Earth's magnetic

field) to keep them properly spaced without using propellant.

Tethered Spacecraft Constellation Design

Two parasol spacecraft designs can be envisioned, based on the tethered spacecraft concept. The first is to use long vertical tethers to hold parasol segments normal to the tethers. It's not clear what size gives the minimum mass per unit panel area, but the spacecraft tether could be 5 km long, with parasols 200 m wide, giving 1 km² of surface area per vehicle. The second design is a large disk of thin-film reflecting material, bounded by a ring conductor that develops electrodynamic forces to control the orientation of the reflector. A hanging electrodynamic tether could control the orbit. The disk parasols must be kept taut, which may require a perimeter current to keep them open and normal to the magnetic field. The spacecraft could be put into equatorial orbit, as shown schematically in Figure 6, where they would shade the winter hemisphere, like the dust ring.

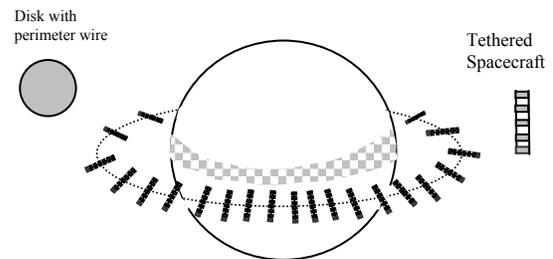


Figure 6. Concept of the Earth Ring Using a Tethered Spacecraft Constellation

As an alternative, the spacecraft could be put into medium-inclination retrograde orbits, high enough that nodal regression is once/year (1.6-1.8 Re, for inclinations of 30-40 degrees). The ascending node could be phased so the tethers are north of the equator during the day during northern summer. This gives a low solar beta angle, which means that steerable parasol segments are needed. Then during northern winter (and southern summer), the orbit plane would have a high solar beta angle, and the shadows will mostly miss the Earth. Steerable parasol segments could have their undersides reflect light onto the winter hemisphere, mostly around dusk and dawn, to extend the hours of

daylight. However, this is a less efficient use of the total shading area than the equatorial ring of spacecraft, and would only be used if the winter shading were unacceptable.

The spacecraft can be very lightweight. Existing aluminized film weighs ~ 3 grams/m². The film polyethylene naphthalate (PEN) is made in weights down to 3 g/m², and aluminization thick enough to be opaque weighs a tenth of this. Future improvements may allow the whole spacecraft to approach 1 g/m², or 1 metric ton (MT) per square kilometer. Applying the spacecraft ring in place of the particle ring at $R = 1.2$ - 1.5 with an opacity of 0.356 gives a total area required of 3.7×10^7 km². Because the spacecraft parasols can be pointed at the sun rather than staying in the plane of the ring, the effective area is reduced to about 5×10^6 km², or about 3.9% of the Earth's cross-sectional area. At a mass of 1 MT/km², this gives a total required mass of 5×10^9 kg.

If each spacecraft has a parasol area of 1 km², then we will require 5 million individual spacecraft of 1 MT each. If each actively controlled spacecraft can be made to last for 100 years, we will need to launch an additional 137 spacecraft per day, each with a mass of 1 MT. We will also have to remove 137 malfunctioning spacecraft from orbit each day. This is not a small task; to reduce the requirements, we may want to build gigantic spacecraft with 100 km² area, reducing the total number to 50,000, and the replacement rate to just 10 per week. However, the launch capacity required would still be a total payload of 1000 MT per week, orders of magnitude greater than our current space launch rates.

Spacecraft Control

Some force is needed to prevent the individual parasol segments, which need to be thin films of about 1 km², from folding. This can be done by spinning the tethered configuration, or by driving a current through a wire at the perimeter of the disk configuration, to keep the film stretched and normal on average to the magnetic field. It is possible to maintain reasonable solar pointing of the tethered petals, by modulating their natural oscillations about the radial

direction. An uncontrolled parasol presents an effective area ratio to the sun of $2/\pi$, or 64%. A simple one-axis control system can increase this to about 90%. Because of the cosine relationship, this does not require precision control, but only moderate accuracy. A pointing error of 20° reduces the shaded area by only 6%.

Beletsky and Levin (1993) describe hanging EDT petals in near-equatorial orbits. Basically, they tend to orient perpendicular to the magnetic field lines. Films wired on the perimeter are expected to behave similarly. It would be a petal-like parasol with a perimeter wire and a small satellite with a power source and control system. At least one electron collector area at the far side of the petal would be needed to produce thrust.

