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SOLAR SAILS - A REALISTIC PROPULSION FOR SPACECRAFT

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The Phenomenon of Light Pressure

The pressure of light is one of those phenomena which were observed as far back as the prehistoric times. We have in mind a phenomenon accompanying the motion of comets whose appearance in the skies inspired anxiety in some and scientific curiosity in others.

As it approaches the Sun, a comet acquires the characteristic shape of a streak with a widening tail. The size of this tail can sometimes be several times larger than the diameter of Earth's orbit. As the comet approaches the Sun, the tail spreads behind it. When the comet nucleus passes the Sun and begins to recede from it, the tail catches up with and overtakes it, as happens with the smoke of a steamer sailing with the wind.

This curious phenomenon of comet tail reversal contrary to the forces of gravity was observed long ago. Among others, this problem claimed the attention of Galileo, Keppler, and Newton. The force responsible for the reversal of the comet tail is the pressure exerted by solar radiation. This radiation, blowing from the Sun in all directions like a gigantic gale, compels comet tails to change direction in defiance of the laws of gravity.

Peter Lebedev (1866-1912) is regarded as the discoverer of solar pressure. He demonstrated experimentally the existence of light pressure by means of an instrument called the Crookes radiometer.

This consists of a glass bubble housing a small fan consisting of four mica plate wings. One side of the mica plates is blackened while the other is precision polished. When the radiometer is illuminated, a rotary movement is induced because of the nonuniform absorption of radiation by the two different types of surface.

The magnitude of the pressure exerted by the Sun's light radiation is, of course, dependent on the distance between the Sun and the surfaces exposed to its radiation. At a distance equal to that of the diameter of our planet from the Sun, this pressure equals about $0.9\ \text{dyne/m}^2 = 0.5\ \text{mg/m}^2$, or $0.5\ \text{kg/km}^2$.

The magnitude of the pressure exerted also depends on the type of surface. The above data apply to a blackbody surface, i. e., one which completely absorbs radiation. On the other hand, this magnitude is twice as large for a surface reflecting 100 percent of the radiation.

As an example, it can be said that the pressure exerted by solar radiation on the surface of a Tu-114 plane flying in a cloudless sky is about one gram. The pressure on the entire Earth (assuming that the albedo factor, which tells us what proportion of solar radiation is reflected from the Earth's surface, equals 0.4) amounts to 80,000 tons. The radiation pressure increases on approaching the Sun, and attains a value of 30 kg/m^2, which corresponds to a 10-force gale on the Beaufort scale.

Solar Sails

The first proposal for using the pressure of sunlight to propel spacecraft was made by K. Tsiolkovskiy. The mathematical aspect of the "solar sail" was worked out in 1926 by G. Cander (1887-1933).

The work of B. L. Garvin must be considered among the more important achievements. In Poland, Teisseyre was occupied with this problem. Initially regarded as unrealistic, this problem has experienced broad development in recent years, as demonstrated by 150 large papers in specialist publications and collections.

At present, the solar sail project has full mathematical background which guarantees its feasibility.

The propulsive force attainable, given a sufficiently large sail surface, would cause translation of the sail in interplanetary space, in which aerodynamic resistance in the pertinent range of velocities is virtually nil (according to Alfven the interplanetary space contains about 1,000 H_2 atoms/cm^3 which, at a craft speed of $3 \cdot 10^6$ m/sec, would give a resistance of the order of 10^{-8} dynes/cm^2).

The propulsive force perpendicular to the surface of a solar sail would enable travel along certain trajectories in the direction of the nearest planets and the return to the Earth.

Three fundamental conditions must be fulfilled for the functioning of a solar sail:

1) The spacecraft must be taken outside the gravity field of the mother planet by means of some other propulsion or, according to other proposals, placed in a satellite orbit from which it would sail into the interplanetary space after the hoisting of the solar sail.

Removal beyond the terrestrial gravitational field is considered to involve a distance at which the attraction force on the vehicle is smaller than the incident force of light pressure on the sail surface.

