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A Project Report on

"Feasibility of a Dyson Ring"

As a part of B.Sc (Physics) degree of Savitribai Phule Pune University

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Feasibility of a Dyson Ring

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Abstract

Solar power being an important energy source for life on earth, is least exploited. This project will attempt at studying and predicting whether it is possible to substantiate the idea of Dyson ring, which has been around for a long time, in order to utilize solar energy on a larger scale. In order to simulate this idea, Wolfram Language (Mathematica) was used.

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1 Introduction

> The primary means of energy generation is going to solar. It will at least be a plurality, and probably be a slight majority in the long term.
>
> *Elon Musk*
> *CEO of SpaceX & Tesla*

Freeman Dyson, in his 1960 paper [**3**], gave a perspective on how an advanced civilization can harness and utilize the power of it's parent star. He proposed that such a civilization might build a megastructure around it's parent star. In his words[**3**]:

> "The most likely habitat for such beings would be a dark object, having a size comparable with the Earth's orbit, and a surface temperature of 2000 to 3000K. Such a dark object would be radiating as copiously as the star which is hidden inside it, but the radiation would be in the far infrared, around 10 microns wavelength."

This object was later known by his name as Dyson sphere and is quite popular among sci-fi authors[1]. But practically, such a structure would be highly unstable as it might drift and even collide with the central star, unless the movements of this sphere as a whole are corrected. Another issue is resources especially minerals required to build this megastructure. In case of our solar system, it would take mining all the terrestrial planets in order to gather resources for creating a Dyson sphere of radius 1 A.U. Obviously, this isn't economical viable plan in the long term considering the maintenance of power storage devices and radiation sinks of this sphere.

The closest we can get to building a Dyson sphere is a structure called Dyson swarm, which is discontinuous unlike Dyson sphere. A Dyson swarm involves collectors (basically, solar power collecting satellites) orbiting the star in a specific fromation. The simplest of which is a ring formation[2] called Dyson ring (or Niven ring[3]). A Dyson ring is maneuverable and cost effective compared to a Dyson sphere. It will consist of a limited number of collectors and these will orbit the star (in our case, the Sun) in circular orbits at a specified distance (say, a few solar radii). These collectors will be equipped with power storage devices such as a battery or a supercapacitor, for later use. In order to transfer this collected power at large distances, a laser network can

[1] Such as Star Maker, by Olaf Stapledon, which inspired Dyson to propose this concept.
[2] Other formations being a Dyson bubble and collection of Dyson rings
[3] Named after the author Larry Niven who explored this concept in his 1970 sci-fi novel *Ringworld*.

be used. This laser network will then convert the collected energy into a beam of laser and transmit it to a receiver at desired location(s).

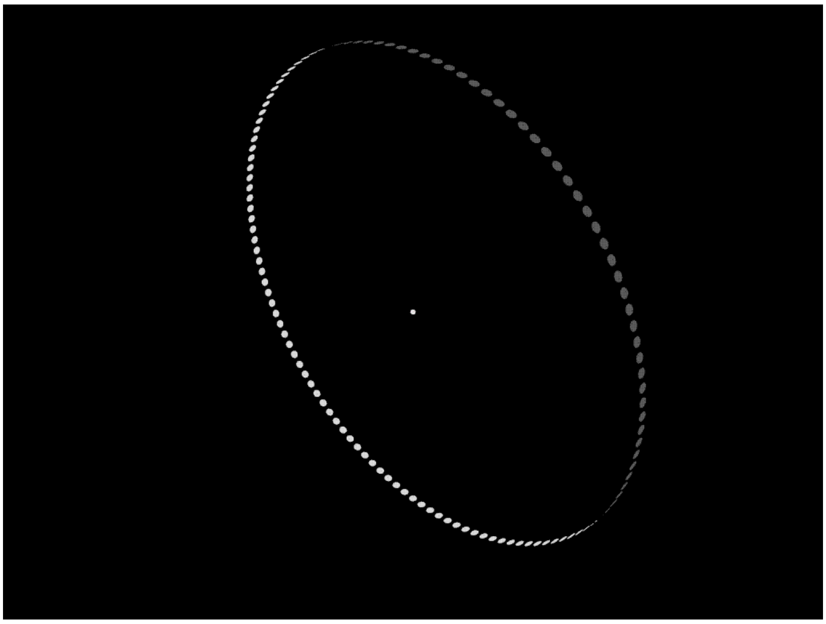

Figure 1: An illustration of a Dyson Ring (to scale). Orbit is depicted at 1 AU radius.(Image courtesy: Wikimedia Commons)

Fig.1 shows an illustration of how a Dyson ring might actually look like if the collectors are revolving at a radius of 1 A.U. from the Sun. Though the collectors shown are huge, in actuality, this might not be the case due to limitations of resources and orbital mechanics of this system. The ring will have to face immense yet finite amount of gravitational force if placed close to the Sun. Also, synchronized revolution is difficult to achieve. Thus, reducing the size of collectors can help tackle this problem.

This paper will present calculations associated with collection and power transmission of such a Dyson. The orbital mechanics and gravitational effects are out of scope of our discussion. Although, possible problems or challenges will be discussed in brief.

