Solar Photon Thrustor

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A space vehicle that uses a solar sail for propulsion can be significantly improved in performance by separating the function of *collecting* the solar photons from the function of *reflecting* the solar photons. In the Solar Photon Thrustor concept, the collector is a large reflecting surface similar in size and mass per unit area to that of a standard flat solar sail. The collector always faces the sun so as to present the maximum area for collection of sunlight. The collector is also designed to be a light concentrator. The concentrated sunlight is sent to a reflecting surface of much smaller mass, which redirects the light at the proper angle to provide the desired direction of net force. Since the collector surface is always facing the sun no matter what the desired direction of thrust, the Solar Photon Thrustor always operates in a maximum solar light power collection mode.

Background

THE idea of attaching large sheets of reflecting material to a spacecraft and "sailing" through space using the radiation pressure from the sun[1-7] has been in the literature since the days of the early space pioneers. Usually, for simplicity of analysis, the sail is assumed to be a flat, mirror-like specular reflector with negligible losses, and the incoming light is assumed to be incident on the sail at nearly broadside angles. The total radiation pressure force in this case is normal to the back of the sail, and by tilting the sail, this force vector can be directed over a considerable angle without a significant decrease in the force vector magnitude. The sail velocity change vector from the resulting acceleration can then be added to or subtracted from the sail orbital velocity vector to cause the sail and payload to be "flown" anywhere in the solar system, including toward the sun.

Introduction

A new solar sail propulsion system concept called the Solar Photon Thrustor is proposed. In the Solar Photon Thrustor, the function of *collecting* the solar photons is separated from the function of *reflecting* the photons. As is shown schematically in Fig. 1, the collector is a large reflecting surface similar in size and mass per unit area to that of a solar sail. The collector faces the sun so as to always present the maximum area for collection of sunlight. The collector is modified in structure so it is a light concentrator. The concentrated sunlight is directed to a reflecting surface of much smaller mass, which redirects the light to provide net solar photon thrust in the desired direction.

To minimize undesired torques, the collecting and reflecting portions of the system can be arranged so that the net force vector passes through the center of mass of the total system including payload. Variation of the collector and reflector positions can produce spacecraft rotational torques if desired.

Since the collector of the sunlight in the Solar Photon Thrustor is always facing the sun no matter what the desired direction of thrust, the Solar Photon Thrustor always operates in a maximum solar light power collection mode. This is in contrast to a standard flat solar sail propulsion system where the collector and reflector are the same sheet of reflecting material. (The arguments that follow also apply to the Heliogyro type of sail[7] as well as any other design where the light collector and the light reflector are the same structure.)

In a flat solar sail propulsion system, if the desired direction of thrust is not directly away from the sun, the sail must be tilted at some angle Θ with respect to the sun-sail line. Since the sail is tilted toward the sun, the effective collecting area of the standard solar sail propulsion system is decreased by an amount proportional to $\sin\Theta$.

This means that the Solar Photon Thrustor always collects more solar light power and therefore provides higher total solar photon radiation pressure force for the same area of collector. Since the mass of any optimized light pressure propulsion system is dominated by the mass of the light collecting area, the Solar Photon Thrustor system will have better total system performance in terms of maximum payload capability, maximum propulsive thrust, and minimum mission time than standard solar sail propulsion systems.

It was originally thought that the idea of separating the function of collecting the light from the function of reflecting the light to produce the improved performance of the Solar Photon Thrustor concept was a novel concept. A review of the literature prior to filing for a patent, however, discovered that the general concept was discussed in the notebooks of Tsander,[1] and specific designs of spacecraft using multiple reflections from multiple sails were discussed in the Russian literature[2-4] in the 1970s. The Russian journals containing these papers are so small and provincial that the journals are not translated into English, and most university libraries do not get them. The prior publications only came to light because of a recent Russian technical book[5] that reviews all of the literature on solar sails, eastern as well as western.

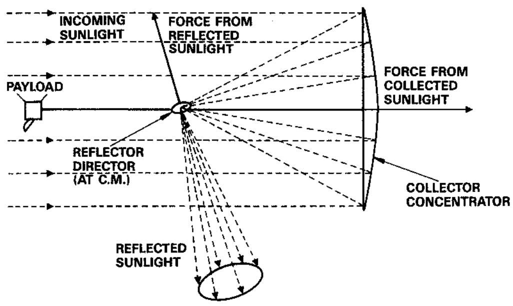

Fig. 1 Schematic of Solar Photon Thrustor.

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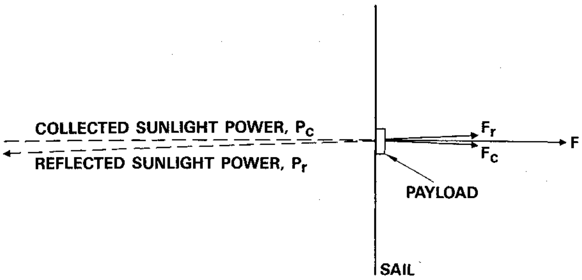

Fig. 2 Light forces on a solar sail.

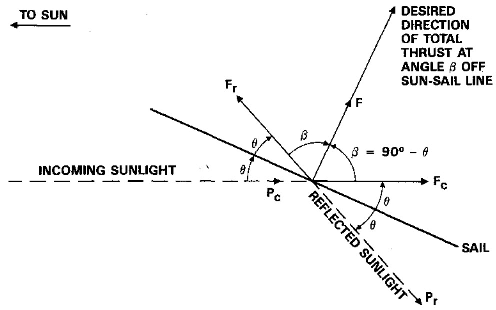

Fig. 3 Light forces on a flat tilted sail.