This distance depends on the mass of the planet, the surface area of the sail, its distance from the Sun, and the angle at which the sun rays strike the sail.

2) The ratio of the force developed on the sail surface to its surface density (the product of the sail mass and the surface area) must be sufficiently large.

3) The orientation of the sail in the direction of the incident rays and with regard to the proposed course must be assured.

The feasibility of solar sail is mainly contingent on the state of technology in the production of thin metal foils from which sails are to be made.

It follows from the mathematical considerations below that the condition of attaining real interaction with the sun rays is to assure that the sail has the largest possible surface area and the lowest mass. Together, these parameters constitute a value discussed in detail in the mathematical section, which determines whether at a given distance from the Sun the sail will predominantly be the subject of radiation or gravitational forces.

F. Cander's project envisaged such a sail to be a specular surface of a thickness of the order of 10^{-3} mm stretched on a skelton of thin wire to impart rigidity.

According to Cander, such a sail would have a surface of 1 km^2 and a weight of 5,000 kg. Under the action of perpendicular solar rays (total reflection), such a sail would develop a thrust of 1,000 g. The time needed for a satellite placed in an orbit to develop the second space velocity needed for independent flight in the solar system would be about one month. The present state of technology enables the fabrication of foils twice as thick as those postulated by Cander. A period of over four months would be required for a similar operation of accelerating the satellite to the second cosmic velocity.

T. Tsu suggests the use of a sail $9 \cdot 10^9$ cm^2 in area, corresponding to a circle 500 m in diameter, made of 0.004 mm thick foil with a specific gravity of 1.2 g/cm. Such a sail could overcome the solar gravitation up to the orbit of Mars.

The mass of this sail would be 1,000 kg. It would be made of a light organic polymer foil covered with a monoatomic layer of metal for reflection of sun rays. When exposed to solar radiation, such a sail would develop a thrust of 200 g.

In developing the forms and designs of solar sails, Jasman arrived at the conclusion that a circular shape would be the best. It is thus to be hoped that developments in foil production and metallization will make the production of solar sails realistic.

Of course, the spreading of such an enormous "sail" will be possible only in space completely devoid of gravity. A separate problem consists in conferring sufficient strength on the entire structure, enabling it to withstand the bending moments arising from the action of the solar wind.

What will the travel of a space vehicle equipped with solar sails be like? After introducing the spacecraft with folded sails into a terrestrial orbit, the sails will be spread out and oriented with respect to the Sun.

By executing a large number of revolutions around the Earth on an unfolding spiral path, the craft would increase the distance from it while gathering speed. In traveling "against the wind" the sails would be set edgewise toward the Sun, exposing their full surface when traveling "with the wind." Away from the Earth, the sail would become a satellite of the Sun; then braking with the aid of the sail would begin, resulting in a loss of speed in a way similar to spaceships entering the Earth's atmosphere. Thus it would enter the orbit of Venus and become its satellite by suitable maneuvering. After completing scientific experiments, the craft would leave the vicinity of the planet by means of the expanding spiral acceleration maneuver to be blown Earthward by the solar wind.

T. Tsu calculated some approximate trajectories and gave the optimum attitude of sail with respect to the Sun for the individual phases of flight. He has shown that the solar sail constitutes a propulsion method particularly suited for voyages to Venus and Mars. He calculated the voyage times to these planets by a solar sail-propelled vehicle. These times are considerably shorter than those attainable by ionic or chemical rocket engines, as shown in the following table:

Voyage	Chemical Propulsion	Ionic Propulsion	Sail
Earth-Venus	146	125	52 days
Earth-Mars	260	222	118 days

Recently a proposal was made on the basis of modern technological achievements, envisaging the construction of a laboratory vehicle with a sail of 70 m diameter and a payload of 10 kg for a voyage to Venus and back to Earth.

