Sailing the Solar System:

Solar Wind as a Method of Propulsion

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Most people think of solar energy as a panel capturing light to convert into electricity or heat. However, another element of solar energy is pressure in the form of solar wind. This is because light has momentum and can therefore exert a pressure on objects; even though a photon has no rest mass, it has energy, which gives rise to momentum. Solar wind was predicted by the German astronomer Ludwig Biermann in the early to mid-1950s and later explained in 1958 by solar astrophysicist Eugene Parker. In space, it is possible to use solar wind for propulsion, very similar to how sailing ships on Earth use normal wind. Even if solar wind is not used as a means of propulsion, it must still be accounted for when sending probes into interplanetary space as the accumulation of solar wind pressure can knock a probe several hundred or thousand kilometers off the intended trajectory (Georgevic, 1973). Solar wind is already being used to help propel space probes as a low-thrust, or low acceleration, propulsion method. Dr. Pekka Janhunen patented the design of electric solar wind sails in 2010. NASA is working on the Sunjammer project, which will be the largest solar sail tested to date. While not necessarily the best in terms of thrust, solar wind can be used to augment a spacecraft's efficiency by allowing it to make small changes in direction without spending too much fuel.

In order to explain how light exerts a force, it is important to understand two concepts: photons have momentum (Nave, 2012), and force and momentum are directly related using basic calculus as originally shown by Isaac Newton (Thornton & Marion, 2004, p.50). The momentum of a photon is given by the following equation:

$$p = \frac{E}{c}$$

where p is momentum, E is the photon's energy, and c is the speed of light. It is derived from the general energy expression:

$$E = mc^2 = \sqrt{p^2c^2 + m_0^2c^4}$$

by setting the rest mass, m_0, equal to zero because a photon has no rest mass and then rearranging to solve for momentum, p (Nave, 2012). Using basic dimensional analysis, it can be found that the flow of momentum per unit time is the same as pressure. Force is measured in Newtons or in SI base units kilogram·meters per second squared, kg·m/s^2. Pressure is described mathematically as force over an area, giving

$$P = \frac{F}{A} = \frac{m\frac{dv}{dt}}{A} = \frac{\frac{dp}{dt}}{A}$$

The SI unit of pressure is the pascal (Pa), which is equivalent to a Newton per square meter (N/m^2 or kg·m^{-1}·s^{-2}), which follows from the equation describing pressure above (Halliday, Resnick, & Walker, 2011, p.360). Therefore, light can exert pressure on an object because it has momentum.

Solar wind does not consist of just photons, however; it also contains immense numbers of charged particles (such as electrons or positive ions), which have momentum described by the more classical equation:

$$p = mv$$

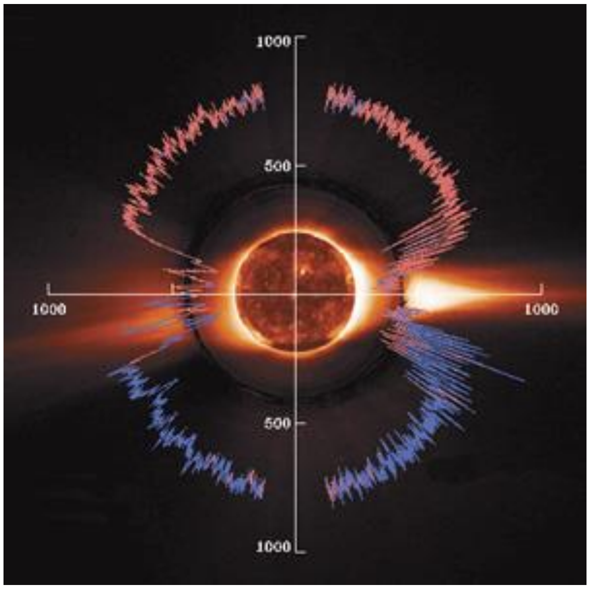

Figure 1: Plot of solar wind speed around the sun (http://385888a2d8aaf2499c5f-64d142b35093ce125caba6c3b31274a9.r81.cf1.rackcdn.com/philipsastronomy/fig375b.jpg).

where p is momentum, m is the mass of the particle, and v is the velocity of the particle (Marion & Thornton, 2004, p.50). These charged particles are accelerated by the sun's magnetic fields and the sun's corona, or outer atmosphere. In 1958, Eugene Parker, building on the predictions of Biermann, posited that gravity being weaker further away from the sun causes a transition in the coronal material flow from subsonic to supersonic.

