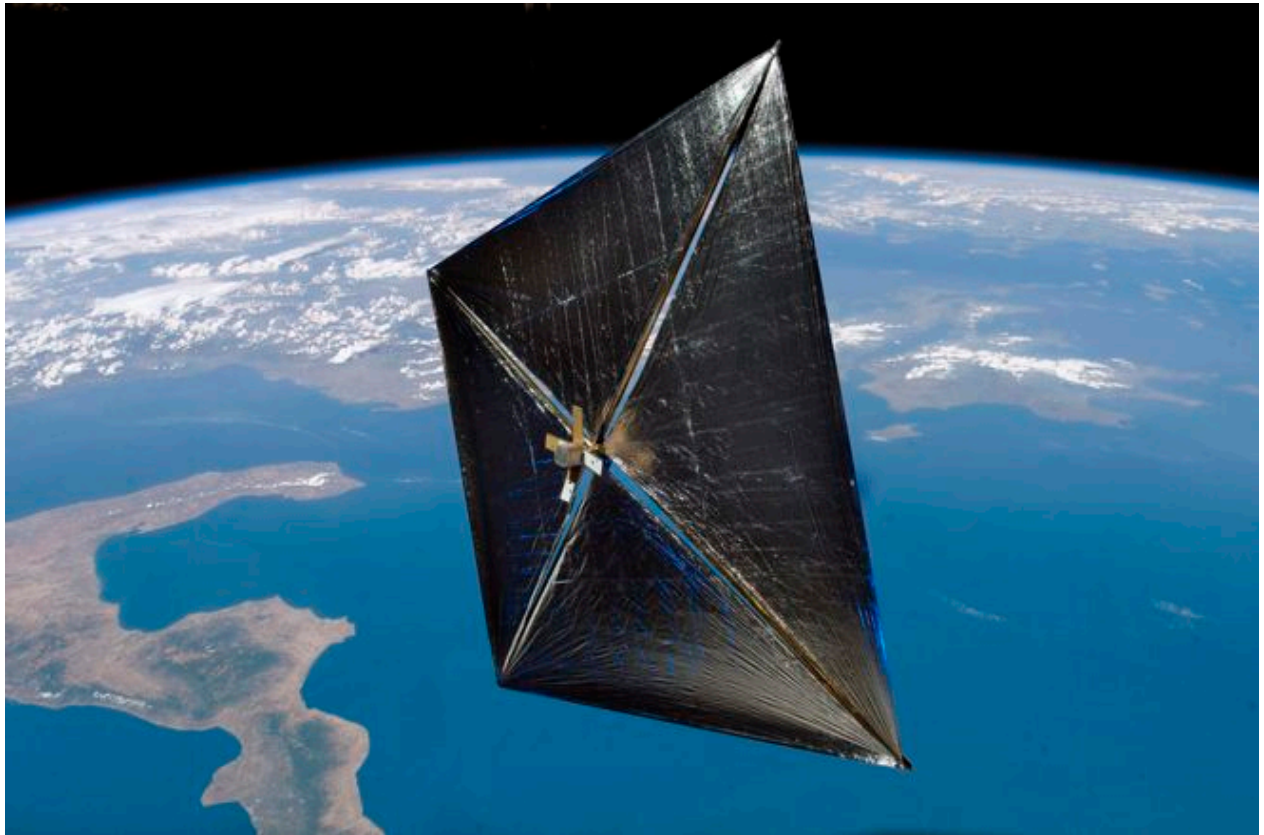


# Solar Sails

## And the Physics of Space Travel



(1)

Bailey Knapp  
H3

The earliest sea-faring vessels utilized by humans were for the most part man-powered. Whether in large ships with multiple sets of oars, or small ships which could be maneuvered with a paddle, man was the fuel for these early vessels. Eventually, a group of ancient people called the Phoenicians revolutionized water travel with the invention of the sail. This new invention “was the foundation for all the improvements and new discoveries that allowed big vessels to navigate extensively on the seas” (1). A whole new world was opened to them and man was now able to travel and explore more than ever before.

While in modern times man has mastered the art of sea sailing, a similar advancement may now be taking place in space travel. Until now, man has relied on rockets to explore the solar system. While rockets have served fairly well thus far, a new age in space travel may be on the horizon. Solar sails, space sails that are propelled by light, could potentially be the future of space travel. Although a relatively new idea, these space sails show promising potential to travel even farther into space than currently possible with modern rocket technology.