In summary, it may be stated that vehicles equipped with solar sails may be able to move in the interplanetary space, but only within certain limits. The trips may be shorter, however, than would be possible with classical propulsion systems. Nevertheless, in view of the difficulties of motion in the vicinity of large planets (except for the Sun, where on approaching, the ratio of attractive to repulsive forces remains the same), the sails can be used only as an auxiliary means of propulsion permitting a shortening of flight times, correction of flight aspects, and action after the exhaustion of other propellants. The system is certainly more realistic than a number of others presently discussed.

An Outline of the Theory of Solar Sail

The propulsive force arising on the surface P of a solar sail under the influence of incident electromagnetic radiation is directly proportional to the surface area P, the number of radiation quanta incident on the sail surface per unit time, and their momentum $m\nu$ (mc).

$$F = f(P, N, mc,)$$

$$c = 2.99792\ 10\ (\text{cm sec}^{-1}) \qquad (1)$$

The mass of the individual quantum may be calculated from the equation

$$h\nu = mc^2 = E$$

$$m = \frac{h\nu}{c^2} = A\nu \qquad (2)$$

where h is Planck's constant = $6.6252\ 10^{-27}$ (erg sec).

Thus this mass is proportional to the vibration frequency ν of radiation and inversely proportional to the wavelength λ

$$m = \frac{h}{c\lambda} = \frac{B}{\lambda}$$

Therefore, the momentum mc is

$$mc = \frac{h\nu}{c} = \frac{h}{\lambda} = B\nu = \frac{Bc}{\lambda} \tag{3}$$

The total energy emitted by a blackbody in the form of radiation at all wavelengths is proportional to the fourth power of its absolute temperature in K.

From the Stefan-Boltzmann equation:

$$E = \sigma T^4$$
$$\sigma = 5.77 \cdot 10^{-12} \text{ erg cm}^{-2} \text{ stop}^{-4} \text{ sec}^{-1} \tag{4}$$

This energy is not uniformly distributed over all the wavelengths and its maximum is at a characteristic wavelength λ max which is determined by the Wien law:

$$\lambda \max \cdot T = \text{const}$$
$$= 2.898 \text{ mm } °K \tag{5}$$

This relationship is shown in Figure 1.

The nonuniformity of energy distribution in the radiation spectrum, both of a blackbody and the Sun, requires the introduction of the concept of a mean quantum frequency $\bar{\nu}$ or $\bar{\lambda}$. Then the total energy emitted by a given body will be

$$E_c = h \cdot \nu \cdot N \tag{6}$$

This energy can be calculated with the aid of equations (4) and (6)

