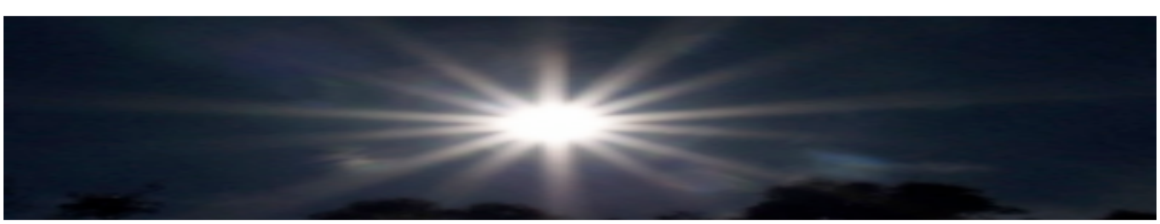
Solar Sails and The Physics of Space Travel

April Moore: H3



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Space Travel: A Brief History

Space travel has been investigated both philosophically and scientifically for centuries, but the possibility of space flight became more of a reality around the mid-1900's. Physics professor Robert Goddard began experimenting with liquid-fueled rockets following World War I, and the first rocket able to reach the Earth's outer atmosphere, the German V2, became a major player in attacks on London during World War II, spurring greater international attention to rocket development. (Cornelisse) Soon after, several world powers began developing programs for research and space flight development. After the orbit of Sputnik in 1957, rocket propulsion emerged as the primary potential mode of launching spacecraft. The U.S. launched Explorer 1 in 1958 and scientific figures as well as prominent political leaders like President J.F. Kennedy lobbied to promote a national space program that would lead to the outcome of man's flight in space. (Cornelisse) Now that so many space missions have been accomplished, by both isolationist and cooperative measures, depending upon the state of national security, engineers and other scientists have optimized and continue to produce more efficient methods, calculations, tools, and materials involved in space travel. One of the first objectives in studying space travel, from a physics standpoint, was to understand how space flight would be affected by natural laws.

Propulsion According to Newton's Laws

Although interplanetary travel takes place in the near-vacuum of space, the concepts of force, mass, velocity, acceleration, and pressure can still be defined by Newton's Laws in describing propulsion systems to move objects at certain speeds. (Ahrendt)

Law 1: Objects resist acceleration (changes in motion) unless acted upon by another force.

Law 2: Force on an object is the product of mass and acceleration (F = ma).

Law 3: For every force, there exists a force in the linearly symmetric opposing direction equal in magnitude.

A Comparison of Astronautics to Aeronautics

In inner-atmospheric flight, the basic calculated forces are weight (gravitational acceleration), lift, thrust, and drag. (Ordway) The properties of the medium are used in conjunction with the shape of a plane's wings to cause the lift that counteracts gravity while, during take-off, the plane produces a force against the ground to propel it forward. Unlike aeronautics, in astronautic flight there are little to no forces of gravity or air resistance acting on the craft, thus we see an unconditional application of Newton's First Law. (Kunesch) The third law best explains the concept of thrust in space. In a vacuum, there is no medium against which to cause a force, so in order to propel itself, the spacecraft must induce a force on itself. This is how space vehicles can move by propelling exhaust, or, by reflecting radiation energy as a solar sail does. (Vulpetti)

Solar Sails: An Early Concept

Four centuries ago Johannes Kepler, a German astronomer known for Kepler's Laws, suggested that large reflective sails could be used to push devices through a vacuum. (McInnes) We have now successfully tested this technology in controlled environments as a possible means of transporting vehicles through space. The irony is that, in earlier days, nautical navigators used astronomical bodies to guide ships. Astronautical scientists now apply the concept of the sail (using photo energy instead of wind energy) as a means to guide spacecraft.

Solar sails are used to propel spacecraft using the pressure of light from a star or laser. Unlike conventional rocket systems that move spacecraft by thrust from burning fuel, solar sails harness radiation energy to push large extremely thin mirrors at high speeds. (Vulpetti) The larger these mirrors are, within reason, the more effective they can be in reflecting a greater number of photons; however, scientists encounter problems in the practicality of using sails that are so large.

