# Introducing the Future of Solar Sails.

Take a glimpse into the future of space exploration.

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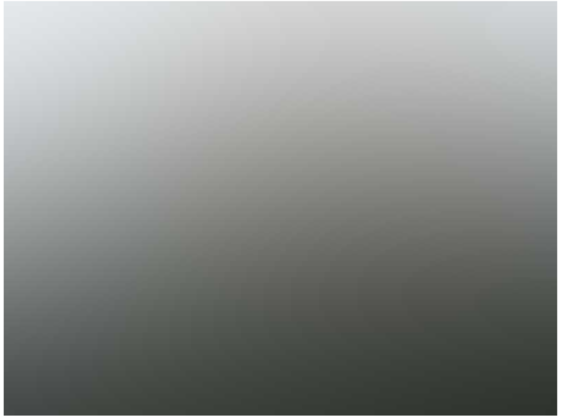
## The Problem



### Inefficiency

Solar sails are crucial for the future of space travel - the backbone of interstellar exploration, the root of human evolution. However, solar sail technology has not progressed far enough to enable long distance space travel. Solar sails are not very efficient, only returning about 90% of the energy put into them at solar wavelengths.

### Weight and Durability

If solar power is to have a stronger role in supplying an abundant source of energy in the future, the panels need to be lighter, more durable, and more cost effective. Currently, they are none of these.

## Our Solution



### Efficient

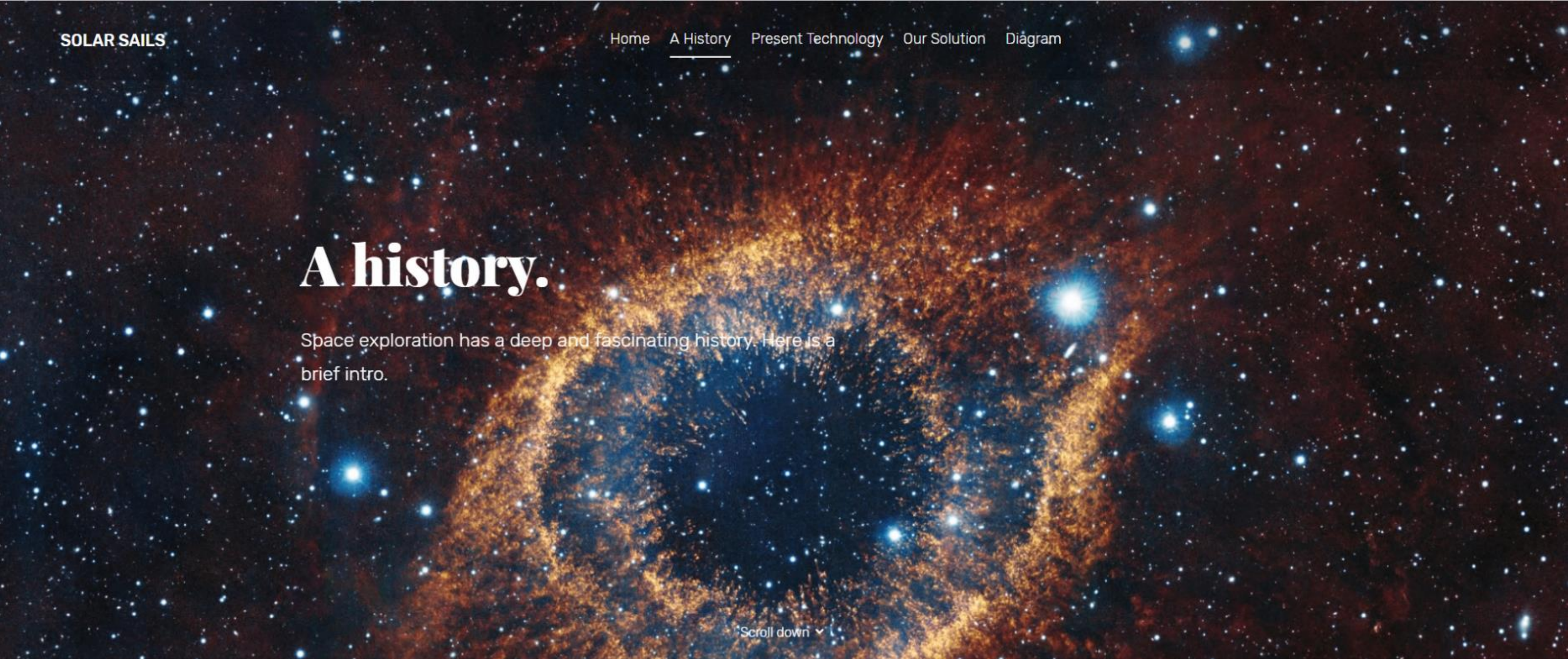
Our proposed solution maximizes the efficiency of solar sails. The reflective properties of CVD diamonds would potentially increase the current efficiency of solar sails to almost 100%.