$$E_c = \sigma T^4 = h \cdot \bar{\nu} \cdot N$$

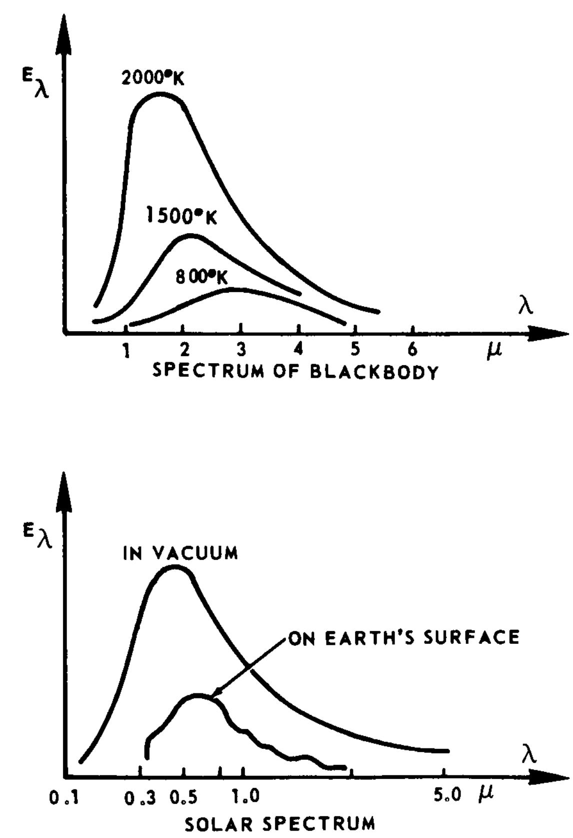

FIGURE 1. DISTRIBUTION OF ENERGY IN SPECTRA

$$\bar{\nu} = \frac{\sigma T^4}{hN} = \frac{T^4}{N} \cdot D \qquad (7)$$

The value of $N \cdot \bar{\nu}$ for solar radiation may be calculated by measuring the quantity called the solar constant S. This is the amount of solar energy reaching 1 m^2 of the Earth's surface perpendicular to the radiation in one second

$$S = \left(\frac{3.16\ 10^{24}}{427}\right) r^{-2} \left(\frac{\text{kcal}}{m^2\ \text{sec}}\right) \qquad (8)$$

where r is the distance from the Sun.

$$S = 0.33\ \text{kcal}\ m^{-2} \text{sec}^{-1}$$
$$= 142\ \text{kg}\ m^{-3} \text{sec}^{-1}$$

This value corresponds approximately to the energy of radiation $E = \sigma \cdot T^4 = N \cdot m \cdot c^2$.

The total mass of photons is

$$N \cdot m = \frac{E}{c^2} = \frac{S}{c^2} = 1.54\ 10^{-15}\ \text{kg} \cdot \text{sec}\ m^{-3} \qquad (9)$$

and their momentum

$$N \cdot m \cdot c = \frac{E}{c} = \frac{S}{c} = 4.7\ 10^{-7}\ \text{kg} \cdot m^{-2} \qquad (10)$$

If N photons/sec fall on a surface P normal to their motion, then

$$N = \frac{\phi}{E_0} \qquad (11)$$

ϕ - light flux
E_0 - energy of a single quantum

In the case of total absorption of incident radiation (blackbody) the pressure exerted by a photon flux is equal to the quotient of their momentum and the surface

$$R = -\frac{F}{P} = \frac{N \cdot m \cdot c}{P} = \frac{N\frac{h}{\lambda}}{P} = \frac{1 \cdot \phi}{P \cdot E_0} \qquad (12)$$

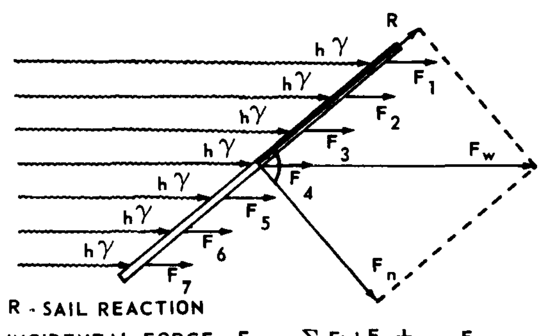

FIGURE 2. DISTRIBUTION OF FORCES ON THE SURFACE OF A SOLAR SAIL

On the other hand, for total reflection (a specular surface), the pressure is

$$R = -\frac{F}{P} = 2\frac{N \cdot m \cdot c}{P} = \frac{2N\frac{h}{\lambda}}{P} = \frac{2}{P}\frac{\phi}{E_0} \tag{13}$$

If the coefficient of light reflection by the surface under consideration is ρ, and $0 < \rho < 1$, then

$$R = \frac{F}{P} = \frac{N \cdot m \cdot c}{P}(1 + \rho) = \frac{N\frac{h}{\lambda}}{P}(1 + \rho) = \frac{1}{P}\frac{\phi}{E}(1 + 0) \tag{14}$$