### **The History of Solar Sails**

The German astronomer Johannes Kepler first considered the concept of solar sailing nearly 400 years ago. After seeing a comet shoot through the night sky, he concluded that the tail was the result of a solar “breeze.” From this observation, he suggested that “ships and sails proper for heavenly air should be fashioned” (9).

While Kepler was right about sails being useful in space, he was wrong on the way that they would be propelled. The use of solar wind to travel through space, as it

turns out, is not the best form of propulsion. Solar wind is merely ionized particles being ejected from the sun at a speed much slower than the speed of light. Because momentum is dependent upon velocity, these particles would not have a significant impact in propelling a spacecraft (12). Light, however, could be utilized to propel spacecraft through the void of space. In the 19<sup>th</sup> century, James Clerk Maxwell was the first person to theorize that electromagnetic radiation, including light, exerts pressure and carries momentum (11). The pressure exerted by sunlight could be utilized to propel spacecraft. This discovery forms the foundation for modern solar sailing technology.

The first success with solar sails was an accident. In 1974, NASA's Mariner 10 ran low on attitude control gas, so its solar arrays were pointed in the direction of sunlight, using the pressure of the sun for attitude control. Although not originally intended to be a solar sailing mission, this vital maneuver proved the practical use of sunlight to propel ships (9).

Russia and Japan have also been highly involved in the development of solar sails. In 1993, Russia successfully deployed Znamya, a 20-meter diameter thin-film reflector meant to reflect sunlight back to the arctic regions of Russia. Its design was nothing more than that of a modified heliogyro sail (1). Japan successfully deployed the first true solar sail into space in 2004. "True to their country of origin, the sails were opened using the principles of origami" (1). This first success of unfurling a solar sail in space is a significant step in the development of this new technology.

NASA is also working to develop solar sails. Most recently was the success of Nano-Sail D2. After five weeks of refusing to deploy, the sails finally unfurled, and the craft has now begun on its 70-120 day mission (5). Currently, various designs of solar

sailing crafts are being ground tested with the intention of one day engineering a space craft that will be able to travel interstellar distances.

### **How Solar Sails Work**

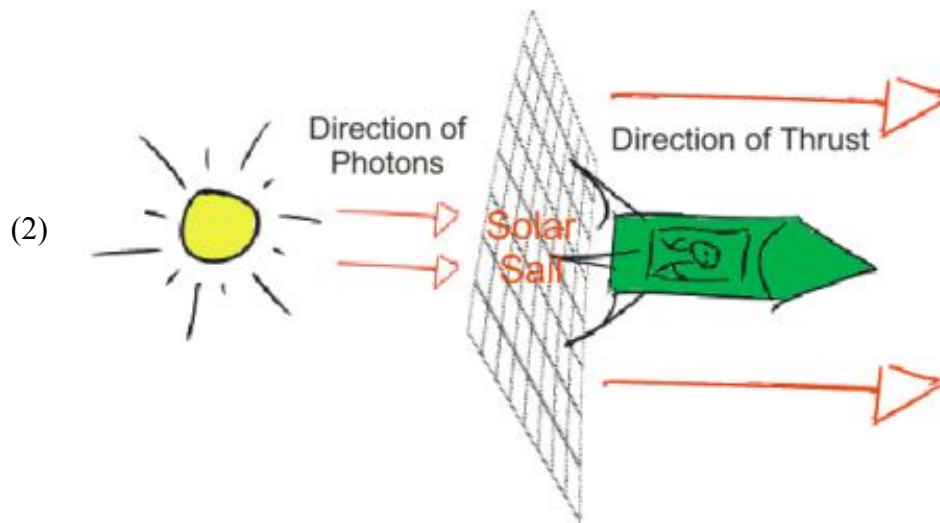
Solar sails are spacecraft that use light as the main source of propulsion. Light possesses a “particle-wave duality,” meaning it possesses properties of both a wave and of a particle (2). Experiments by Thomas Young and Augustin Fresnel completely validated the theory of light as a wave in the nineteenth century (2). Albert Einstein validated the concept of light as a particle in the twentieth century with his explanation of the photoelectric effect. He found that different colors of light contained a constant amount of energy despite varying brightness, proving that light contained a set amount of energy depending on its frequency. He explained this phenomenon with the theory that light exists as a particle that contains a quantized amount of energy. With this, the idea of the photon (particle of light) was born (7). It is now accepted that light behaves as both a particle and a wave. Like a wave, light can reflect, refract, interfere, and diffract. On the other hand, light also possesses a quantized amount of energy and contains momentum like a particle (6).

