Solar Sails: Engineering Efficient Interplanetary Space Travel

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Space…the vast, dark ocean humans have barely dipped their toes into. It is a place of mystery. People have always looked to the night sky, wondering about the mysteries of the universe. Naturally, humans began exploring space, pushing the limits and improving modern technology. At first, rockets seemed the best candidate for exploration. And since the beginning of its use, rocket technology has improved immensely. But while improving rocket spaceflight technology, scientists have realized the limitations, inefficiency, and complexities of rockets. Sometimes, simplicity surmounts complexity. Thus, the idea of solar sails gained popularity. Solar sails are large, magnificent sails that transport satellites through space (What is 2011). Solar sails' simple, attractive design appeals to the imagination, and continues to gain more scientific focus. Although unsuitable for human spaceflight, solar sails easily carry small satellites. In today's world, solar sails stand out as the leading contender for interplanetary satellite space travel.

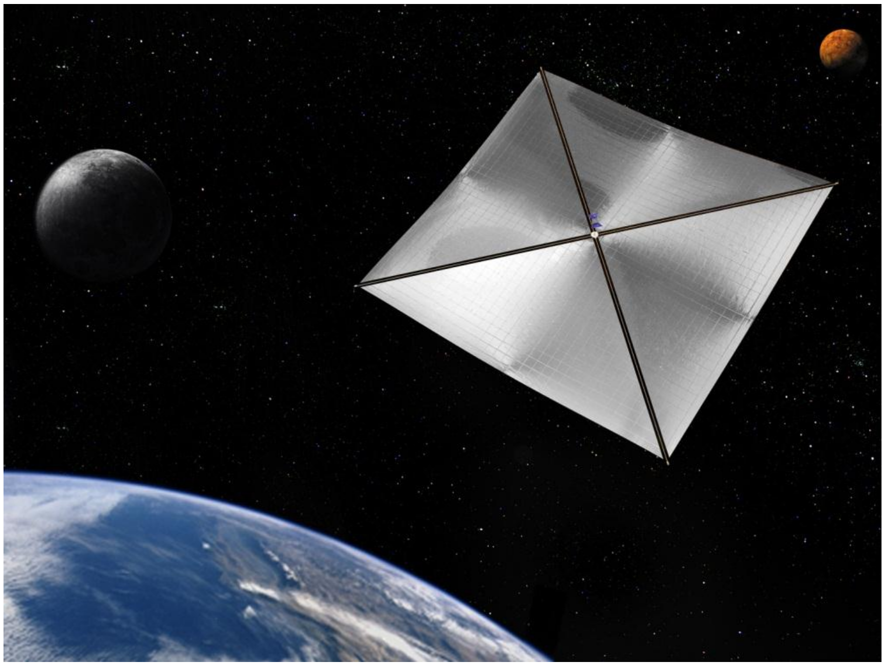

Figure 1: Artist's Depiction of a Solar Sail (Newton, NASA)

Throughout history, the challenge of navigating space inspired many great thinkers and scientists to ponder the idea of space sails. In the 1600's, Johannes Kepler observed comet tails streaking through space, hypothesizing that the tails were caused by a "solar breeze." Using this breeze, Kepler imagined elegant ships majestically surfing the heavens. However, scientists at the time lacked an accurate understanding of light, limiting the practicality of Kepler's ideas (Coulter 2008). More than 200 years later, James Clerk Maxwell emerged as the forefather to the modern concept of light. He described light as a type of electromagnetic radiation. In doing so, he showed that light exerts a very small amount of pressure (Vulpetti 2008, 56-57). His theory gained success in the scientific community, and further experimentation led to the idea of the photon, the quantum of light. Building upon Maxwell's work was Soviet scientist Konstantin Tsiolkovsky, the first to consider using photon pressure for spacecraft propulsion in the 1920's. Unlike Kepler's idea of sailing across space using an unidentified "breeze," Tsiolkovsky imagined sailing space using solar light to physically push spacecraft (McInnes 1999, 2). Soon after Tsiolkovsky's time, the space race began. Photon pressure played a vital role immediately. In the 1960's, NASA launched Echo-1, a thin balloon-like satellite, into orbit. Its thin material was ripped to shreds and scattered across the atmosphere by sunlight and radiation (Coulter 2008). Ten years later, NASA sent Mariner 10 to Mercury's orbit to explore and photograph the planet. During the mission, Mariner 10 ran out of control gas, losing its steering capability. NASA's mission control, desperate to save Mariner 10, decided to angle the ship's solar arrays towards the sun. The maneuver worked, and Mariner 10 became the first spacecraft to positively utilize photon pressure (Coulter 2008). Because of Mariner 10's success, solar sailing jumped to the front of many scientists' minds. One of these scientists was Dr. Louis Freidman. Friedman "conceived the exciting idea of propelling a probe via solar sail to rendezvous with [Halley's