Differentiating the kinetic energy equation of a photon $E = m\nu^2/2$, we obtain

$$dE = d\left(\frac{m\nu^2}{2}\right) = \frac{2m\nu}{2}\,d\nu = \nu \cdot d(m\nu) \tag{15}$$

for a photon in motion with a velocity $\nu = c$:

$$dE = c \cdot d(mc) = c \cdot dp$$

$$p = mc = \text{photon momentum}$$

therefore

$$E = c \cdot p,\ E = c \cdot mc = mc^2 \tag{16}$$

Then the radiation pressure will equal

$$R = \frac{\phi}{p \cdot c}(1 + \rho) = \frac{1}{c}(1 + \rho) \tag{17}$$

P - surface
I = ---

The number of photons striking the surface of a "sail" depends on the angle of the latter's attitude to their motion. This angle is called the angle of attack α

$$N = N_0 \sin \alpha \tag{18}$$

similarly

$$F = F = F_0 \sin \alpha \qquad (19)$$

N_0 and F_0 are the values at $\alpha = 90°$

The force F induced on the sail surface is always perpendicular to it. Its distribution is shown in Figure 2.

The balance of forces acting on a solar sail is as follows:

1) Attractive force of the Sun:

$$F_s = F_{s0}\left(\frac{r_0}{r}\right)^2 \qquad (20)$$

2) The force of light pressure

$$F = F_m \sin \alpha \qquad (21)$$

where F_{s0} is the force with which the sail is attracted by the Sun at a distance equal to that between the Sun and the Earth, F_m is the maximum pressure force on the sail surface, r_0 is the distance between the Sun and the Earth, and r is the distance between the sail and the Sun.

Assuming the values of the two forces as they would be in the case of equilibrium:

$$F_{s0}\left(\frac{r_0}{r}\right)^2 = F_m \sin \alpha \qquad (22)$$

The force with which the Earth attracts the sail is taken to be 0 in view of the great distance between the two and the small mass of the sail.

Translation of the sail in space will be dependent on the magnitude and direction of the forces F_s and F (Figure 3).

In effect, the sail will move either along a path bringing it closer to the Sun or along one removing it farther away, depending on which force predominates.

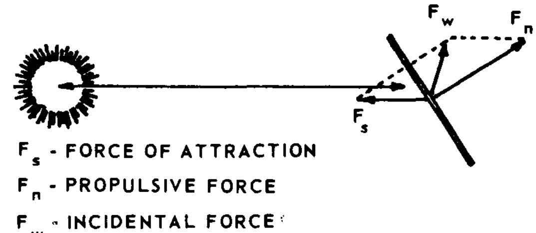

FIGURE 3. BALANCE OF FORCES ACTING ON A SOLAR SAIL

Knowing the value of the resultant force F_W, we can calculate the magnitude of the sail acceleration due to it

$$F_W = m\alpha$$

$$\alpha = \frac{F_W}{m} \tag{23}$$

The acceleration attained by the sail will be directly proportional to its effective surface area = P sin α and inversely proportional to its mass which, in turn, is also a function of the surface area.

It follows from the foregoing that in order to attain high acceleration values the sail should have the largest possible surface area at a small mass. Therefore, its surface density G = mass/surface area should be as small as possible.

Acceleration α attained by the sail

$$\alpha = \frac{F}{m} = \frac{R \cdot P}{L \cdot P \cdot d} \frac{R}{1d} \tag{24}$$

where L is the thickness and d is the density of the sail.

Thus $\alpha = R \cdot H$ for a given sail is independent of its surface area, but depends only on the thickness and density of its material.

Together these two quantities form a parameter H defining the "voyage capability" of a given sail. Of course, the acceleration attained by a sail depends on local values of the solar photon flux.

It thus follows that, assuming the constancy of the surface area and the mass of a sail, its acceleration will become smaller on receding from the Sun because of a decrease of the photon flux and light pressure R_{loc_1}. On the other hand, the ratio of the Sun's attractive force and the force resulting from light pressure away from the Sun is a constant quantity independent of the distance between the sail and the Sun.

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13. ABSTRACT

Vehicles equipped with solar sails may be able to move in interplanetary space, but only within certain limits. The trips may be shorter than when using classical propulsion systems. Presented is an outline on the theory of solar sail.

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