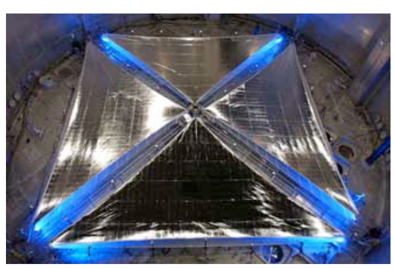
The 21st century has introduced the first generation of practical development and testing of solar sail technology. The first solar sail mission planed to investigate Halley's comet was not approved by NASA. Then in 1997, sail craft Daedalus received disapproval from the ESA council. In 2005 it seemed the first successful sail craft mission was underway. The Cosmos-1, a project of the Cosmos Studios and The Planetary Society was launched from Russian submarine-based launch vehicle upon the Borisoglebsk. This test failed when a rocket malfunction threw the craft off of its intended orbit. (Kondo)

Development

In spite of the failed preliminary attempts to demonstrate solar sail capabilities in space, the turn-of-the-century projects incited public interest in further sail studies, theoretical research, and deployment of small sail tests. The most recently developed sails have been composed of aluminized reinforced Mylar or biaxially-oriented polyethylene terephthalate, a synthetically produced polyester film. It is manufactured for its strength to resist puncture or surface damage, chemical stability, and, especially conducive to the purpose of its use in solar sails, high reflectivity. The sails are on average about 4.5 microns thick or about ¼ the thickness of a trash bag. (Vulpetti)

<u>Designs</u>:

While most solar sail devices appear as the image below, with several triangular sails attached at the center, there are a variety of designs.



A four quadrant, 20-meter solar sail system is fully deployed during testing at NASA Glenn Research Center's Plum Brook facility in Sandusky, Ohio. Image credit: NASA. Digital image. Nasa.gov. Kim Newton, Marshall Space Flight Center, 23 May 2005. Web. 14 Feb. 2010.

Shown here is an original design by the Canadian Solar Sail Project in 1992. They proposed the race of a sail craft to the moon to commemorate the 500-year anniversary of the arrival of Columbus to the Americas. It is constructed of six large panels with pieces like Venetian blinds to change the orientation of the surface normal with respect to the Sun.

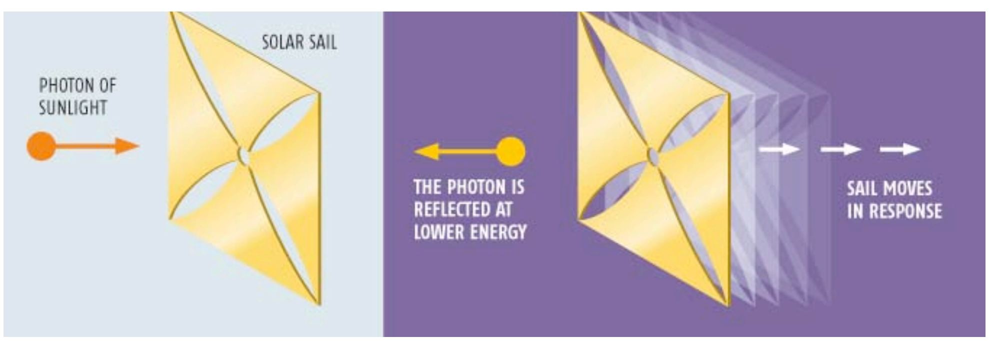
The sail shown below is designed similar to one constructed by the World Space Foundation for an Earth-Moon Race. The structure is supported at its center by fixed booms that bend and compress the sail components as radiation pressure acts on the sail.

Digital images. Http://images.google.com/images?hl=en&q=solar%20sails&um=1&ie=UTF-8&sa=N&tab=wi. Web. <google.com/images>.
"What Is a Solar Sail?" The Planetary Society. Web. 14 Feb. 2010. <http://www.planetary.org/programs/projects/innovative_technologies/solar_sailing/whatis.html>.

Solar Sail Propulsion

<u>Force</u>:

Light is “composed” of photons or discrete quantities of electromagnetic radiation, which behave like high-energy atomic particles. (Brown) Applying Newton’s Laws of Mechanics, discussed in “Propulsion…” section, the physics of reflected radiant energy as a propulsion source for these giant sails can be explained. Perceiving the system instantaneously, the reflective surface is impacted by the initial contact of the photon and the reflection of the photon back off the surface, thus there is a casualty, or relation of an action and reaction between the two events. (Rigden) According to Newton’s Third Law of Motion, the force on the reflective surface will be opposite the direction of the reflected light.



As previously mentioned, the problem with solar sails lies in the second portion of this kinetic law: the directionally opposite force is equal in magnitude. If force is equal to mass times acceleration and a photon has no perceivable mass, then one might ask, “What produces the non-zero force?” Ordinary electromagnetic fields have energy and thus have mass, so how does a photon, or colloquially a “light particle", have momentum but no mass? This is where the aforementioned Einstein's Theory of Relativity comes into play.

Inertia is a numerical representation, or quantitative measurement of an object's internal resistance to acceleration. (Brown) The estimation of inertia, however, as being approximately equal to the object's mass is only true for an object traveling no greater than about one-tenth the speed of light. The calculation of momentum as a product of inertia and velocity,

$p = mv$,

is, therefore, only an approximation.