To combine the solar shading of these spacecraft with the production of solar power would add an additional control element for the Earth's temperature. If a significant amount of solar power is beamed down to the ground, reducing the requirement for fossil fuel burning in the atmosphere, the total amount of shading mass is reduced. There is thus a tradeoff between power production and shade production from the spacecraft. If it became necessary to increase rather than decrease the Earth's insolation, the optimum placement would probably become twilight sun-synch orbits. That will primarily increase solar input in early morning and late afternoon, which will probably cause the least problems with local overheating. The time required to move from equatorial to polar using the spacecraft electrodynamic thrust could be years, but that is fast enough on the timescale of climate changes.

Spacecraft Ring Side Effects

The major side effect of these spacecraft would be to provide a multitude of bright "stars" in the morning and evening skies, which could interfere with astronomical observations from the ground. However, the reduction in launch costs from emplacing these satellites could be used to launch many space telescopes at much lower costs. The satellite ring will have occasional failures, requiring a constant

replenishment of the satellites, and a continuing demand for new launches.

The spacecraft ring may lower the Van Allen radiation enough to allow the shading spacecraft to become solar power stations. This combination would greatly lower the cost of space solar power, at the expense of requiring actively pointed receiving antennas on the ground.

Spacecraft Ring Development Scenario

This system can be developed and deployed gradually, one step at a time, without a complete commitment up front, and the program can be stopped at any time, or delayed for whatever reason, making it much more manageable.

The first step would be aimed at designing a low-altitude test system weighing about 50 kg, with a parasol of about 100 m in diameter, orientation controlled by a 300-m wire loop, with an option to use a 100-m segment of wire to produce a low electrodynamic thrust. The parasols might even be used as electron collectors, improving efficiency of the electrodynamic thrust. Deployment can be assisted by the ampere force on the wire loop (an “inflating” loop that pulls the film out of the storage canister).

The satellites would be launched into LEO, and then would ascend to the proper orbit under their own power before deployment to full extent. Any failure would result in re-entry without damaging the existing ring of spacecraft. The ring could consist of multiple controlled satellites in different orbital altitude bands, with gaps between the orbits. Thus, if there is a spacecraft control system failure, the errant spacecraft could be repaired, using service vehicles kept in orbit for that purpose, before it had time to move to an altitude that would interfere with other spacecraft.

Spacecraft Ring Additional Applications

A spacecraft design could have various electrodynamic propulsion elements distributed and embedded into the film surface, including thin-film solar arrays, electron and ion collection areas, and tape conductors. The parasol is

designed like an electronic board, with distributed elements connected together. The spacecraft then becomes much more resistant to micro-meteoroid damage, and becomes a solar power satellite with control of its orbit and attitude.

With such a controlled spacecraft, we could increase or decrease sunlight as desired over certain areas of the Earth. If the shading objects are below 2000 km altitude, the shaded or illuminated regions can be <50 km across in most cases, and the shading is effective within 10 degrees of the equator. This would allow local directed night time lighting for ~3 hours after sunset, and could help burn morning fog off the fields in large agricultural areas during the growing season.

The spacecraft areas involved in shading the Earth are larger than those envisioned for solar power satellites. That means that even very inefficient power generation would make solar power available for beaming to the ground over latitudes up to $\pm 45^\circ$. There may be a weather-related control of parasols aimed at maximizing shielding/shining efficiency over clear (not clouded) areas, while using time over clouded areas to better control the orientation. Mautner and Parks (1990) even suggest that energy could be focused on incipient cyclones and the El Niño phenomenon to improve local weather.

The launch of the spacecraft for the ring will require continual launching of many rocket vehicles, and it is possible to use these launches to reduce the need for as much solar shielding. The addition of aluminum to the rocket exhaust, to create small aluminum oxide particles in the stratosphere is an additional method for global cooling (Brady, 1994). The optimum mix might be to use sufficient spacecraft to dissipate the radiation belts, and use them for solar power, thus lowering the greenhouse gas emissions. This will lower the total spacecraft area needed. The addition of aluminum oxide to the rocket exhaust might further reduce the spacecraft requirements. If the rocket exhaust particles and lowered emissions accomplished most of the required cooling, then the number of spacecraft might be drastically reduced.