Comet]" (Coulter 2008). However, after a year of research, NASA discarded the project. Despite this, the research laid the framework for other groups to design solar sails. Among these groups was Russia. Russia launched Znamya 2, a large, lightweight, spinning mirror, into Earth orbit. Its thin material quickly burned up in the atmosphere, much like NASA's Echo-1 30 years previously. Nonetheless, many consider it a minor stepping stone for solar sailing. In addition to the Russians, the Japanese joined the solar sailing playing field, launching their own small experimental solar sail (Coulter 2008). But the biggest player was the private American company, the Planetary Society, headed by decorated NASA project manager, Dr. Louis Friedman. The Society planned to launch their prime solar sail, Cosmos-1, in 2005. Cosmos-1 was to be the first solar sail to escape Earth's orbit and fly only under the influence of solar photon pressure. However, the launch vehicle experienced technical failures and the Cosmos-1 mission never happened (Coulter 2008). Although Cosmos-1 never saw deep space, it remains the prototypical model for current solar sails. Because of the advances like Cosmos-1 and waning popularity of rockets, solar sails have gained immense popularity over the past decades. And although rockets "have opened the solar system to preliminary human reconnaissance and exploration, there are several limitations on rocket performance" (Vulpetti 2008, 23). Solar sails hope to overcome these physical limitations.

The physics of solar sails eliminate many problems of conventional rocket propulsion systems and bring efficient interplanetary space travel to the horizon. In the simplest explanation, solar sails use sunlight to fly (What is 2011). Sunlight, a form of electromagnetic wave radiation, creates a force, known as solar radiation pressure, which has the ability to push objects in space by transferring its momentum to the object (McInnes 1999, 32). Solar sails use massive, lightweight, and reflective sails to capture this pressure and glide through space. Light bombards the reflective sail, pushing it forward. Maximizing the push involves several factors. First, if solar sails use a reflective surface instead of an absorptive surface, the light momentum transfer doubles. On a reflective surface, like a mirror, light transfers its momentum once upon impact, and then transfers its momentum again upon reflection. Radiation pressure doubles (Vulpetti 2008, 55).

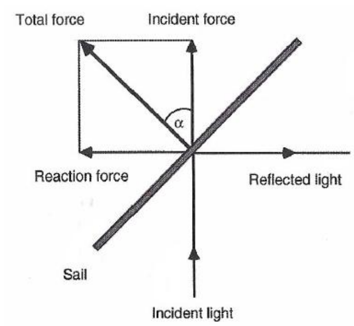

Figure 2: The radiation pressure doubles as light's momentum is transferred once by the incident light and once by the reflected light (McInnes 1999, 18)

Secondly, in order to capture as much sunlight as possible, sails require an enormous surface area. For example, the Planetary Society's Cosmos-1 consisted of eight triangular sails, each 15 meters long. When completely extended, the total surface area of the sails approximately equaled the size of one and a half basketball courts, about 600 square meters. Although seemingly large, Cosmos-1 is small compared to other designs (What is 2011). For more ambitious missions, scientists needed to create much larger sails. In the 1970's, when Dr. Louis Friedman conceived his idea of exploring Halley's Comet via solar sail, he proposed making a sail "the size of 10 square blocks in New York City," or almost 7 million square feet (What is 2011). The third factor of maximizing sunlight's push is weight. The sails need to be as lightweight as possible. The lightweight minimizes the sail's inertia, allowing an easier push, or force, from sunlight. Thus, the sail maximizes the effect of the solar radiation pressure (McInnes 1999, 32). Defining solar radiation pressure presents problems because of the wave-particle duality of radiation, which states that electromagnetic radiation, light in this case, acts as both a wave and a particle. So, to conceptualize the solar radiation pressure, one must view the term from both the wave and particle positions. The first position describes electromagnetic waves. Momentum transfers to the solar sail via waves. As the wave hits the solar sail, it creates an induced electric current and magnetic field along the surface of the solar sail. These two components cause a Lorentz force in the direction of the wave's momentum (McInnes 1999, 36).