2 Theoretical Background

2.1 The Sun

The Sun being the closest star to Earth is essentially a hot sphere of plasma with an average radius of the order 10^8 km and at a distance of 1.5×10^{15} km[4] or 8 light-minutes. It rotates about it's axis once every 4 weeks but not as a solid body. The equator takes around 27 days whereas the poles take about 30 days to complete one rotation.

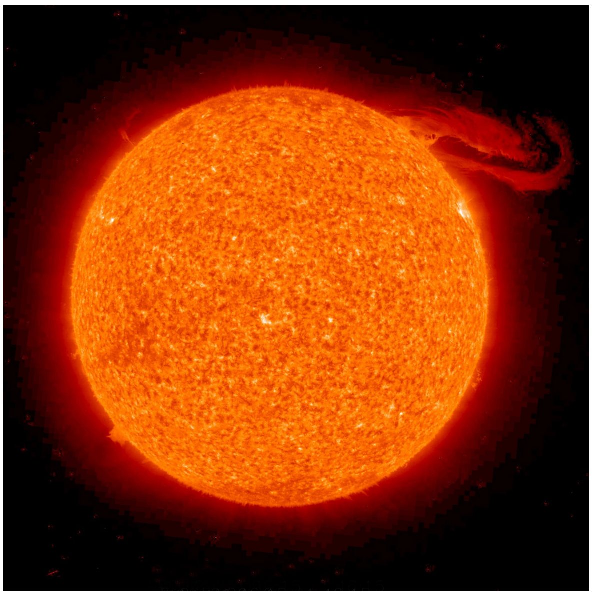

Figure 2: False color image of Sun as seen in UV region captured by STEREO spacecraft in 2008. (Image courtesy: NASA)

Effective surface temperature of the Sun is around 5772 kelvin. At it's core, the temperature is about 15 million kelvin[**2**]. This temperature is necessary to carry out the fusion reactions which produce 99% of energy which is given out in the form of radiation by the Sun. Hydrogen fusion (also called, proton-proton chain reaction) is an important reaction among all [5] the fusion reactions that take place inside the core. This reaction is called proton-proton cycle and involves fusion of four H atoms to create a single He atom, releasing 26.7 MeV energy. Every second approximately 600 million tons of hydrogen is fused inside the core converting 4 million tons of matter into energy. The gamma rays produced in the fusion reaction scatter into millions of visible photons, this is the light that we mainly perceive and utilize.

Solar energy is radiated through space and it reaches Earth in the form of sunlight. This energy supports life on Earth by photosynthesis. The photosynthesis reaction uti-

[4]This distance is called one astronomical unit (A.U.)

[5]The other reaction is carbon-nitrogen-oxygen cycle (CNO cycle) which generates less than 10% of total solar energy

lizes sunlight (photons) in order to break down water molecule while producing glucose using carbon dioxide and giving out byproduct oxygen which is essential for respiration by organisms on Earth. Along, with supporting life, solar radiation also shapes climate on Earth. A significant amount of sunlight reaching Earth is attenuated by Earth's atmosphere. The sunlight reaching Earth's upper atmosphere has the following composition - about 50% infrared light, 40% visible light, and 10% ultraviolet light (70% of which is filtered as it ionizes the ozone present in the upper layers of atmosphere). The value of solar constant[6] is 1368 W/m^2 at a distance 1 A.U. from the Sun. This value reduces to 1000 W/m^2 near the surface of Earth. This radiation has directional characteristics that are defined by a set of angles that determine the angle of incidence of the radiation on a surface. The maximum value is obtained when the absorbing surface is normal to the incident radiation.

The solar constant (also called Solar Irradiance) is an important factor which determines the solar power which an object absorbs if held at a distance (say, R) from the Sun and is an important factor in this study. This value increases as we go closer and closer to the Sun. Irradiance can be calculated from luminosity.[7] In this case, solar irradiance (henceforth denoted[8] as $I_\odot$ is what interests us most, thus we would require Solar Luminosity (henceforth denoted as $L_\odot$) for calculating $I_\odot$. We define $I_\odot$ as follows (where R is the distance from Sun's photosphere):

$$L_\odot = 4\pi R^2 I_\odot \tag{1}$$

$L_\odot$ has an approximate value[**2**] of 3.848×10^{26} W. Note that luminosity is not same as brightness of the star which is a quantity that depends upon luminosity as well as other factors such as distance between observer and star and the absorption of light along the path from star to the observer.

Another important property of Sun is it's radius, usually referred to as Solar radii (henceforth, denoted by $R_\odot$) which is the distance between Sun's center and the photosphere[9]. $R_\odot$ has an approximate value of 6.957×10^8 meters. This value is 109 times the average radius of Earth. It should be noted that this value changes from poles to equator due to rotation of the Sun. $R_\odot$ is unit in which orbital radius of spacecrafts revolving around the Sun is usually measured. For example, the Parker Solar Probe which was launched in 2018 currently en route to study the structure and dynamics of

[6] Amount of power incident on a surface of unit area when exposed to sunlight

[7] Luminosity is the total amount of energy emitted per unit of time by a star, galaxy, or other astronomical object. In terms of units, it is synonymous with power.

[8] The subscript $\odot$ signifies that the quantity is related to the Sun

[9] The photosphere is a star's outer shell from which light is radiated.

upper solar atmosphere i.e. solar corona, will approach within $9.86R_{\odot}$. This will be the closest a spacecraft has ever passed the Sun.