MATERIALS AND LAUNCH COSTS

To achieve the result of cooling the Earth by planetary rings, we must emplace the required mass of 5 billion kg of spacecraft or 2 trillion kg of rocks. The material can come from the Earth, the Moon, or the asteroids. We will examine the costs of each of these sources.

Launching Earth Material

Launching the ring material from the Earth's surface would require the development of very large boosters, perhaps larger than the Saturn V booster that was used for lunar launches in the Apollo program. It would also add to the pollution of the atmosphere from rocket exhausts.

Koelle (1998) developed a cost methodology for calculating cost per kg into orbit, and Pearson et al. (2000) used this to calculate the costs for launching Earth material into orbit in terms of the size of conventional rockets and the number of launches required. For a mission requirement of 10^8 kg, for example, the minimum cost is achieved at 500 launches of a 200,000-kg payload vehicle, and is about \$2800/kg, as shown in Figure 7.

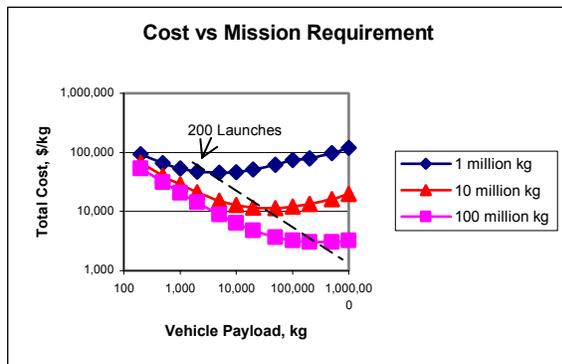


Figure 7. Cost per kg of Launching Earth Material for the Ring

Pearson, et al. (2000) proposed a ram accelerator and orbiting tether to achieve \$250/kg to LEO. Even this latter combination would cost \$1.25

trillion to launch the spacecraft ring and \$500 trillion for the particles. The cost of launching Earth materials is seen to be extremely high, even with advanced launch techniques.

Retrieving Lunar Material

For the use of lunar material, a system for launching lunar material from the moon's surface would be required, with a catcher in Earth orbit. Gerard O'Neill (1978) envisioned the use of lunar materials for the construction of space colonies, and proposed lunar mass drivers to send lunar material into high Earth orbit. With each mass driver delivering 10^9 kg/year, the 3×10^{11} kg of mass required could be obtained by using 10 mass drivers, each operating continuously for 30 years. To bring back lunar materials on a large scale, Pearson (1979) proposed a lunar space elevator, and Hoyt and Uphoff (1999) proposed a system of rotating tethers. Early (1989) estimated a total cost of \$1-10 trillion for a 10^{11} -kg solar shield using lunar materials, or \$10-100/kg, which he proposed to achieve by using robotic techniques and a minimal human presence on the moon.

Using Asteroid Material

For asteroidal material, a system for capture or processing asteroids *in situ* would be required, plus the catcher and processor in Earth orbit. Asteroids that pose a danger cross the Earth's orbit, and therefore also require only a relatively low delta-V for rendezvous and retrieval. Semi-autonomous and remote-controlled spacecraft could carry propulsion systems to candidate asteroids for *in situ* long-term retrieval operations.

Several potential propulsion techniques could be used to retrieve asteroids. A mass driver based on the Gerard O'Neill design of the 1970s (O'Leary, 1977) could be assembled in Earth orbit and launched to the target asteroid, using a high-specific-impulse ion propulsion system. This system could be robotically emplaced on the asteroid, fire asteroid material to stop its rotation, and then be aimed to provide the required delta-V to bring back the asteroid. Once the material is brought into Earth orbit, it must be processed into the proper form and placed into the proper orbit to provide a long-

lived ring. A simple grinding and sieving operation may suffice to give suitable millimeter-sized particles (O’Leary et al., 1979).

Alternatively, an ion-propelled spacecraft could simply rendezvous with the asteroid, load a large amount of material in its cargo bay, and then use its ion propulsion or a rotary “rock” rocket (Pearson, 1980) to return part of the asteroid to the Earth. Multiple trips by multiple spacecraft could provide a constant supply of asteroid material. Once sufficient mass is removed from the asteroid, the remainder could then be propelled into high Earth orbit.