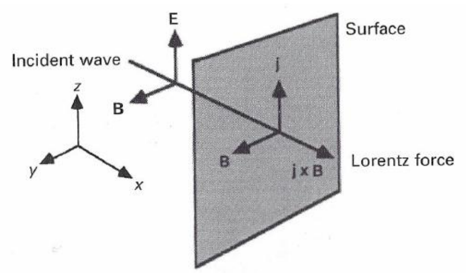

Figure 3: Lorentz Force – The cross product of the magnetic field (B) and electric field (j) generated by the incident light wave (McInnes 1999, 15)

The second position deals with describing radiation as packets of energy. Photons, the particles of light, transfer momentum to the solar sail (McInnes 1999, 35). Similar to the photon-sail interaction is the example of the rubber ball-door interaction. If one throws a rubber ball perpendicularly against a hinged door, the ball bounces back towards the person while the door swings shut away from the person. Now, if the person bombards the door with multiple rubber balls, the door accelerates shut, just like photons bombarding a solar sail (Vulpetti 2008, 66). This phenomenon of acceleration demonstrates a major advantage of solar sails over typical rocket propulsion. Solar sails accelerate constantly. Rockets, on the other hand, only accelerate for a short period of time, run out of fuel, and then reach a constant cruising speed because the chemical force ceases to apply. But rockets accelerate faster. For example, the rocket propelled Mars Exploration Rovers accelerated at 59 meters per second squared when first launched (What is 2011). Solar sails accelerate much slower.

Acceleration of an Ideal Solar Sail above Earth's Atmosphere (Vulpetti 2008, 73-74):

Given Equations (Stewart 2011, 2):

Solar Radiation Pressure $(\mathrm{P_R}) = \frac{2\mathrm{I_s}}{c}$

Intensity of the Sun $(\mathrm{I_s}) = \frac{\text{Power of Sun}}{4\pi(\text{Distance from Sun})^2}$

Force on Solar Sail $(\mathrm{F}) = \mathrm{P_R}(\text{Surface Area of Sail})$

Acceleration of Solar Sail $(\mathrm{a}) = \frac{\mathrm{F}}{\text{Mass of Solar Sail}}$

Given Information (Stewart 2011, 2):

$\mathrm{c} = \text{speed of light} = 3 \times 10^8\ \frac{\mathrm{m}}{\mathrm{s}}$

$\text{Power of Sun} = 3.846 \times 10^{26}\ \mathrm{W}$

$\text{Distance from Sun to Earth} = 1.5 \times 10^{11}\ \mathrm{m}$

$\text{Ideal Mass/Area Ratio of Solar Sail} = 91\ \mathrm{g/m^2}$ (Vulpetti 2008, 73)

Solve for Acceleration

$$\mathrm{a} = \frac{2(\text{Power of Sun})(\text{Surface Area of Sail})}{4\pi \mathrm{c}(\text{Distance from Sun})^2(\text{Mass of Solar Sail})}$$

$$\mathrm{a} = \frac{2(3.846\times10^{26}\mathrm{W})(1\ \mathrm{m}^2)}{4\pi(3\times10^{8}\,\mathrm{m}/\mathrm{s})(1.5\times10^{11}\mathrm{m})^2(0.091\ \mathrm{kg})}$$

$$\mathrm{a} \approx 9.96 \times 10^{-5}\ \frac{\mathrm{m}}{\mathrm{s}^2}$$

$$\mathrm{a} \approx 1 \times 10^{-4}\ \frac{\mathrm{m}}{\mathrm{s}^2}$$

$\text{Ideal Acceleration} \approx 0.1\frac{\mathrm{mm}}{\mathrm{s}^2}$ (Vulpetti 2008, 73)