2.2 Solar cell and arrays

Collection and consumption of all incident solar energy is not possible for a variety of reasons:

- The atmosphere captures and scatters some of the solar radiation, which is why the sky is blue and sunsets are red. This effect is stronger in latitudes away from the equator.
- Because the earth turns, half the time the sun is not visible at all. And for much of the day the sun is near or not very far from the horizon. Solar arrays that track the sun are expensive and complex, with moving parts that must be maintained. Solar arrays that do not track the sun absorb less energy than is available.
- Clouds interfere with solar radiation in most parts of the earth, and surfaces of solar arrays can be fouled by dust and other crude that falls from the sky.
- Existing technologies for conversion of solar radiation into electricity are, currently, expensive relative to other sources.

There are two principal means of solar generation of electricity[**4**]:

– One employs heat engines similar to fossil fuel or nuclear generation, using sunlight to heat the top end of the heat engine cycle. Often this is in the form of a 'solar tower', with the element to be heated at the focus of a lot of mirrors. The operational issues with this sort of a system are chiefly associated with tracking and focusing the sunlight on the top element. The method of operation of the power plant is similar to that of any other heat engine.

– The second means of generating electricity from sunlight employs photovoltaic cells. These are large area junction diodes that, when sunlight shines on them and splits electron/hole pairs, produce a current. The cost and efficiency of these cells are not very favorable at the present time, although for certain applications such as powering space stations (where solar energy is more abundant than it is on the surface and where other fuels are very expensive) or powering remote, low power services would otherwise be very expensive, they are the power source of choice. There has been and continues to be substantial development of solar cells and it is to be anticipated that cost and performance will continue to improve.

Photovoltaic energy conversion is what concerns this discussion. It involves a few steps which are described below[**4**]:

- Excitation in the absorber material due to light absorption.
- Conversion of this excited state into a free positive and negative charge carrier pair.
- A transport mechanism which causes these charge carriers in opposite directions, in effect, creating current in the electrodes used.
- Combining of these charge carriers after doing work at an electrical load bringing the absorber back to ground state.

Photovoltaic (PV) cells can be designed to be effective for conversion of electromagnetic radiation other than the visible radiation (sunlight), for instance, PV cells that convert infrared radiation into electricity can be designed and these are called thermal PV devices. At the heart of PV cells are semiconductors composites (or compounds). Solar cells consists of a absorber material sandwiched between two electrodes. In order to reduce losses due to reflection, AR (anti-reflection) coating is applied on the surface. The output power and efficiency of a PV cell depends upon the current density (J) produced and operating voltage (V). Maximum power (P_{out}) is obtained when the voltage and current are maximum[**4**].

$$P_{out} = J_m \, V_m = \frac{I_m \, V_m}{A} \tag{2}$$

where A is the area of that PV cell.
Efficiency of a PV cell is given by the following equation:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{J_m \, V_m}{P_{in}} \tag{3}$$

For cells collecting light over a larger area than that generating the current (i.e., for concentrator solar cells), this expression is replaced by:

$$\eta = \frac{A_s \, J_m \, V_m}{A_c \, P_{in}} \tag{4}$$

where A_s is the area responsible for generating current and A_c is the area collecting photons.

An ideal J-V curve is rectangular with the maximum coordinates as $(V_m, \; I_m)$ i.e. the ideally shaped J-V characteristic would be rectangular and would deliver a constant current density J_{sc} until the open-circuit voltage V_{oc}. For such a characteristic, the

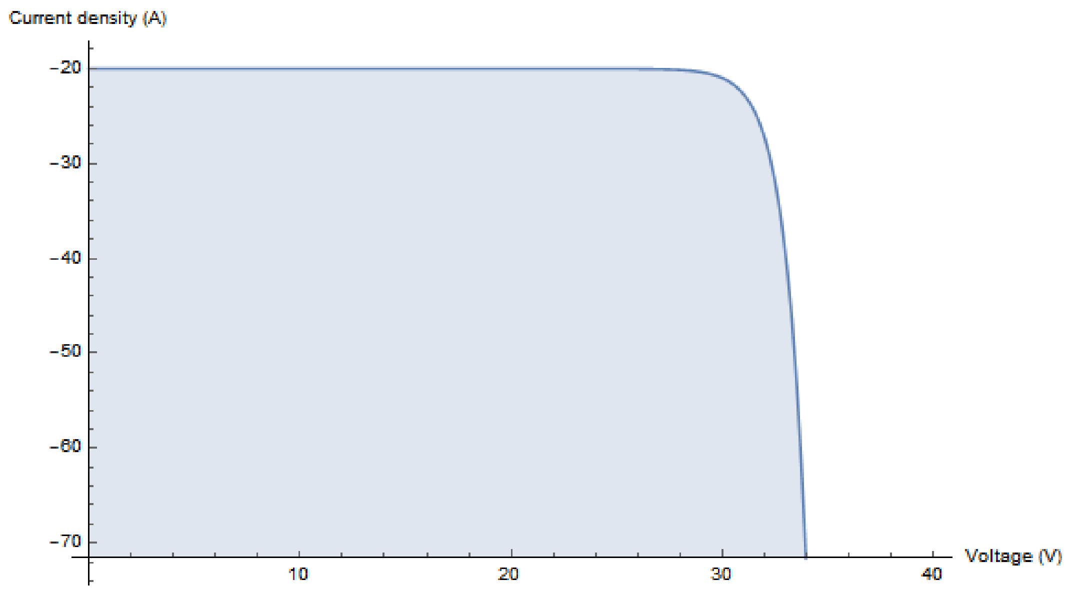

Figure 3: A typical J-V curve

maximum power point would have a current density of J_{sc} and a voltage of V_{oc}. A term called as fill-factor has to be introduced in order to measure the "squareness" of a J-V curve or how close a normal curve is to the ideal one. Fill-factor is mathematically expressed as:

$$FF = \frac{J_m V_m}{J_{sc} V_{oc}} \tag{5}$$

Value of FF is less than or equal to 1, by definition.