Light is made of photons, or tiny packets of electromagnetic radiation, which carry an amount of energy (2). The energy of a photon is directly proportional to its frequency and inversely proportional to its wavelength (1). Because photons contain energy, they must possess momentum. For objects with mass, momentum of an object is expressed by  $p = mv$ , where  $m$  is the mass of the object, and  $v$  is the velocity at which it is travelling. Photons, however, are massless particles. In order to understand how a

photon possesses momentum, Einstein's Theory of Relativity must be applied. Einstein's famous relationship for energy,  $E = mc^2$ , can be rearranged to the form

$E = \sqrt{p^2c^2 + (m_0c^2)^2}$  where  $p$  is the momentum,  $c$  is the speed of an electromagnetic wave in a vacuum, and  $m_0$  is the mass of the object. The mass of a photon is non-existent, so by substituting zero into the equation, the momentum of a photon becomes  $p = E/c$  (14). Max Planck determined the quantum energy of a photon to be equal to  $E = hv$ , where  $h$  is Planck's constant ( $6.626 \times 10^{-34} \text{ Joule} \cdot \text{seconds}$ ) and  $v$  is equal to the frequency of radiation (frequency of the wave) (15). This can be substituted into the previously derived momentum equation to yield  $p = E/c = hv/c$ . The wavelength of a particle is equal to the speed of light divided by the frequency, so the equation can even further be derived to the form  $p = h/\lambda$ , where  $\lambda$  is representative of the wavelength of the electromagnetic radiation (14).

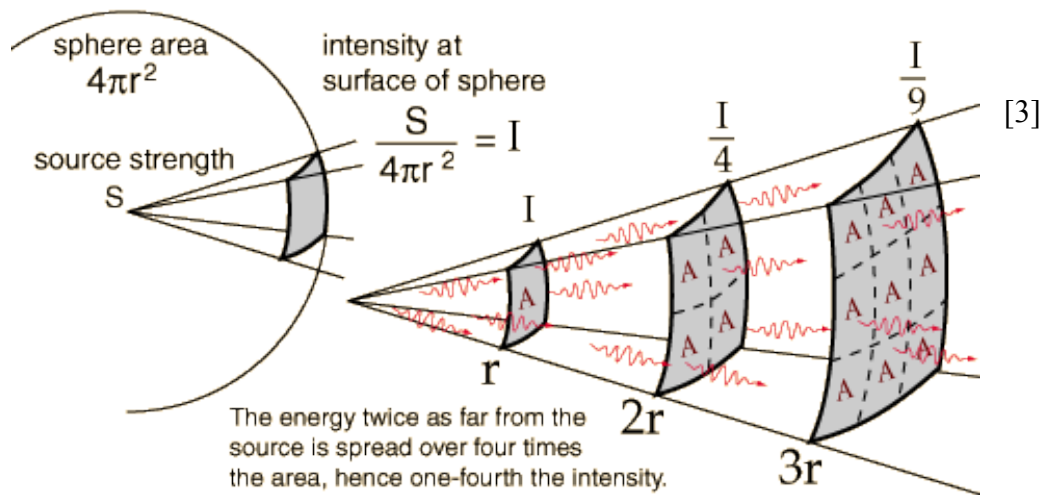
The momentum transferred when photons bombard the reflective surface propels solar sails. When a photon crashes into the sail at the speed of light, it transfers its momentum to the sail. Newton's Third Law States that "for every action there is an equal and opposite reaction" (13). According to this law, the momentum that the photon transfers to the sail will push the sail forward and cause the craft to accelerate. By the law of conservation of momentum, the entire momentum is conserved and completely transfers to the sail.



The sun is constantly producing a stream of photons, which will constantly hit the surface of a solar sail. These photons produce a constant pressure (force per unit area) on the sail, which causes the spacecraft to accelerate (10). This is where the reflectiveness of the sails comes into play. If the sails were made of material that absorb light, the radiation pressure received by the sail would be equal to  $P_r = I/c$  where  $P_r$  is the radiation pressure,  $I$  is the intensity of light impacting the sail (power per unit area), and  $c$  is the speed of an electromagnetic wave in a vacuum. If the surface of the sail completely reflects the photons, however, the radiation pressure is doubled to yield  $P_r = 2I/c$  (4). When the surface is completely reflective, the radiation pressure is doubled because the craft receives an initial boost of momentum when the photon initially hits the surface, and a second dose of momentum as the photon bounces off of the sail (12). The acceleration the solar sail craft experiences due to the radiation pressure can be represented by the equation  $a = P_r/M$ . In this model,  $a$  is the acceleration experienced by the craft,  $P_r$  is the radiation pressure exerted by light, and  $M$  is the mass of the solar sailing craft.