Thus, an ideal solar sail accelerates at 0.1 millimeters per second squared, 59,000 times weaker than the acceleration of the Mars Exploration Rovers (What is 2011). But rocket acceleration is not constant whereas sunlight delivers constant thrust to the solar sail. “In 100 days, a sail-propelled craft could reach 14,000 kilometers per hour. In just three years, a solar sail could reach over 150,000 miles per hour. At that speed, you could reach Pluto in less than five years” (LightSail Mission 2011). Additionally, solar sails never have to conserve fuel to make a round trip journey back to Earth. These advantages, all due to the power of the sun, make solar sailing an efficient form of interplanetary space travel. The sun provides a free and near perfect renewable fuel source. Due to the sun’s power, recent advancements in solar sailing provide promising evidence of the potential of solar sails. On May 21, 2010, the Japan Aerospace Exploration Agency launched their solar sail, IKAROS. IKAROS, a 200 square meter sail, became the first successful interplanetary solar sail. On December 8, 2010, IKAROS flew by Venus. Now, mission specialists want to fly the sail to the other side of the sun. After the launch of IKAROS, the United States’ NASA launched their solar sail, NanoSail-D. NanoSail-D, a 100 square foot sail, was deployed in low Earth orbit to test the effects of solar radiation pressure. For NASA, NanoSail-D provided a small stepping stone for more ambitious solar sailing missions in the future (Newton 2011). Perhaps the most exciting solar sail experiment is the Planetary Society’s LightSail-1. After the Cosmos-1 mission in 2005, the Planetary Society decided to build a better sail, LightSail-1. LightSail-1, with a mass of less than 5 kilograms, “will have four triangular sails, arranged in a diamond shape resembling a giant kite.” The Planetary Society plans to place the sail in an orbit 800 kilometers above Earth’s surface, giving them an accurate trial of sunlight propulsion (LightSail-1 2011). After LightSail-1 deploys, the Planetary Society will launch LightSail-2 and LightSail-3. The goal for LightSail-2 is to fly at a higher altitude for a longer duration. LightSail-3 will fly towards the sun, and serve as a solar weather station to detect geomagnetic storms (LightSail Mission 2011). But these solar sails are not the only major competitors in the spacecraft playing field.

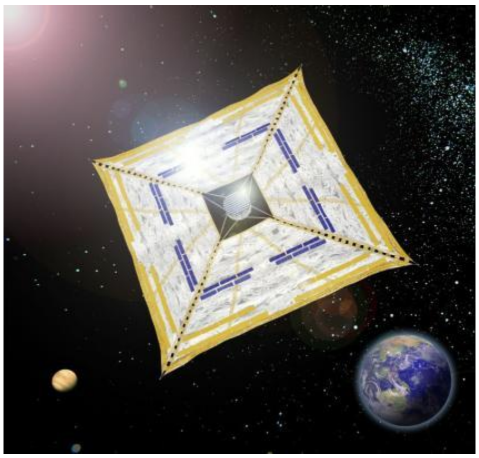

Figure 4: Artist's Depiction of JAXA's IKAROS (DeFreitas 2010)

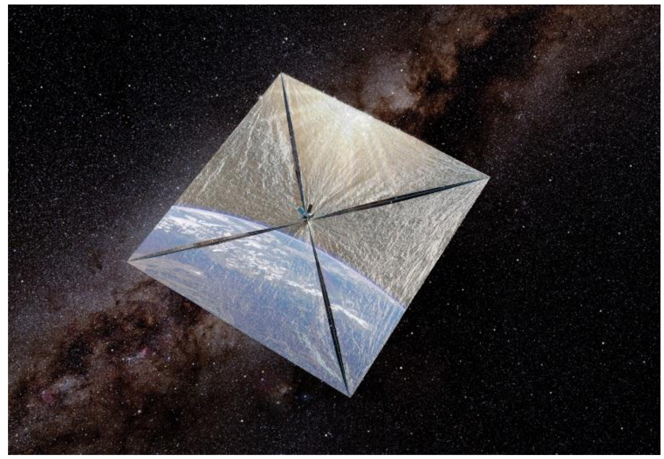

Figure 5: Artist's Depiction of The Planetary Society's LightSail-1 (Sternbach 2011)

Theoretical alternatives use a modification of the solar sail through propulsion by the solar wind. Solar wind differs from electromagnetic radiation. Electromagnetic radiation consists only of waves of different wavelengths, which includes the visible spectrum of light. But the sun produces something else, the solar wind. The sun, a fiery ball of mainly hydrogen and helium, releases explosive bursts of charged particles from its surface. Negatively charged electrons, and positively charged hydrogen and helium ions erupt from the surface into space at velocities up to 800 kilometers per second (Vulpetti 2008, 68). Several spacecraft designs, the magsail, plasma sail, and electric sail, expanded on the idea of the light-propelled solar sail by utilizing charged particles in space. Magsails use a magnetic field. Magsails face the problem of finding a magnet with a small enough mass to create a practical spacecraft. Low mass objects yield a higher acceleration, given a certain applied force. Traditional magnets are heavy. To solve the weight problem, magsails wrap current carrying loops of wire around the sails. Ideally, magsails use lightweight, low resistance wires in order to maximize the current flow. The flowing current through the wire loops produce a magnetic field which surrounds the sail. When charged particles released by the sun hit the magnetic field, they experience a Lorentz force given by the equation$\vec{F} = q\vec{v} \times \vec{B}$, where $\vec{v}$ represents the velocity of the charged particle and $\vec{B}$ represents the magnetic field of the magsail (Stewart UPII 2011, 327). A force in one direction must create a force in the opposite direction. So, as the charged particles deflect away, the magsail accelerates forwards (Vulpetti 2008, 68). The second design using the solar wind is the plasma sail. This elegant design uses a magnetic field just like the magsail. However, once current carrying wire loops create a magnetic field, “a plasma, which is a gas composed of electrons, ions, and their electromagnetic forces, would then be injected into the field to form a plasma ‘bubble’ around the magnet” (Vulpetti 2008, 69). So, once infused in the magnetic field, the ions and electrons remain trapped on a continual path, forming a charged bubble in the shape of the magnetic field. Then, charged particles from the sun barrage the plasma bubble, pushing the sail forward (Vulpetti 2008, 69).

