

2002

NASA FACULTY FELLOWSHIP PROGRAM

**MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA**

THE PHYSICS OF SOLAR SAILS

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Introduction

The concept of using photon pressure for propulsion has been considered since Tsiolkovsky in 1921 [1-7]. In fact, Tsiolkovsky and Tsander wrote of "using tremendous mirrors of very thin sheets" and "using the pressure of sunlight to attain cosmic velocities" in 1924 [1-4]. The term "solar sailing" was coined in the late 1950s and was popularized by Arthur C. Clarke in the short story *Sunjammer (The Wind From the Sun)* in May 1964 [5]. The National Aeronautics and Space Administration (NASA) used sailing techniques to extend the operational life of the Mariner 10 spacecraft in 1974-1975. A problem in the control system was causing Mariner 10 to go off course. By controlling the attitude of Mariner 10 and the angle of the solar power panels relative to the Sun, ground controllers were able to correct the problem without using precious fuel [4, 6, 7].

Once thought to be difficult or impossible, solar sailing has come out of science fiction and into the realm of possibility. Any spacecraft using this method would need to deploy a thin sail that could be as large as many kilometers in extent. Candidate sail materials should be: 1) strong, 2) ultra-lightweight (density of a few g/m^2), 3) able to be folded or crushed until deployed, 4) subject to minimal sagging or stretching, and 5) resistant to ionizing radiation, such as galactic and solar particles (electrons and protons), x-rays, ultraviolet light, and magnetically trapped charged particles. Solar sails must be resistant to each of these types of radiation [8].

Theoretical Considerations

Since photons are electromagnetic quanta, they have associated electric and magnetic fields [4, 7, 9]. For distances larger than several solar radii, an electromagnetic plane wave can be used to approximate the interaction of photons with a sail. Assume a sail is positioned in relation to the Sun as shown in Figure 1.

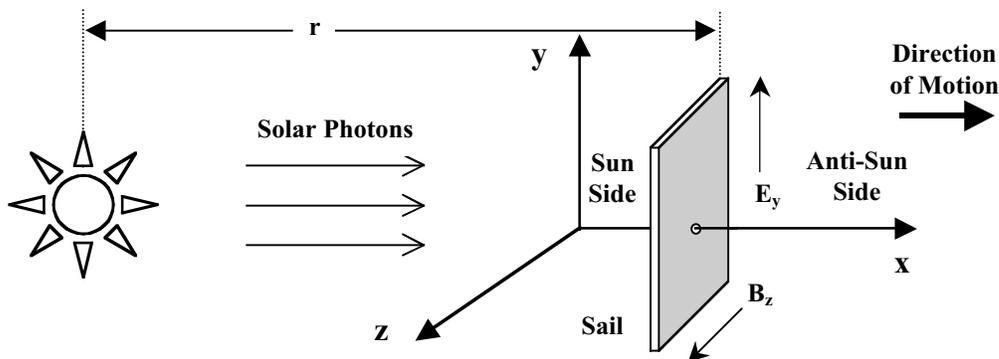


Figure 1: Solar Sail Model

In this model, the sail is positioned at a distance r from the Sun. Photon pressure will cause the sail to move along the $+x$ axis. Using a plane wave solution for photons in a vacuum, the electric and magnetic fields will be in phase along the $+y$ and $+z$ axes respectively. Both the fields will be perpendicular to the direction of photon motion. The main components of the electric (E_y) and magnetic fields (B_z) can be written as

$$E_y = E_0 \sin\left[\omega\left(t - \frac{x}{c}\right)\right] \quad (1a)$$

$$B_z = \frac{E_0}{c} \sin\left[\omega\left(t - \frac{x}{c}\right)\right]. \quad (1b)$$

The E_0 parameter is the constant value of the electric field (N/C), ω is the angular frequency (rad/s), t is elapsed time (s), x is the displacement along the axis (m), and c is the speed of light in a vacuum. These equations assume the incident solar photons are monochromatic, which allows the quantity (E_0/c) in (1b) to be equal to the constant value of the magnetic field (B_0), which is in tesla (T).

The flux vector (\mathbf{S}) transported by the fields is equal to

$$\mathbf{S} = \epsilon_0 c^2 (\mathbf{E} \times \mathbf{B}), \quad (2)$$

where ϵ_0 is the permittivity of free space, \mathbf{E} is the electric field vector, and \mathbf{B} is the magnetic field vector. All vector quantities are shown in bold font. The flux is also known mathematically as the Poynting vector and can be calculated using (1a), (1b), and (2) as

$$\mathbf{S} = \epsilon_0 c^2 \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 0 & E_y & 0 \\ 0 & 0 & B_z \end{vmatrix} = \epsilon_0 c^2 E_y B_z \mathbf{i} = \epsilon_0 c^2 E_y \sin^2\left[\omega\left(t - \frac{x}{c}\right)\right] \mathbf{i}. \quad (3)$$

Obviously the flux vector and the solar photons are both moving in the $+x$ direction. The average of the Poynting vector in the $+x$ direction over one period (τ) is known as the intensity (I_x), and can be calculated as

$$I_x = \frac{1}{\tau} \int_0^{\tau} S dt = \frac{\epsilon_0 c E_0^2}{2}. \quad (4)$$