As long as a solar sail is provided with a continuous source of sunlight, it will continue to accelerate. While this free source of energy is extremely useful, it also greatly limits the ability of solar sails. As a solar sailing craft gets farther from the sun, the

amount of light available for propulsion decreases by the “inverse square law,” which can be represented by  $I = S/4\pi r^2$ . In this equation, I is equal to the intensity of light, S is the source strength, and r is the radius, or distance from the sun (16). Light is ejected from the sun in all directions in what is essentially a giant sphere. The farther away from the sun a craft gets, the greater the radius, and as a direct consequence, the greater the surface area of the “sphere” of sunlight. The amount of light being emitted by the sun is constant, but because it is being spread out over a larger area, its intensity decreases as the radius of the sphere increases (1).



Eventually, the sail will reach a distance where the intensity of the sunlight is so weak that it will no longer be able to accelerate the craft. In our solar system, this distance is approximately the orbit of Jupiter. At this point in the solar system, the intensity of sunlight according to the inverse square law is too weak to continue accelerating the craft (1). Despite this misfortune, it is important to remember that even though the craft will no longer be accelerating, it will continue to move at a constant

velocity. Newton's First Law of Motion states, "every object in a state of uniform motion tends to remain in that state of motion unless an external force is applied to it" (13). As long as no outside forces act on the sail, it will continue at a constant speed.

The greater the intensity of light, the more photons that are present to exert a force on the sail and provide it with a greater acceleration. According to the inverse square law mentioned earlier, the light generated by the sun has a greater intensity as the distance from the sun decreases. Force from sunlight is what drives solar sails, and the greater the radiation pressure exerted on the sail, the greater the acceleration of the sail ( $\frac{P_r}{M} = a$ ). Therefore, solar sails can be given a boost of acceleration at the beginning of a mission with the use of a powered perihelion maneuver. This involves a "solar fly-by" of the sun in order for the craft to receive a greater acceleration before beginning its mission (10).

When the intensity of sunlight is no longer strong enough to accelerate the sail, using lasers to propel a solar sail craft is a possibility. A laser is a "coherent monochromatic light source that utilizes the stimulated emission of radiation" (2). A laser emits a narrow beam of light in one wavelength (monochromatic). Lasers are for the most part immune to the inverse square law because they emit light in a narrow stream, but some diffraction will occur and the light will spread out slightly. Pointing continuously at the solar sail craft, a laser could provide a continuous source of propulsion even when the sail is far past the reaches of the sun. More than likely, the most advantageous spot for a solar sail propelling laser would be either in orbit about the sun or approximately about the orbit of Jupiter (1).

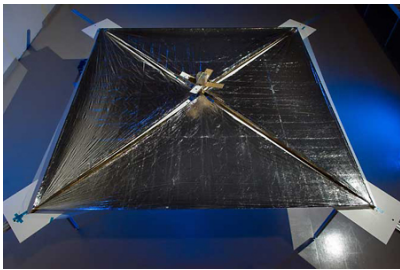


## Development and Design

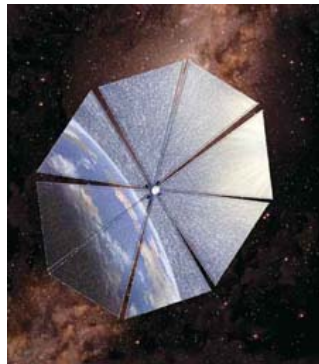
As briefly mentioned earlier, the surface of a solar sail must be completely reflective in order to provide maximum thrust. Most solar sails in development today are made of durable plastics such as Mylar or Kapton, which are coated with a reflective metal (10). These sails must be extremely thin and as lightweight as possible so that the craft can reach the highest speeds possible. The lighter the sail, the easier it will be to accelerate. This is easy to see with the equation  $a = P_r/M$  where M represents the mass of the craft. As M gets larger, acceleration decreases (10). NASA is currently testing sails that are approximately 100 times thinner than ordinary stationary. The materials used in the construction of these sails must also be able to withstand extreme temperature changes, charged particles, and the micrometeoroid hazards of space (10). The surface of the sails must also be very large. Photons are extremely small particles, and a small amount of them will do next to nothing to propel the craft. In order for maximum propulsion, the sails must be able to catch as many photons as possible. The larger the surface area of the sails, the greater the amount of photons the sails will be able to capture, and the greater the acceleration will be (8).