### Effective

Although the objective cost of CVD diamonds is higher than that of aluminum, the increase in efficiency renders our solution to be cost effective. Additionally, future advancements in diamond synthesis could lower costs by a dramatic measure.

### Ethical

The synthesis of diamonds does not harm the planet in any way. They are used in a variety of applications and can replace a genuine diamond in jewelry without noticeable difference.





# A history.

Space exploration has a deep and fascinating history. Here is a brief intro.

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In the early 1860's, James Clerk Maxwell's theory of electromagnetic fields and radiation, which shows that light has momentum and exerts pressure on objects, created a foundation for the idea of "sailing" with light pressure. Consequently, by 1864, the the concept that sunlight could exert a force on an object and spur movement was a widely accepted phenomenon.

The first significantly successful demonstration of light pressure was conducted by Ernest Nichols and Gordon Hull in 1901 by precisely measuring the radiation pressure of light on a macroscopic body. Their results agreed with Maxwell's equations to better than less than one percent. Though Pyotr Lebedev had conducted a similar and moderately successful experiment just 2 years before in Moscow, it was far less accurate than Hull and Nichols's measurement, with an error bound of roughly 20 percent.

Soviet rocket scientist Konstantin Tsiolkovsky was not only the first to propose using sunlight to move spacecraft, but even made reference to the idea of a solar sail. Throughout the early 1900's, the use of mirrors to take advantage of light pressure became an idea that was constantly alluded to. In 1925, Friedrich Zander published his paper that detailed the technical aspects and mechanical properties of solar sails. Within the next 4 years, this idea was further corroborated by the likes of J.B.S. Haldane and J.D. Bernal.

Since 1976, NASA's Jet Propulsion Laboratory has been working on a solar sail propulsion system that would use large reflective mirrors to propel spacecraft using solar radiation. This project is the first formal effort for a solar sail, and is planned to be used for a mission to rendezvous with Halley's Comet.

# Present Technology

Currently, many technologies have been developed that can expand the potential of solar sails.

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## Current Technology

Solar Sails work by using the way mirrors reflect incoming photons as a source of momentum in the opposite direction of the reflected photons. Against a thin-enough material (roughly 40 to 100 times thinner than paper), a continuous stream of photons provides sufficient propulsion for navigation. This idea can easily be confused with the way winds on Earth propel sailboats and ships, but the two are of significant distinction. Solar radiation, rather than actively pushing on a surface, exerts a pressure on it as a result of the momentum carried by incoming photons. Though relatively new to the world of tech, there's no doubt that the development of solar sail technology has been a rigorous, ongoing effort in recent decades.

Current solar sails are heavily dependent on how efficient their mirrors are. In other words, the more photons that a mirror can reflect, the more movement the payload will experience. Such efficiency is described using what is called specular reflection. Ideally, solar sails want 100% specular reflection so that every photon will be used toward moving the payload (i.e. "more bang for your buck"). In reality, mirrors used in solar sails have an efficiency around 90%, so they are incapable of fully taking advantage of the solar radiation around them. This lack of efficiency is due to the mirrors' metallic material, namely aluminum.