Intensity has the same units as flux, namely watts per square meter (W/m^2). The stored energy density (U) in the fields for the solar sail is

$$U = \frac{1}{2} \left[\epsilon_0 \mathbf{E}^2 + \frac{1}{\mu_0} \mathbf{B}^2 \right] = \epsilon_0 \mathbf{E}^2 = \epsilon_0 E_0^2 \sin^2\left[\omega\left(t - \frac{x}{c}\right)\right], \quad (5)$$

where μ_0 is equal to the permeability of free space. The square notation is shorthand for the vector dot product. The quantity U has the units of joules per cubic meter (J/m^3), which is analogous to pressure (N/m^2 or Pa). The average pressure (p) on the solar sail due to photon bombardment is equal to the average energy density over one period, as shown by

$$p = \langle U \rangle = \frac{1}{\tau} \int_0^{\tau} U dt = \frac{\epsilon_0 E_0^2}{2}. \quad (6)$$

Dividing both sides of (4) by the speed of light and equating the result to (6), gives an expression for p , shown as

$$p = \frac{\epsilon_0 E_0^2}{2} = \frac{I_x}{c}. \quad (7)$$

Equation (7) assumes the sail material totally absorbs the incident solar photons. If the sail has a constant reflectivity (R), the total pressure (p_t) on the sail is

$$p_t = (1 + R) \frac{I_x}{c}. \quad (8)$$

Momentum imparted to the sail by the reflecting photons introduces the extra term in (8). The R parameter is a constant for a given sail material and is a fraction between zero and one. The light intensity (I_x) shown in (4) is an experimentally determined constant. Since the sail distance r is large compared to the solar radius, the intensity will fall off with the inverse square of the separation distance, and be equal to

$$I_x = \frac{3.83 \times 10^{26}}{4\pi r^2}. \quad (9)$$

The constant in the numerator is the luminosity in watts at the surface of the Sun. At 1 AU, I_x reduces to the familiar vacuum solar constant of $1,368 \text{ W/m}^2$. Substituting (9) into (8) gives the result for total pressure of

$$p_t = \frac{(1 + R)}{r^2} \frac{3.83 \times 10^{26}}{4\pi c} = 1.02 \times 10^{17} \frac{(1 + R)}{r^2}. \quad (10)$$

Equation (10) can be simplified to

$$p_t = 4.56 \times 10^{-6} \frac{(1 + R)}{r_{\text{AU}}^2}, \quad (11)$$

where r_{AU} is equal to the distance to the sun in AU and p_t is in N/m^2 . Using (11), a perfectly reflective solar sail ($R = 1$) at a distance of 1 AU from the Sun experiences a light pressure of $9.1 \mu\text{N/m}^2$.

It is often wrongly stated that particle pressure from the “solar wind” powers sail spacecraft. Solar wind is composed of low-density protons and electrons moving at high velocity. The pressure due to the solar wind (p_w) is on the order of

$$p_w \sim m_p \rho_w v^2, \quad (12)$$

where m_p is the mass of the proton (kg), ρ_w is the particle density, and v is the velocity [4]. Near the Earth, a solar wind density of $6 \times 10^6 \text{ m}^{-3}$ at a velocity of $4 \times 10^5 \text{ m/s}$ gives a particle pressure of about 1 nN/m^2 , which is more than three orders of magnitude smaller than the equivalent photon pressure [4, 10, 11].

Sail Materials

Physical characteristics for several candidate solar sail materials can be found in Table 1. These materials shown in Table 1 were selected due to their relevance to the application, availability, and manufacturability. These sails each have a density of a few grams per square meter.

Table 1: Tested Solar Sail Material Properties

Sample Description	Base Polymer	Base Thickness (μm)	Front Coating		Back Coating	
			Thickness (nm)	Element	Thickness (nm)	Element
Aluminized Mylar	Mylar	3.0	50	Al	50	Al
Aluminized Mylar With Chromium	Mylar	0.9	50	Al	20	Cr
Aluminized Kapton	Kapton	8.0	30	Al	30	Al
Aluminized CP1	CP1	3.0	50	Al	None	

The back surface of one mylar sample was coated with 20 nm of chromium. Chromium was selected because it has a higher emissivity than aluminum and radiates heat more efficiently. The selected aluminized mylar uses stock that contained Kevlar threads to serve as a rip-stop mechanism. These threads were positioned 25 mm (1 inch) apart. The aluminized Colorless Polyamide 1 (CP1) is a moisture resistant polymer that can be stored for long periods of time without significant property degradation. The aluminized CP1 sample did not have a metal coating on the back surface. Kapton maintains its properties at extreme temperatures. Mylar, Kapton, and Kevlar are trademarks of E. I. duPont de Nemours and Company. CP1 is a registered trademark of SRS Technologies.

MSFC Sail Research

The Environmental Effects Group (ED31) at the National Aeronautics and Space Administration's Marshall Space Flight Center (MSFC) maintains world-class facilities to simulate the effects of radiation on an assortment of space-qualified materials. Starting in 2001, ED31 began a comprehensive program to characterize the radiation survivability of candidate solar sail materials. Results from this research indicate that degradation in mechanical properties was observed after radiation exposure [12]. The data reinforces the fact that the thermo-optical properties do not significantly degrade. From this preliminary data, it appears the space environment will not significantly affect the propulsion performance of the sail. Electron exposure measurements are underway and will continue for the rest of 2002. Results from the electron measurements will be presented at the International Solar Energy Conference in Hawaii in March 2003. Proton and ultraviolet irradiation measurements will be completed in the future.

Acknowledgements

The author would like to thank Dr. David Edwards and the entire ED31 team at MSFC for their help and support during my stay in 2002. I appreciate the support and kindness of the entire team. I would like to continue this relationship in the future.

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