Solar cells can be manufactured from 'absorber' having a mono-crystalline or poly-crystalline structure. A mono-crystalline structure comprises of single crystal material in which long range order is preserved. Whereas poly-crystalline structures comprises of many single crystal regions (grains) separated by grain boundaries. These can be further classified into micro and nano crystalline solids on the basis of size of the grains.

Carriers, free electrons in a semiconductor conduction band (CB) and the free holes in a semiconductor valence band (VB), are what are needed to make a solar cell work. Once electrons are excited to the conduction levels and the corresponding holes are created in the valence levels, or once excitons[10] dissociate, producing electrons in the conduction levels and holes in the valence levels, the aim is to get them to do work.

In order to enhance the efficiency, the process of upconversion can be used. Upconversion is a process where light can be emitted with photon energies higher than those

[10] An exciton is a bound state of an electron and an electron hole which are attracted to each other by the electrostatic Coulomb force

of the light generating the excitation.[11] The term upconversion is also sometimes used for other types of processing which generate shorter-wavelength photons. An example is the upconversion of infrared photons to the visible spectral range by sum frequency generation in a nonlinear crystal. This can be used e.g. for single photon counting at long wavelengths, where no suitable detectors are available. See [**6**] for more information on a multi-photon upconversion, which can be utilized so as to increase the efficiency of a PV cell upto 50%.

Interconnected solar cells are called as *modules* and many modules arranged in series form a solar *array*, Shown in Fig. 4. In Fig. 5 we can observe that a PV cell is sandwiched between an AR coated glass and backing sheets and protected by an aluminium frame. Depending upon the purpose and placement of an array, the composition of glass has to be changed.

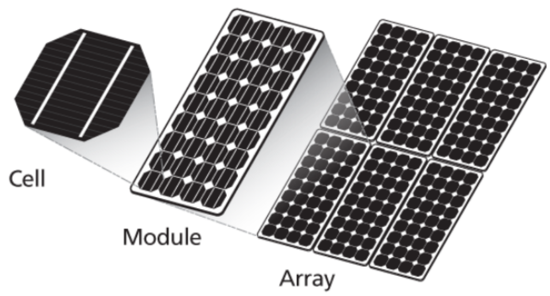

Figure 4: A PV cell, a module and an array.

(Image courtesy: Samlex Solar)

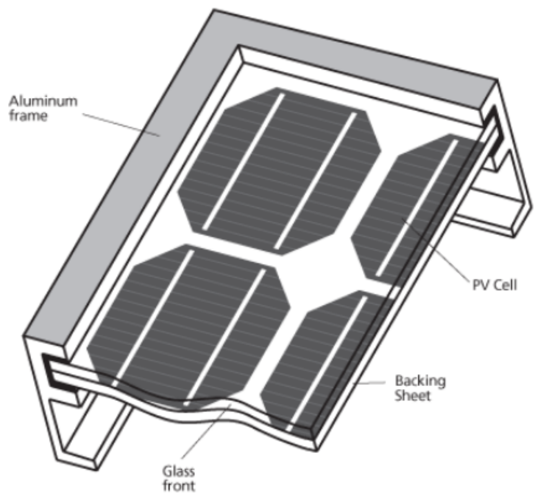

Figure 5: Construction of a mono-crystalline PV panel.

(Image courtesy: Samlex Solar)

[11] `https://www.rp-photonics.com/upconversion.html`

2.3 Laser power transmission (LPT)

Wireless power transmission has been around for many years and microwave power transmission (MPT) is mostly used for communication purposes on Earth and to communicate with spacecrafts. But LPT is comparatively new to this field and hasn't been put to real test since LPT faces huge losses and thus isn't economical. But using MPT is tedious as it requires huge receivers and transmitters and isn't practical for large scale power transmissions, for instance, in space. Microwaves (MW) can also interfere with communication devices and that could cause a major issue. Also, MW gets reflected by the atmosphere and thus have to face some losses in this case.

Laser energy transmission systems are very similar to energy transmission via microwave technology: the power source (solar, electricity) is converted into an emitter or an emitter array that generates the directional electromagnetic radiation, which is subsequently absorbed in a receiver, which transforms the energy back into a more useful transportable form, e.g. electricity, heat, hydrogen. The key difference, the wavelengths used, implies the major other differences between the laser and microwave-based concepts: While most wireless power transmission rely on microwave frequencies of either 2.45 or 5.8 GHz (0.12-0.05 m; in (ISM) frequency band[12]), laser energy transmission takes advantage of the atmospheric transparency window in the visible or near infrared frequency spectrum[**5**].