Figure 6: Artist’s Depiction of a Plasma Sail (Winglee 2011)

Yet, despite the appealing visual image of the plasma bubble and the theoretical simplicity of the magsail, each faces problems. First, both designs use magnets. With today's technology, magnets lightweight enough for practical spaceflight do not exist. Next, the sun releases charged particles in bursts. These bursts are not constant. This dilemma means the magsail and plasma sail fail to accelerate at a constant rate, unlike the solar sail which uses the constant light force. Furthermore, controlling the flight trajectories of the magsails and plasma sails is much more difficult than controlling the standard solar sail (Vulpetti 2008, 70). However, a third design, the electric sail, seeks to solve these problems. The electric sail, instead of creating a magnetic field, creates an electric field that surrounds the sail. An onboard field generator keeps the sail at a positive voltage. By keeping the sail at a positive voltage, protons released by the solar wind repel. In addition, solar wind electrons and negative ions are emitted from the sail system by an onboard electron emitter. This design prevents the buildup of electrons, which would counteract the positive charge of the protons (Vulpetti 2008, 70). Protons, about 1,800 times more massive than electrons, repel from the sail with a greater force than electrons. Every force requires an equal and opposite reaction, so the sail accelerates in the opposite direction with an equal force. The electric sail also tries to solve the problems with the non-constant stream of solar wind particles. The magsail and plasma sail both use a constant magnetic field, meaning the movement of these spacecraft is subject to the amount of solar wind particles available. But the electric sail can control the strength of its electric field via the onboard field generator. At times when solar wind particles are sparse, the electric sail switches off the generator to save energy (Vulpetti 2008, 70).

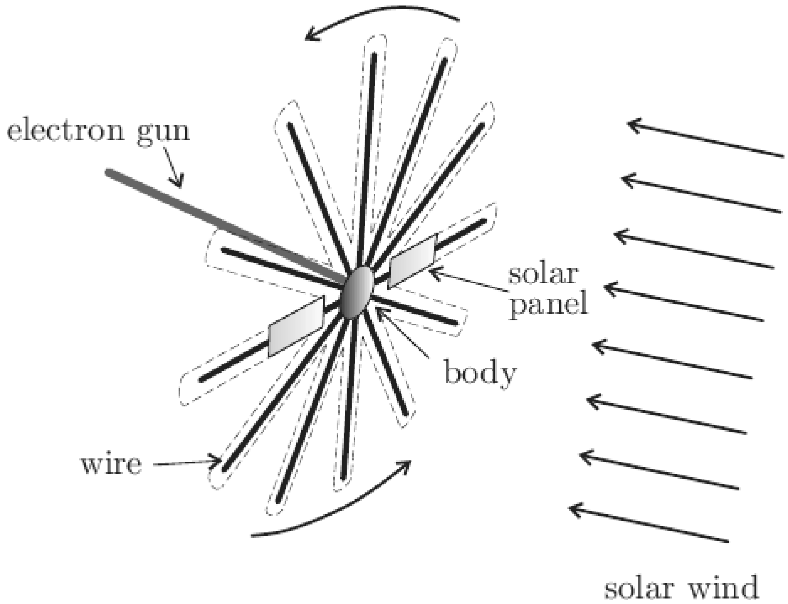

Figure 7: Artist's Depiction of an Electric Sail (Mengala 2008)

The electric sail is the most feasible design to use solar wind, but solar sails are still the preferred alternative for the future of interplanetary space travel. Some scientists believe solar sails could be used for more than just interplanetary space travel, and want to use the technology to travel to distance stars. However, this ambition is improbable.