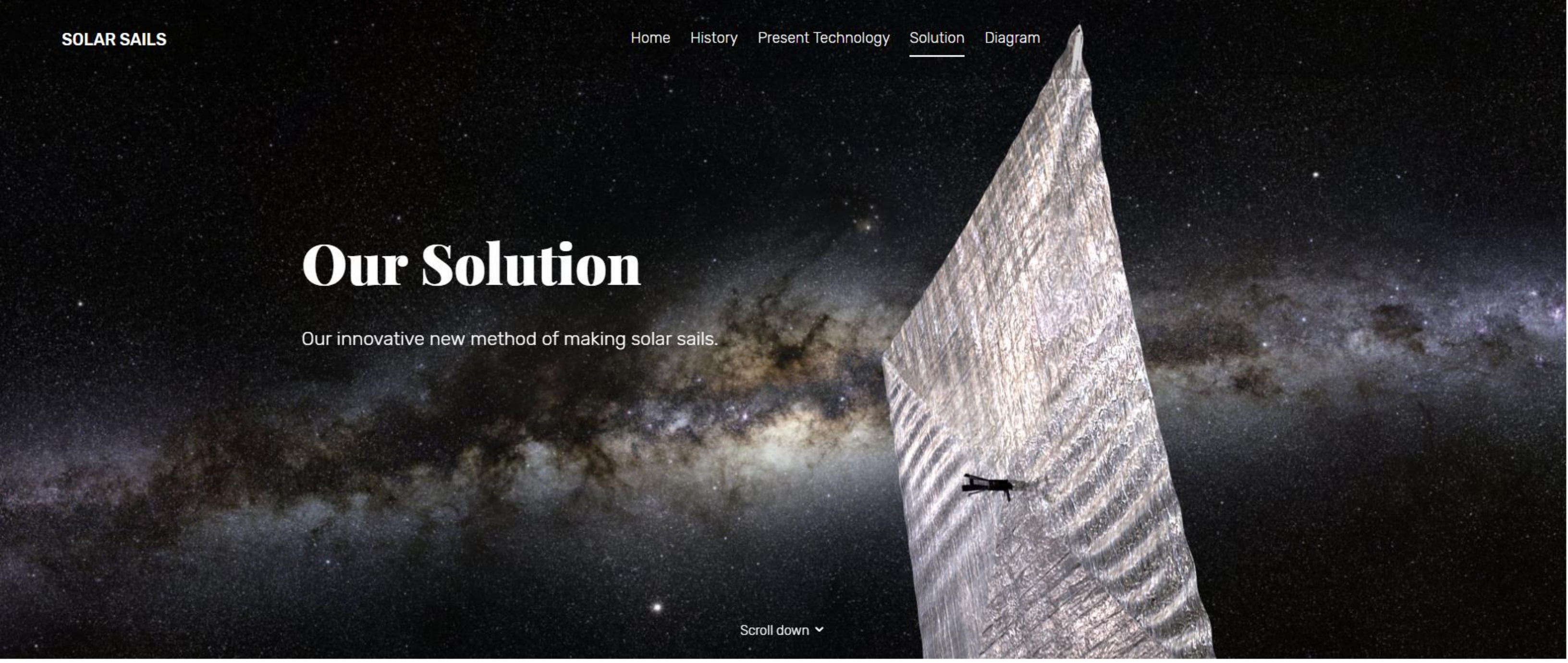
Dielectric mirrors are a type of mirror composed of thin sheets of dielectric material. Dielectric material is essentially any electrical insulator whose molecules can be polarized by an applied electric field. The polarization of these molecules induces a displacement in the positive and negative charges such that they face opposite of one another. The result is an internal electric field that reduces the overall field within the dielectric itself. Dielectric mirrors are especially useful to solar sails because they are capable of achieving reflectivity well over 99.99%.

Our proposed solar sail utilizes a dielectric mirror made up of synthetic CVD diamond in an effort to maintain heat resistance and structural integrity while increasing reflectivity. Solar sails provide a low-cost, long-lifespan alternative to current spacecraft, but are presently unable to function at full capacity due to limitations in current technology.