A major drawback of LPT is its low efficiency. Lasers generate phase-coherent electromagnetic radiation at optical and infrared frequencies from external energy sources by preferentially pumping excited states of a "lasant" to create an inversion in the normal distribution of energy states. Photons of specific frequency emitted by stimulated emission enter and are amplified as standing waves in a resonant optical cavity. The most efficient DC-to-laser converters are solid-state laser diodes commercially employed in fiber optic and free-space laser communication.[**5**] Alternatively, direct solar-pumping laser generation has a major advantage over conventional solid state or gas lasers, which rely on the use of electrical energy to generate laser oscillation since the generation of electricity in space implies automatically a system level efficiency loss of roughly 60%.

A key to efficient LPT is selection of laser rods (or lasant). The power output of direct solar pumped lasers depends fundamentally on the overlapping between the

[12]ISM (industrial, scientific and medical) radio bands are radio bands (portions of the radio spectrum) reserved internationally for the use of radio frequency (RF) energy for industrial, scientific and medical purposes other than telecommunications

standard solar emission spectrum and the laser absorption one. Hence, in order to increase this overlap, the unwanted frequencies have to be filtered out. Another key to large scale laser power transmission is the thermal system design. The concentration factors and lasing efficiencies require the efficient rejection of substantial amounts of heat.

Laser diodes prove to be perfectly suited for this project. Laser diodes can have a narrow spectral bandwidth and high brightness. Laser diodes can be tuned by varying the composition. Wavelength tuning was achieved by varying the ratio of Ga to Al. Later, quantum well laser diodes were tuned by varying the width of the quantum well. Laser diode arrays for pumping solid state lasers are available between about 0.67 to 0.69 μm using GaAlInP, 0.78 to 0.84 μm using InGaAsP, as well as 0.90 to 1.00 μm using InGaAs[13]. Spectral bandwidths can be as small as a few nm, commensurate with the absorption features of many lanthanide series lasers. Narrow spectral band width diodes, tuned to strong absorption features, provide much higher absorption efficiencies. Advantages of laser diodes include a narrow spectral bandwidth that is tunable to strong absorption features, high brightness, and a long lifetime, often in excess of several 1000 hours. Disadvantages include a relatively high cost. However, as demand for diode pumped lasers increases, the cost of laser diode arrays continues to decrease.

2.4 Orbital velocity

Although, there will be no discussion on the 'precise' orbital mechanics of the Dyson ring, small mathematical introduction on the topic might prove to be fruitful in the long run. Using Newtonian mechanics it's can be found out that orbital velocity can be found when an equilibrium between gravitational force (directed towards the center) and centrifugal force (directed outwards) is achieved. Mathematically, this can be expressed as:

$$\frac{mv^2}{R} = \frac{GMm}{R^2}$$
$$\therefore \quad v_{orb} = \sqrt{\frac{GM}{R}} \tag{6}$$

It should be noted from eq. 6 that, orbital velocity is independent of mass of the object revolving (in our case a collector) and depends only[14] on the mass of the Sun and the orbital radius (R).

[13] `https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080007132.pdf`
[14] G is universal gravitational constant having value $6.67 \times 10^{-11}\ Nm^2kg^{-2}$

3 Explanation of work

3.1 Orbit of collectors

Selection of orbit for the collectors[15] is an essential factor which will determine the power that the system will receive. Smaller the orbit, densely packed the system and more is the incident radiation (i.e larger irradiance). But placing the collectors closer to Sun will heat up the system quickly and might even damage the delicate electronic devices. Getting rid of this heat will require additional machinery which can increase the overall weight of the collector and so will the cost. The closest a spacecraft has been to the Sun is the Solar Orbiter[16] which flew at a distance of $45R_\odot$ though it has a stable eccentric orbit at $60R_\odot$ The recently launched Parker Solar probe will break this record by flying at a distance of $9R_\odot$. But the purpose of these missions was different. In our case, a collector cannot go this close to the Sun as the amount of radiation would be high and can significantly reduce the lifetime of the PV cells. Also, a larger fraction of power generated will be utilized by the thermal control systems and this would make these collectors redundant.

In this paper, we'll consider the orbital radius for collectors as $60R_\odot$ and for the simplicity of calculations the orbit shall be assumed to be circular though in actuality an elliptical orbit might be more stable. Orbital radius is essential for calculating the orbital velocity. From eqn. 6 we can calculate the orbital velocity with mass of Sun ($M_\odot$) being approximately 1.988435×10^{30} kg and orbital radius equal to $60R_\odot$.

$$v_{orb} = \sqrt{\frac{GM_\odot}{60R_\odot}} = 56.367 \text{ km/s}$$

In case we had chosen the orbital radius to be 1 A. U. which is roughly around $215R_\odot$, the value of v_{orb} would've reduced significantly to around 29.777 km/s. This is (for obvious reasons) approximately the orbital velocity of Earth. This velocity is far less compared to the velocity that will be achieved by Parker probe on its closest approach to the Sun which is predicted to be around 200 km/s. In order to simulate this velocity we can define the animation rate as:

$$a_r = \frac{v_{orb}}{c} \times 10$$

This equation is relevant only to the simulation presented along this paper. Upon