Limitations of current technology prevent the use of solar sails for interstellar travel. The sun, the driving force behind solar sails, boasts one large problem. The sun provides constant acceleration. But as the solar sail ventures farther out into space, the value of this acceleration decreases. An ideal solar sail accelerates at 0.1 $\frac{\text{mm}}{\text{s}^2}$ just above Earth's atmosphere, given by the equation (Vulpetti 2008, 73):

$$a = \frac{2(\text{Power of Sun})(\text{Surface Area of Sail})}{4\pi c(\text{Distance from Sun})^2(\text{Mass of Solar Sail})}$$

From this equation, as the distance from the sun increases, the value of acceleration decreases by the inverse square law. The solar sail's acceleration is inversely proportional to the square of the distance from the sun (Vulpetti 2008, 111). The father an object is from the sun, the lower the intensity of the sunlight.

$$\text{Intensity of the Sun } (\mathrm{I_s}) = \frac{\text{Power of Sun}}{4\pi(\text{Distance from Sun})^2} \text{ (Stewart 2011, 2)}$$

For example, Jupiter experiences sunlight intensity 27 times lower than that of the Earth (Coffey 2008).

$$\text{Intensity of the Sun at Earth } (\mathrm{I_E}) = \frac{\text{Power of Sun}}{4\pi(\text{Distance from Sun to Earth})^2} \text{ (Stewart 2011, 2)}$$

$$(\mathrm{I_E}) \approx \frac{3.846\times10^{26}\mathrm{W}}{4\pi(1.5\times10^{11}\mathrm{m})^2}$$

$$(\mathrm{I_E}) \approx 1360\,\frac{\mathrm{W}}{\mathrm{m^2}}$$

$$\text{Intensity of the Sun at Jupiter } (\mathrm{I_J}) = \frac{\text{Power of Sun}}{4\pi(\text{Distance from Sun to Jupiter})^2} \text{ (Stewart 2011, 2)}$$

$$(\mathrm{I_J}) \approx \frac{3.846\times10^{26}\mathrm{W}}{4\pi(7.78\times10^{11}\mathrm{m})^2} \text{ (Coffey 2008)}$$

$$(\mathrm{I_E}) \approx 50.6\,\frac{\mathrm{W}}{\mathrm{m^2}}$$

Ratio of the Sun's Intensity at Earth and at Jupiter

$$\mathrm{R} = \frac{(\mathrm{I_E})}{(\mathrm{I_J})}$$

$$\mathrm{R} \approx \frac{1360\frac{\mathrm{W}}{\mathrm{m^2}}}{50.6\frac{\mathrm{W}}{\mathrm{m^2}}} \approx 27:1$$

Once the solar sail reaches Jupiter's orbit, the low intensity of the sun fails to provide an adequate force upon the sail. Therefore, the solar sail will continue its journey at a constant velocity, losing its fuel source, sunlight intensity. Because of this, scientists need to find another light source. The solution is laser sailing. After the sun fails to provide enough light to the sail, a laser continues the job of directing a concentrated beam of light on the reflective solar sail (Vulpetti 2008, 112). Engineers want to place the laser in Jupiter's orbit. Once the solar sail passes Jupiter, it receives an extra push from the Jovian laser to continue the journey to deep space. The laser derives its power from Jupiter's magnetosphere. A large conducting wire connects to the orbiting laser, and probes into the magnetosphere, which would create a voltage drop, resulting "in the collection of electrons from the Jovian magnetosphere, thus producing a flow of electricity through the wire," powering the laser (Vulpetti 2008, 115). This promising idea extends the life of the solar sail. But a perfect laser does not exist. All lasers diffract, meaning the laser beam spreads out. Eventually, the laser fails to provide enough force to continue the solar sail's acceleration (Vulpetti 2008, 115). Therefore, with today's technology, solar sails are not suitable for quick interstellar space travel. However, solar sails will overshadow all other methods for interplanetary space travel.

Solar sails will dominate interplanetary space travel in the future. Since early space science, astronomers dreamed of a majestic sail smoothly gliding through space. As the idea gained popularity, researchers realized the promise of this simple, efficient design. Sunlight, the greatest renewable energy source of our time, provides all the force necessary for exploring the planets, moons, asteroids, and other wonders of the solar system. And yet, in spite of all advancements made in space travel, people have barely begun to wade across the shores of the skies. Solar sailing is the next stepping stone in space travel.

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