The speed of the solar wind can vary greatly, depending on where in the solar system it is measured.

On average, solar wind is approximately 400 kilometers per second (km/s), though it can vary between 300 km/s over streamers, where closed magnetic field lines trap electrically charged gases, and 800 km/s over coronal holes, where a large number of magnetic field lines originate (Hathaway, 2012). In July of 2012, solar wind instruments on the Solar TErrestrial RElations Observatory (STEREO) spacecraft detected the fastest solar wind speed to be recorded at 3000 km/s, "a speed that would circle the Earth five times in a minute!," which occurred during an extreme space weather event known as a coronal mass ejection where multiple solar flares occur in rapid succession (Reneke, 2014).

Before solar wind was understood, the Russian/Soviet pioneer of rocketry, Friedrich Zander, wrote in 1925 on how one could use extremely large, but thin, mirrors to use light from the sun to propel a ship. Essentially, the idea is to use minute forces over a long period of time. According to Zander, "The possibly of using small forces over prolonged periods also speaks in their favor, since flights to other planets will take a long time" (1925, p. 304). Light does not produce much pressure, which is why the solar sail itself must be large. Zander also explains that even though light has little pressure, the distances between planets are large enough that solar sails could be used to achieve velocities similar to standard rockets (1925, p. 304). Many attempts have been made to send solar sails into space, some successful and some not so much. The Russians have attempted to launch a solar sail with their Cosmos 1 spacecraft in 1999, 2001, and in 2005, but each attempt failed due to mechanical failure in the rocket launch ("Russian Solar Sail Launch Fails," 2005). The first successful launch of a solar sail was in 2010 by Japan launching the IKAROS, Interplanetary Kite-craft Accelerated by Radiation of the Sun, spacecraft, which uses a super-thin sail that also contains embedded solar cells for power generation (Dickie, 2010). The IKAROS spacecraft's solar sail is made with "smart glass," which is a liquid crystal device that can "control the reflectivity of the outer sections of the sail; switching one on creates a mirror-like effect, allowing sunlight to push more on those parts of the sail" ("Japanese Solar Sail", 2010).

Once spacecraft propulsion via solar sails has been achieved, solar sail technology may be used for other applications. For example, solar wind has also been studied as a possible way to deflect asteroids that have the potential to get too close to Earth. Because of the large distances in space, even a small deflection in an asteroid's path can cause it to miss the Earth. In 2010, a study done by Merikallio and Janhunen of the Finnish Meteorological Institute determined that an electric solar wind sail (E-Sail), which was designed in 2004, can deflect an asteroid within five to ten years of being attached. The E-Sail would be attached to an asteroid, via a harpoon shot (firing a cord attached to the E-Sail directly into the asteroid) or gravity tractor (levitating a mass close to the asteroid so that the mutual gravitational pull will transfer the towing force of the E-Sail to the asteroid), and momentum from the charged particles in the solar wind will transfer to the asteroid. Over time, projected at between five and ten years, this momentum will change the asteroid's course away from the Earth. While this will not be too helpful for imminent collisions, if a potentially Earth-colliding asteroid is detected years in advance, E-Sails could conceivably be used to send it on a different path (Merikallio & Janhunen, 2010).

Dr. Pekka Janhunen patented the E-Sail in 2010, which uses a circular mesh of conducting wires fed by a voltage source to intercept and extract momentum from the charged particles in the solar wind via the Coulomb force (U.S. Patent No. 7,641,151, 2010). This is contrasted with other solar sail technologies that use either large mirrors to extract momentum from photons or a large loop of superconductive material to generate a magnetic field to deflect the charged particles in the solar wind magnetically (Janhunen et al., 2014). The extremely thin wires, each between 25 and 50 microns in diameter, in the E-Sail are manufactured from aluminum using ultrasonic welding. Each tether, itself