[15]We define collectors as solar power collecting satellites

[16]`http://sci.esa.int/solar-orbiter/`

substituting the values it turns to be $a_r = 0.00187893058$. [17]

As we've chosen a circular orbit, it would be better to place the collectors symmetrically. This would ensure that they aren't experiencing any force due to each other but due to planetary objects only. Though this wouldn't ensure the stability of the orbit as elliptical orbits would be more fruitful than circular ones. Alas! that's out of scope of this paper. Which is why we'll be sticking with circular orbits. Calculate the angular separation is quite easy. Let's assume that n_s is the total number of collectors in orbit. Angle subtended by circle is 2π rads[18]. Then the angular separation would be given as:

$$\theta = \frac{2\pi}{n_s}$$

Using this angle to render graphics, we obtain the following condition. In order to

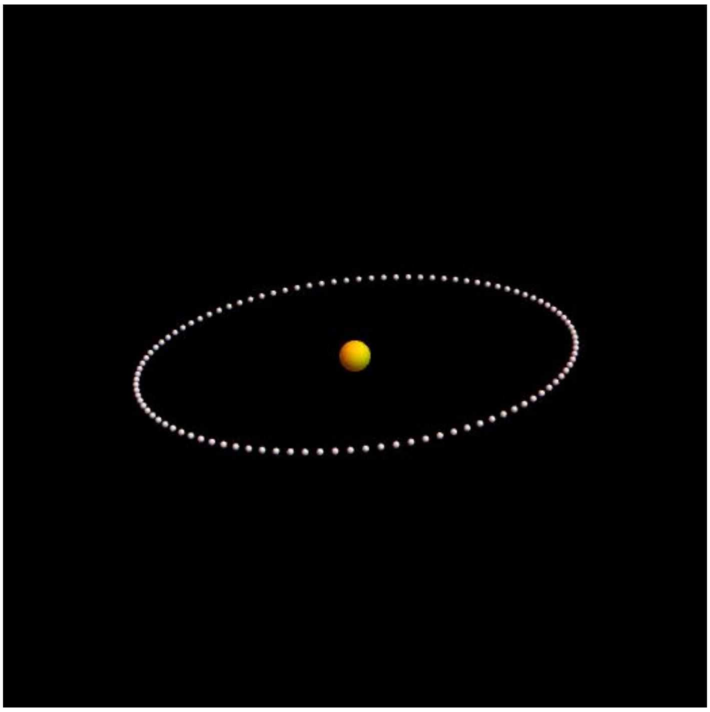

Figure 6: A Dyson ring consisting of 100 collectors (Not to scale)

render this graphic, we've used $n_s = 100$, which yields $\theta =$ 0.0628 rads or 3.6° This seems small but considering the radius which is $60R_\odot$, the distance between any two collectors turns out to be $60R_\odot\theta \approxeq 2.6 \times 10^6$ km which is of the order of $R_\odot$. This gives an idea about the scales we're working with.

[17]This means that v_{orb} is 0.018 times the speed of light.
[18]If 2π is replaced by 360, we'll get the angular separation in *degrees*

3.2 Calculations related to luminosity

Solar luminosity as discussed earlier is a large number and utilizing 'all' of this incident radiation is impossible. That's why, we'll be concentrating only on a specific region of the Sun which will provide maximum normal radiation. The height of which is variable and can be considered according to the dimensions of the collectors. This area will be the central strip (or band) which will coincide with the plane of orbit of collectors. In order to calculate the area of this strip we need to calculate this height then integrate the surface element in spherical coordinate system. For further calculations we'll be referring the Sun as a sphere.

Consider the circle obtained by intersection of this sphere and a plane have radius R, angle subtended by its center be Θ and S be the arc length which (considering R to be very large) will be almost a straight line. Using simple trigonometry, we can deduce that this angle will be,

$$\Theta \;=\; \arctan(\frac{h}{\sqrt{R^2 - h^2}})$$

The angle that we're interested in is 2Θ. Instead of calculating area w.r.t. 2Θ we'll be calculating area w.r.t. Θ, then double it. Surface element in this case will be

$$r^2 \sin\Theta \; d\Theta \; d\phi$$

Here, $r = R$. Ranges of Θ and ϕ being

$$0 \;\leq \Theta \leq\; 2\pi \text{ and}$$
$$0 \;\leq \phi \leq \arctan(\frac{h}{\sqrt{R^2 - h^2}})$$

This integral yields the following (after multiplying by 2 as we've considered only Θ),

$$A_s \;=\; 4\pi R_\odot^2[1 - \cos[\arctan(\frac{h}{\sqrt{R^2 - h^2}})]] \tag{7}$$

As the area of this strip can be manipulated using h, we can write $A_s \;=\; A_s(h)$ i.e. A_s as a function of h. The radius of sphere being larger when compared to the height i.e. $R \;\gg\; h$ simplifies above equation to

$$A_s \;=\; 4\pi R_\odot^2[1 - \cos[\arctan(\frac{h}{R})]] \tag{8}$$

Fig. 8 and 7 compares the area of the strip to the surface area of sphere. Whereas fig. 9 shows how the actual area of strip might compare to the the area of sphere.