The less-often applied relation is

$E^2 = p^2 c^2 + m^2 c^4$,

which is more accurate for an object moving at any speed.

At a small speed, this is reduced to

$E=mc^2 + (1/2)mv^2$ and $p = mv$

But for a particle with no mass, as best describes a photon, this equation is reduced to $E = pc$.

The most apparent cause for not understanding how photons can have momentum seems to be that physicists still do not fully understand light other than reasoning that it is an electromagnetic wave.

Since the force yielded by such a tiny momentum is so small, the only way to propel a spacecraft worthy of most legitimate scientific purposes, that is an advanced spacecraft large enough to perform necessary functions in space, is to have sails that reflect a massive quantity of photons.

Radiation Pressure (P), the pressure exerted on the sail by the electromagnetic waves, as determined by Maxwell, is equal to the power flux density or intensity (power per unit area) divided by the speed of light if the light is absorbed. For a solar sail, where the light is reflected, naturally, there is twice as much pressure:

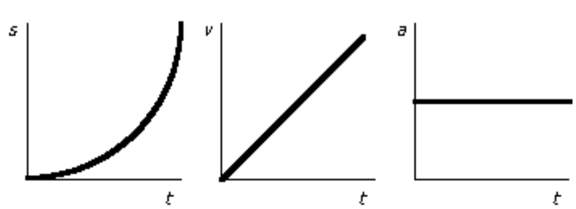
$P = 2I/C$.

Since this pressure depends on the energy density in the radiation field, the effect of the force exerted by radiation is crucial for high-precision trajectory computation and for a high surface to mass ratio. At a higher altitude, where there exists less aerodynamic drag, the radiation pressure is predominant. (Ahrendt)

The essential concept for a successful solar sail-powered spacecraft is time given for the vehicle to accelerate.

Force on a solar sail: $F = P A$

Since there is constant acceleration on an exposed solar sail, the velocity increases significantly given enough time.



Navigation:

Just like the sails on a ship can be moved in accordance with the wind to affect the direction of travel, the angle between solar sails and their light source can be adjusted. The direction of the force on a solar sail is controlled by the angle of the sail with respect to the incoming rays, adding to or subtracting from its orbital velocity. (McInnes) The optical design of the sails is therefore essential to their ability to guide a spacecraft.

One issue with solar sails is that radiation energy is decreased significantly by increasing distance from the light source. Some scientists have suggested the use of long-range lasers as a means for accelerating solar sails, but such currently impractical tools are far from development. (Kondo)

Benefits of Use: "It's Not Rocket Science."

Russian scholar Konstantin Tsiolkovsky, known to many as the father of astronautics, who investigated rocket propulsion and the staged rocket designed to shed weight along its trajectory, reintroduced Kepler's ideas as a potential propulsion method. (Kondo) To effectively propel something, by dimensional analysis of Newton's Second Law, force must be maximized, and mass minimized. Therefore, for an efficient rocket, one would want to minimize payload and maximize exhaust or ejection velocity. Rockets are propelled by combustion, an exothermic chemical reaction between fuel and an oxidizer. (Cornelisse) Solar sails and rockets are both generally massive and expensive, so one may ask why further research and testing of solar sails seems imperative to so many scientific organizations. Primarily, solar sails are more cost-efficient over time. The advantage acquired by the use of solar sails in comparison to conventional rockets is that the use of light energy causes a constant acceleration as opposed to a just a positive decreasing acceleration. So a sail can eventually reach a velocity much greater than that of a rocket. It's not rocket science. Solar energy is free and readily available (at least for a projected 8 billion more years). Rocket propellant is an unrenewable expensive resource that has many other prospective uses. International cooperation on improving fuel systems is also costly for any necessary implementation of security measures. Another benefit of solar sail technology over rocket propulsion is that the use of solar energy is non-pollutive. Most importantly, solar sails experience constant acceleration, so as long as the light source applies the same amount of radiation, the craft will continue to accelerate.

The Future of Solar Sails

NASA, the European Space Agency, and the Japan Aerospace Exploration Agency are now in a cooperative effort to design experimental missions for the employment of solar sails. (Vulpetti) Recent economic downturn is expected to hinder such development at some stages; however, the economic necessity for low-cost energy sources may be enough to reinitiate studies of solar sails if such problems occur. As our knowledge of space, matter, and energy constantly develop, experts are better able to ensure we have the resources to design and improve solar sail technology under the appropriate testing conditions. Progress in the study of solar sails could likely become the next breakthrough for space travel.

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A four quadrant, 20-meter solar sail system is fully deployed during testing at NASA Glenn Research Center's Plum Brook facility in Sandusky, Ohio. Image credit: NASA. Digital image. Nasa.gov. Kim Newton, Marshall Space Flight Center, 23 May 2005. Web. 14 Feb. 2010.

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