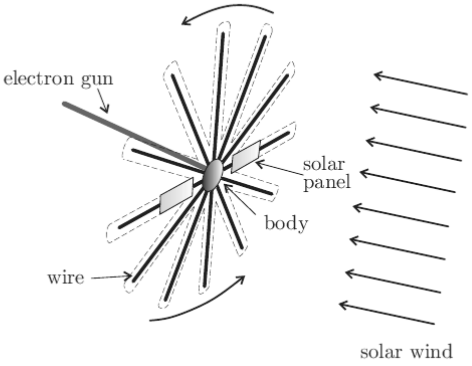

Figure 2: The radial E-Sail design (http://www.electric-sailing.fi/paper4/Fig01.png)

made of multiple wires joined together in centimeter intervals, can be up to 20 kilometers long: "A full-scale sail can include up to 100 tethers, each 20 kilometres long" ("Space sailing soon," 2013, p.381).

As mentioned before, the solar wind has variable speeds, usually between 300 and 800 km/s, which would make using it as a thrust source somewhat unreasonable. However, the E-Sail has a controllable voltage source and can dynamically change the voltage in the sail mesh, which means that the E-Sail thrust will vary much less than the solar wind pressure. Because the thrust of the E-Sail relies on charged particles from the solar wind, it can only achieve propulsive thrust outside of the Earth's magnetosphere, the boundary of which is located at about 10 times the Earth's radius or nearly 64,000 kilometers from the Earth's core, which traps charged particles and may interfere with the E-Sail's propulsion. Special considerations are needed if the E-Sail is to be operated inside a giant planet's magnetosphere, but other than that, the E-Sail will be able to operate anywhere in the solar system.

Some applications of the E-Sail were investigated in 2014: flyby missions to the Venus, Mars, and Mercury as well as asteroids, missions requiring non-Keplerian orbits (orbits that require a continuous propulsive force to be maintained), and one-way missions to the outer solar system. Space weather forecasting based on locations outside of the Lagrange points (locations in space where the gravity between two or more celestial bodies cancel each other out (Cornish, 2012)) and two-way missions of either sample return or data clipping (in which the large amount of scientific data collected by the spacecraft is downloaded when it is near Earth) were also explored. One of the biggest benefits of the E-Sail is that it is has no propellant consumption and makes most planetary missions either cheaper or faster. It is also determined that the E-Sail excels in missions to the asteroids and helps make two-way missions with either samples to be returned or scientific data collection much more feasible, again because of zero propellant consumption (Janhunen et al., 2014).

Another solar sail project currently in progress by NASA titled "In-Space Demonstration of a Mission-Capable Solar Sail," shortened to Solar Sail Demonstrator and nicknamed Sunjammer by the designers after Arthur C. Clarke's 1964 short story of the same name, will be testing the largest solar sail to fly in space. Designed by industry leader L'Garde, Inc., in partnership with NASA, the Sunjammer's sail, at approximately 124 feet to a side or nearly 13,000 square feet, will be seven times larger than any previous solar sail tested in space to this day. Even more impressively, when collapsed, this sail will be able to fit inside a spacecraft the size of a common dishwasher, and it will only weigh 110 pounds, or about 10 times less than the largest sail to be flown so far. Sunjammer will also be a truly propellantless spacecraft as it has solar control vanes to help with orientation rather than small thrusters that use fuel. The Sunjammer mission, which is expected to be launched on a Falcon 9 rocket in 2015, will be used to help NASA researchers test a propellantless spacecraft with orientation control, sail stability, and a mission-capable navigation sequence (Dunbar, 2013).

Theoretically described in 1958 by Eugene Parker, the use of solar wind for propulsion has now been proven. Early attempts to send solar sails into space by the Russians were met with failure in the launch, and it was not until 2010 with the launch of Japan's IKAROS spacecraft that a solar sail was successfully tested in space. Many variations of solar sails have been created, from large mirrors that reflect photons to electric solar wind sails that intercept charged particles. The E-Sail in particular is a promising new technology due to its low cost. Dr. Pekka Janhunen points out that "The electric sail might cheapen all space activities and thereby for example help making large solar power satellites a viable option for clean electricity production" (qtd. in "Electric Sail Invention Approaches Implementation," 2008). Dr. Janhunen is one of the leading experts in solar sail technology, but NASA is also working on solar sails with the in-progress Sunjammer project. If successful, both Janhunen's E-Sail technology and the Sunjammer mission will help drive many future space missions using solar sail technology.

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