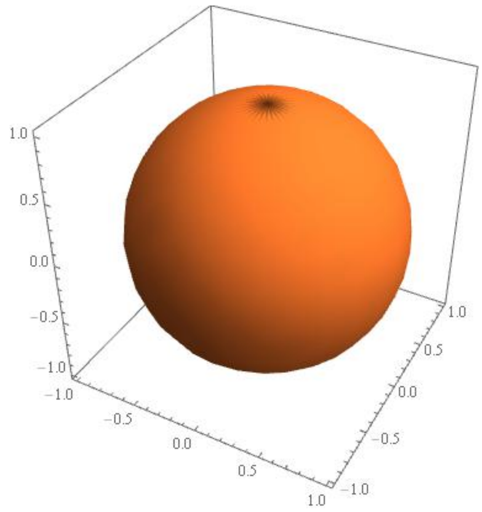

Figure 7: Area of sphere

Assuming that the span of a single collector would be far less than 10 km, we can use this value as h. Substituting $h = 10000\ m$, we obtain $A_s = 6.283 \times 10^8\ m^2$. This area is tiny when compared to the surface area of Sun. Luminosity of this strip can be calculated using the following equation:

$$L_s = \frac{A_s\, L_\odot}{A_\odot}$$

Plugging in the values, we obtain, $L_s = 1.59008871 \times 10^{17}$ W

As we've discussed earlier, the irradiance is dependent on the distance between source and receiver (in our case this distance would be the orbital radius). From eq. 1, we can calculate the irradiance when $R = 60R_\odot$ and $L_\odot = 3.848 \times 10^{26}$ W. The value obtained is $I_\odot = 17574.3266\ W/m^2$ which is approximately 12 times greater than what is in the upper atmosphere of Earth. This will be used while calculating power generated of the system in the next part.

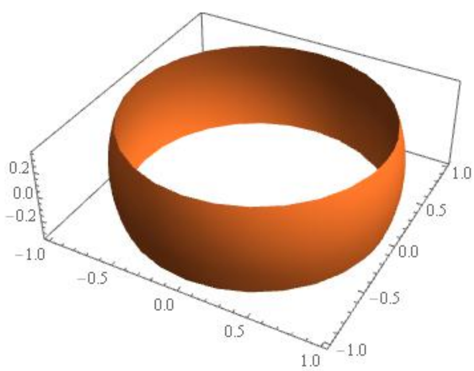

Figure 8: Area of our interest (the strip). Not to scale.

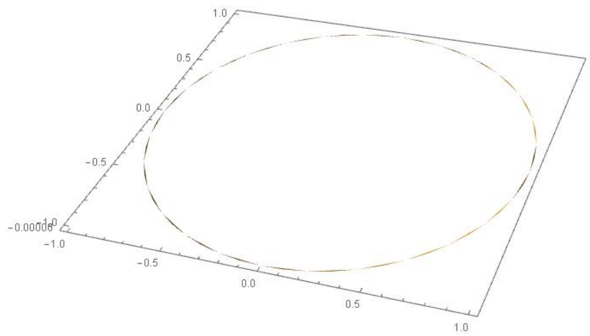

Figure 9: Actual area of strip when R is very large

3.3 Power generated

Power generated by the system depends upon the efficiency of the PV cells used. Also, an important factor will be the area spanned by the solar arrays. The area of solar arrays will also increase the weight of the collector, so it is important that the weight of the collector is optimum in order to reduce the payload when launching the rocket. This will ensure that the launch cost is low. For calculation purpose we'll use the dimensions of solar arrays of ISS[19].

Eight solar arrays of ISS together span an area[20] of 2500 m^2. We can consider the area of a single array for calculations which turns out to be roughly 312 m^2. If a single collector has N_a such arrays which can be rolled, then area span of a single collector will be n_s 312 and for n_s such collectors, the total area spanned by the Dyson ring will be

$$A_d = 312\ N_a\ n_s \tag{9}$$

Let's define two quantities which will be important for further deduction of the argument.

1. **Power received:** It is the product of irradiance and total area of the solar array. Essentially, it is the power which the system receives from the source (here, Sun). Mathematically it is defined as:

$$P_{rec} = A_d I \tag{10}$$

2. **Power generated:** It is the product of power received by the system and the

[19]International Space Station
[20]`https://www.nasa.gov/mission_pages/station/structure/elements/solar_arrays-about.html`

efficiency of the solar arrays. This is a significant quantity which would decide the economical evaluation of the project. Mathematically, it is defined as:

$$P_{gen} \;=\; P_{rec}\,\eta \tag{11}$$

Earlier we've assigned the value to n_s as 100. If we choose $N_a \;=\; 10$, we arrive at the value for the total area spanned by the Dyson ring as 312000 m^2. In order to calculate P_{rec} we refer to the value of irradiance calculated in previous sub-section, which is, $I_\odot \;=\; 17574.3266\ W/m^2$.

$$P_{rec} \;=\; I_\odot\, A_d \;=\; (17574.3266)(312000) \;=\; 5.48318988 \times 10^9 \text{ W}$$

Calculating power generated will require making some assumptions and consideration of a few standard values regarding solar arrays. First of all, efficiency of the system will depend upon the type of material used to manufacture the solar cells. The two types of PV cells that we'll be focusing on are: ordinary silicon PV cell and two step up-conversion PV cell. These have efficiencies approximately as 0.2 (20%) and 0.5 (50%) respectively. Substituting these values in eq. 11 we get the following results:

Type of PV cell	η	P_{gen} (GW)
Si	0.2	1.09663798
TSPC	0.5	2.74159494

The rightmost column shows the power generated in gigawatts for arrays made up of respective PV cells. We can observe that the power generated by TSPC type of PV sell is almost twice of the power generated by normal silicon PV cell. Although, it should be notes that TSPC type of cells haven't been commercially put to test. So, these calculations are purely based upon assumptions that they can be face harsh conditions in space.