## Breakthroughs necessary

Refractive index is a dimensionless measure of how much of the incoming light is refracted. Thus, for solar sails, a higher refractive index would mean more of the photons are reflected, and thus the solar sail would utilize more of the sunlight and consequently achieve a higher velocity. The solar spectrum of sunlight approximately spans wavelengths between .29 μm and 3.2 μm, with visible light between .39 and .70 μm (7). The refractive index of aluminum is around .26 at .29μm and 4.7 at 3.2μm, and the refractive index of CVD diamond is 2.47 at .29μm and 2.38 at 3.2μm (12). The diamond has a significantly higher refractive index, for lower wavelengths, but is outperformed by aluminum at higher wavelengths. Ideally, the mirror should be able to make better use of the infrared light from the sun than aluminum to maximize efficiency and pose a definite advantage over aluminum.

Furthermore, innovations in 3D printing technology would not only improve production speed, but cut costs for manufacturing as well. Lockheed Martin has already made the initiative to incorporate synthetic diamond into the process; in 2016, they reportedly filed patent applications for a diamond-printing 3D printer (9). Current synthesis processes for CVD diamond involves painstakingly waiting for a carbon-containing gas to decompose and for the carbon atoms to be deposited on a surface. It's a long and high-effort process that could significantly benefit from improvements.



# Our Solution

Our innovative new method of making solar sails.

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## Our Solution

Mirrors, or the layer of reflective substance that coats the sail, that are currently utilized in solar sail technology are made of aluminum, as exemplified by 2005's Cosmos 1. Metallic mirrors pose a problem with efficiency; interaction between metals and photons induces an electromagnetic effect, which in turn incurs a loss in energy. Dielectric mirrors, as insulators, lack this response when struck by photons. The photons that hit these mirrors are reflected without any transfer or change in energy. This is ideal for use in solar sails, because solar sails, to perform at optimal levels, require 100% reflectivity.

We propose the use of CVD diamond, a synthetic material with remarkable dielectric properties, in solar sails to increase reflectivity and consequently cut costs for missions. In fact, near 100% reflectivity is an easily attainable level; values of 99.999% can be produced using special techniques. However, current technology is incapable of taking advantage due to the limitation of wavelength - such reflectivity is only achievable over a narrow range. The realm of space encompasses the entire electromagnetic spectrum; encountered wavelength can vary immensely, and if the sail is incapable of taking advantage of a wide variety of wavelengths, in the lack of the specific wavelength it requires to perform optimally, the sail will not perform well.

Current solar sails are comprised of aluminum surfaces. Aluminum is a strong heat conductor, which offers the solar sail extreme heat resistance, a quality useful when travelling near the sun. However, it falls short when it comes to efficiency - not every photon that it reflects is reflected and used for propulsion, because roughly every 1 out of 10 photons gets absorbed into the aluminum, resulting in the aforementioned loss of energy.

Twenty years from now, we are hoping that diamond synthesis becomes a more fluid and quick process. Currently when creating synthetic diamond, the diamond is usually deposited at growth rates between 0.1 and 10 micron per hour. Improved time for synthesis would greatly lower costs; current costs are high because the deposition process requires a lot of energy, time, and expensive equipment. Furthermore, to potentially simplify the process, 3D printing technology should be expanded to printing synthetic diamonds in the future. In fact, the effort to make such technology is already underway; Lockheed Martin filed patent applications for a synthetic diamond printer back in 2016. Great improvements in both 3D printing technology to incorporate diamonds as well as an overall improvement on diamond synthesis would be valuable assets for making our proposition possible.

## How We Will Design This

3 Alternative Ideas that our group had were the following: Thermonuclear weapons, Greenhouse gas factories, and utilizing microorganisms. We chose mirrors over all of these options mostly because of ethical reasons. All of these methods take long time frames; none of them would work in under 30 years (Bonsor). However, with thermonuclear weapons and greenhouse gas factories, we considered that there was a large potential for the weapons to release harmful effects into the atmosphere other than just an increase in temperature. Though raising temperatures is an issue to address, both of these would likely add further problems for human inhabitance of the planet. People may not be as willing to test-inhabit an environment on which nuclear weapons have been used. Microorganisms seem viable, but not enough research has been done on them to conclude them as a viable option, hence NASA has not released it as an option for its official terraformation plan (Bonsor). Mirrors most effectively deal with the issue on ethical terms while isolating global temperature as the only issue. They would minimize the probability of collateral issues as a result of tampering with the atmosphere.

# A Diagram

Here's a more detailed look at what our solar sail will look like.

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