In an appendix to O’Leary et al. (1979), Robert Salkeld compares the cost of retrieving

asteroidal material versus lunar material, using the O’Neill scenario of a mass driver on the moon and a catcher in lunar orbit (O’Neill, 1978). Salkeld concludes that we could bring back 1.1×10^6 tons of asteroid for \$25/kg, and we could bring back 2.4×10^6 tons of lunar material for \$24/kg; both figures include RDT&E costs. These results assume an Earth-to-LEO transportation system based on an updated Shuttle with transportation costs of \$240/kg.

Earth Ring Cost Estimates

The costs of material launching from Earth, moon, and asteroids are summarized and compared in Table 2, and the costs of the Earth rings are summarized in Table 3.

Table 2. Material Sources and System Emplacement Costs

Launch Technique	Unit Cost of Material Launching, \$/kg		
	Earth	Moon	Asteroids
Conventional Rockets	1,000-3,000	100-1,000	-
EM or Gun Launch Plus Orbiting Tether	100-500	24	-
Ion Rockets	-	-	-
Rotating Space Tethers	-	10-100	1-10
Electromagnetic (EM) Mass Drivers	-	10-100	25

Table 3. Cost of Earth Rings

Type of Ring	Mass of System, kg	Launch Cost Versus Source of Materials		
		Earth	Moon	Asteroid
Particle Ring	2×10^{12}	\$200-2000 trillion	\$20-60 trillion	\$6-50 trillion
Spacecraft Ring	5×10^9	\$500 billion-1 trillion	\$500 billion	\$125 billion

DISCUSSION

The particle ring could be composed of material from dangerous asteroids, thereby achieving two objectives. This source of material could result in lower launch and emplacement costs than Earth surface launching. It would also open a new source of raw materials and resources. It would also reduce the intensity of the Van Allen radiation belts and provide a reflector for worldwide radio communications. However, it

could have deleterious environmental effects on LEO spacecraft, and it would reduce nighttime darkness, with potentially harmful effects on nocturnal animals and on the growth cycle of plants. It would also be difficult to remove.

The controlled spacecraft ring could be lighter in weight for the same shielding effectiveness, and could perhaps be fabricated from asteroidal or lunar materials as well. It would provide better environmental control than the particles, allowing directed light to selected parts of the

ground, and providing additional lighting to counter ice ages as well shielding to counter global warming. The spacecraft ring could also perform as solar power satellites, reducing the amount of fossil fuel burning in the atmosphere, and the overall requirement for shading. It would also reduce the radiation belts, but could have far less effect on nighttime darkness. It would be incremental, controllable, and reversible if required.

CONCLUSIONS

The use of an Earth ring for climate control was examined. A ring composed of particles or multiple spacecraft can be used to provide sufficient opacity to reduce insolation by 1.6%. The lower altitude is limited by atmospheric drag at about $R = 1.15 R_e$, and the efficiency drops beyond $R = 1.85 R_e$. A ring of particles would be optimum at $R = 1.3-1.6 R_e$, and a ring of active spacecraft at $R = 1.2-1.5 R_e$. The particle ring was designed to last for 1000 years, by using larger particles at the lower altitudes, ranging from 2.3 mm diameter to 1 micron at the top. Unless the ring is controlled with shepherding satellites, it will produce a severe micro-meteoroid flux on LEO satellites, and is difficult to reverse in the event of unforeseen side effects. However, it can be constructed of lunar or asteroidal materials at a lower cost than Earth launching. The ring of spacecraft allows orbit and attitude control, higher efficiency, and less of a problem for other satellites, but requires multitudes of Earth launches or the processing of asteroid material in Earth orbit for construction. One advantage of the spacecraft ring is that it can be constructed and tested on a small scale, and the satellites themselves can be used for other purposes, such as solar power. The required shading may be reduced if solar power production becomes significant, as the amount of fossil fuel consumed in the biosphere declines. The required shading may also be reduced by using rocket launches to place particulates in the stratosphere for part of the shading. A near-term test of the satellite constellation would have other payoffs, including advancements in thin-film satellite technology for solar arrays and solar sails, and

new capabilities in electrodynamic propulsion for LEO satellites.

In the broader context of world climate control, such schemes would have widespread and perhaps unexpected results, from changing rainfall, sea currents, and wind patterns to even creating or destroying deserts, grassland, forests, and glaciers. No such planetary engineering would be possible without extraordinary precautions, careful engineering, and attention to a myriad of international and regional concerns.

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