3.4 Power incurred

The power that can be transmitted from a Dyson ring depends upon the type of laser being used for conversion/transmission purposes. Laser diodes can convert electrical power to optical power with efficiency[21], η_L, as high as 0.7 . Thus, we'll be considering laser diodes for the purpose of calculations. Diode laser take less space which implies that we can increase the number of lasers to be accommodated in a collector. But let's limits this number in order to maintain thermal efficiency of the collector. We'll assume the number of lasers per collector to be 10 and $\eta_L = 0.7$ as the efficiency of the laser array. We define another quantity called power incurred as:

$$P_{inc} = P_{gen}\, \eta_L \tag{12}$$

Above equation can be used to calculate power incurred when $\eta_L = 0.7$. These calculations yield the following

	Si	TSPC
P_{inc} (GW)	0.7676	1.91911

It can be seen that a Dyson ring with mere 100 collectors can generate power in the order of gigawatts. Increasing the number of collectors can significantly increase the power incurred. This whole energy won't be transmitted at once, thus collectors need to have batteries in order to store this energy. Or this energy can be transmitted to relay satellites which will store energy. This will reduce the battery weight in collectors.

[21] `https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080007132.pdf`

4 Result and Discussion

4.1 Economic viability

In the last section, we have seen how a Dyson ring as a system of collectors might work. Running the numbers yield a minimum power of 0.768 GW which is huge. We can compare this to the power used on daily basis we might get an idea of how significant this amount is. An active computer and monitor may use up to 270 watts. A small refrigerator uses about 725 watts. A power hungry city of one million people consumes 1500 MW power yearly. A hydroelectric dam generates around 3000 MW of power. Which means this power is enough to to power a city. But we should note that the calculations are for 100 collectors separated by a large distance. If the number of collectors is increased then the area spanned increases significantly and power output will increase too. The incurred power that we've obtained is enough to power 1 million such refrigerators. If a Dyson ring has to be build with the current technology, it might not be as efficient as we want.

The cost of launching a kg of weight into space is \$2200 with SpaceX's Falcon Heavy rocket. A typical collector whose solar panels can be rolled will weigh approximately 1 ton or 1000 kg. Which implies that launching cost for a collector will be \$2.2 million. And so the cost of launching 100 such collectors will be \$220 million. These are just launching costs. The amount of fuel and power it will take to put these into orbit will increment the cost by at least 10%.

In order to estimate the project cost we can consider the cost of Parker probe which is \$1.5 bn[22]. If we assume the cost of placing a collector into orbit to be approximately \$1 bn, then the project cost rises to \$100 bn. These prices depend on the factors:

- type of PV cell (material of solar cell)
- heat sinks
- thermal insulation
- maneuvering instruments
- lasers and temperature control systems
- maintenance

[22] abr. billion

4.2 Applications

Building a Dyson ring, though pricey project currently, might prove to be helpful for space exploration as it can be used to transmit power to spacecrafts. This will reduce the weight of those spacecrafts as they'll be receiving energy from somewhere else and thus won't need to generate power on their own. As the ring surrounds the Sun, it will be able to transmit power in almost every direction. This will ensure that there will be continuous power distribution to the receiving end.

If we use relay satellites, then a Dyson ring can also provide for the energy needs on Earth. These relay satellites will act as reflectors which will divert the laser beams from collectors to a desired location. Here, we see one advantage of using LPT, i.e. less atmospheric loss. Hence, maximum amount of laser power will reach the receiving end. Diode lasers provide tunability because of which we can adjust the wavelength of the laser beam. As a Dyson ring have number of collectors, different collectors can transmit power at various frequencies depending upon the location the power is to be transmitted.

5 Future Scope

There are many aspects of Dyson ring which haven't been discussed in this paper. Following are a few points which haven't been discussed yet will play an important role while actualizing a Dyson ring.

- **Orbital stability**: In our discussion, we've assumed the orbits to be circular whereas they should be elliptical, which would change the position and velocity of collectors. Although, the functioning of the collectors will be the same, they will have to face extreme temperature variations in an elliptical orbit. One solution to this can be placing them in an orbit having eccentricity closer to 0 in order to maintain the constancy of speed.

- **Thermal system designing**: When working with PV arrays and lasers a lot of heat is generated and if this isn't removed then it can damage the delicate machinery inside the collectors. Heat sinks can be effective but will add up to the weight of the collectors increasing the launch costs. One way to solve this problem is by utilizing the low temperature in space and diverting heat where there is more temperature difference.

- **Trajectory**: Launching a satellite towards the Sun is more challenging and costlier than launching something outside the solar system. This is because a satellite/probe being launched in outer solar system can get assistance from Jupiter's gravity which is considerably large. Whereas while launching a probe towards the Sun, Venus's gravity assist has to be used, which isn't much. This increases the project cost as more fuel is required.

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