Like all developing technology, it is not yet understood what the most efficient design for a solar sail is. Currently, there are several major designs of solar sails being tested. These designs include the square sail, the disc sail, and the heliogyro sail (10). Square sails, also known as “three axis stabilized solar sails,” must be supported by a system of booms, much like on an ocean-sailing vessel. The booms provide structure and support for the sail, keeping it from collapsing on itself. This design can best be described as resembling a giant kite. The next design, the disc sail, eliminates the extra mass

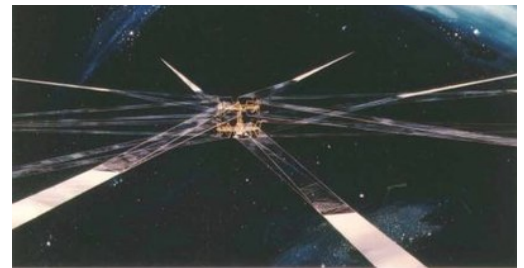
generated by the booms. Solar sails need to be as lightweight as possible, so a design that does not need the extra weight of booms is advantageous. Also known as the “spin stabilized solid solar sails,” the disc sail is continuously spun around a central axis. The centrifugal force generated by this rotation provides tension to the sail material, keeping it flat as sunlight reflects on it (1). The final design, the heliogyro sail, also rotates to eliminate the need for booms. Instead of being solid, however, this sail design is composed of several separate vanes, similarly to a windmill (1).



[4] square sail



[5] disc sail



[6] heliogyro sail

### **Rockets vs. Solar Sails**

Rockets are nothing more than bombs that explode slowly over an extended period of time. Modern rockets create energy when chemicals are heated up and cause a rapid expansion of hot gas. In order to produce useful thrust, the gas is released in a controlled manner in one direction (3). A rocket engine is an action-reaction engine, so when hot gas is released from the back at high speeds, it creates a thrust in the opposite direction, causing the rocket to be propelled upward (17).

While rockets have thus far provided humans with a decent way of escaping the confines of gravity, solar sails could possibly give rockets a run for their money. Rockets do possess advantages over solar sails when travelling close to home, but solar sails will eventually be able to take humanity places rockets simply cannot.

One advantage solar sails possess is that as long as they have a light source, they can continue to accelerate. Rockets, on the other hand, can only accelerate for a few minutes until the fuel supply fizzles out, at which point they coast until they reach their destination (12). Rockets rely on a chemical fuel to accelerate, and because they can only carry a limited supply of this fuel, the acceleration ends when the rocket runs out of fuel (8). The only fuel required by a solar sail is light. Although solar sails can continuously accelerate, this acceleration is very slow. Even with the largest sails to catch the maximum amount of photons, the predicted acceleration of a sail craft is about one millimeter per second squared. Rockets are able to accelerate at a rate of fifty-nine meters per second squared. This acceleration is about 59,000 times greater than that of a solar sail (8).

While this may seem like a significant difference in acceleration, sail craft will be able to reach much greater speeds than rockets, especially on deep space missions. If it continues to be pushed by sunlight, a solar sail could potentially reach speeds of up to ninety kilometers per second. This is about ten times greater than the speed of a space shuttle in orbit (eight kilometers per second) (10). The Voyager I spacecraft, the most distant man-made craft, has been travelling through space for 20 years. NASA claims that if it were to launch a solar sail, it would be able to catch the Voyager in a mere eight years (10).

Another advantage of the solar sail is the non-existent need for fuel. In rockets, the fuel carried to create thrust makes up about 95 percent of the mass of the rocket (12). After a rocket runs out of fuel, it no longer has any means of accelerating itself. As mentioned numerous times before, solar sails require no fuel except light, which is vastly abundant in the universe. Without a constant supply of fuel, rockets will never be able to reach speeds great enough for interstellar travel. However, with their constant supply of fuel, solar sails have the potential to eventually make the journey to neighboring stars.

### **The Future of Solar Sails**

While it is difficult to exactly predict where solar sail technology will take humanity, an optimistic viewpoint imagines that one day humans will develop solar sails advanced enough to allow travel to distant stars. Countries such as the United States, Japan, and Russia are currently constructing prototypes in the hopes of successful solar sailing missions in the future. However, “lack of political will, tight funding, and competing scientific objectives” could potentially slow down the development of this emerging technology (1). According to Carl Sagan, “we have lingered for too long on the shores of the cosmic ocean; it’s time to set sail for the stars” (1). With the development of solar sails, this wishful thinking is quickly becoming reality.

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## Images

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