Standard Solar Sail Systems

In the standard solar sail propulsion system, a large, usually flat, sail of reflecting material is attached through a connecting structure to a payload to form a total spacecraft. Solar photons from the sun strike the reflecting material and rebound. The change in momentum of the reflected photons produces a radiation pressure force on the sail. This radiation pressure force can be used to propel the spacecraft from one point in space to another.

The net radiation pressure force off a flat reflective sail is normal to the back of the sail. Thus, by tilting the sail, this force vector can be directed over a considerable angle. The light pressure force then causes the spacecraft to accelerate in that direction. The spacecraft velocity change from the resulting acceleration can then be added to or subtracted from the spacecraft orbital velocity vector to cause the spacecraft to be "sailed" anywhere in the solar system. The maximum sail acceleration is obtained when the desired direction of thrust is directly away from the sun. In this case the sail is broadside to the solar light flux coming from the sun as shown in Fig. 2.

The solar light flux S or light power per unit area in space at any given distance D from the sun is

$$S = S_0 (D_0/D)^2 \tag{1}$$

where the solar flux constant $S_0 = 1.4$ kW/m^2 is the solar flux at the distance of the Earth from the sun, $D_0 = 1$ A.U. $= 1.50 \times 10^{15}$ m.

The power P in the solar light flux S passing through any given region with an area A is

$$P = SA \tag{2}$$

In basic physics or optics textbooks on the physical properties of light, it is found that the momentum of the collected solar photons of total power P_c striking the sail during the photon collection process produces a radiation pressure force F_c that is in the direction of the collected light and has a magnitude of

$$F_c = P_c/c = P/c = SA/c \tag{3}$$

where $c = 300$ Mm/s is the speed of light.

If the sail is highly reflecting (which is relatively easy to accomplish in practice), then, as is shown in Fig. 2, nearly all of the solar photons rebound from the sail. The total reflected light power P_r from the sail then produces an additional reflected radiation pressure force F_r equal in magnitude and direction to the original collected radiation pressure force F_c.

The total radiation pressure force F on the sail is then just the sum of these two forces, one force F_c occurring during the light collection process and one force F_r occurring during the light reflection process.

$$F = F_c + F_r = 2\,(SA/c) \tag{4}$$

This is the standard equation seen in elementary discussions of solar sails, except that in Eq. (4) the separate contributions of the light collection and light reflection processes have been explicitly brought out.

If the desired direction of travel is not directly away from the sun, then the equations describing the standard solar sail propulsion process become more complicated. If the desired acceleration direction is at an angle β off the sun-sail line, then, simple principles of mechanics and geometric optics, as illustrated in Fig. 3, show that the optimum performance is obtained when the sail is tilted at an angle $\Theta = 90\ \text{deg} - \beta$ off the sun-sail line. At this angle, the net radiation pressure force vector F is aligned along the desired acceleration direction. The tilting of the sail has two effects. Since distinguishing between the two effects shows the difference between the standard solar sail propulsion system and the Solar Photon Thrustor system, they will be discussed separately.

When the solar light flux impinges on a flat solar sail of area A that is tilted at an angle Θ with respect to the sun-sail line, as is shown in Fig. 4, then the effective light collection area A_c of this sail is

$$A_c = A \sin\Theta \tag{5}$$

The total solar light power P_c collected by the sail is then

$$P_c = SA_c = \sin\Theta SA \tag{6}$$

which is different from Eq. (2) by the sine of the sail tilt angle Θ.

This collected solar light power then produces a radiation pressure force F_c that is in the direction of the incoming light and has a magnitude given by

$$F_c = P_c/c = \sin\Theta\,(SA/c) \tag{7}$$

If we make the reasonable assumption that the sail is flat and highly reflecting, then the reflected light power P_r is equal in magnitude to the collected light power P_c given by Eq. (6):

$$P_r = P_c = \sin\Theta SA \tag{8}$$

As shown in Fig. 3, however, the direction of the reflected light power is at an angle of Θ with respect to the solar sail surface and 2Θ with respect to the sun-sail line. This reflected light power P_r produces a radiation pressure force F_r that is opposite in direction to the reflected light power as shown in Fig. 3. Assuming the reflectance is 100%, the magnitude of the radiation pressure force from the reflected light power is the same as the magnitude of the radiation pressure force from the collected light power

$$F_r = P_r/c = \sin\Theta\,(SA/c) \tag{9}$$

It should be noticed at this point that both the collected light pressure force given by Eq. (7) and the reflected light pressure force given by Eq. (9) are decreased by the factor $\sin\Theta$ from the maximum obtainable at the broadside sail angle (when $\Theta = 90$ deg). This results solely because the effective collection area of the sail is decreased by $\sin\Theta$ as shown by comparing Eq. (2) with Eq. (6).

For the case of the broadside-to-the-sun sail angle considered first, the collected light power force F_c and the reflected light power force F_r are in the same direction and can be added directly, as was done in Eq. (4) to get the total light power force F. For angles other than broadside to the sun, however, the directions of the two forces are different, and they must be added vectorially. Since the forces are vectors, to sum them up into a net force vector involves taking their separate components along two orthogonal directions, summing the components from each force along those two orthogonal directions, and then recombining the two summed components back into a new total force vector as shown in Fig. 5. When this is done, another factor of $\sin\Theta$ is generated.

As is shown in Fig. 5, the collected light power force vector F_c can be broken into two components. One component F_{ct} is tangent to the sail surface:

$$F_{ct} = F_c \cos\Theta = \sin\Theta \cos\Theta (SA/c) \tag{10}$$

and one component F_{cn} is normal to the sail surface:

$$F_{cn} = F_c \sin\Theta = \sin^2\Theta (SA/c) \tag{11}$$

Similarly, the reflected light power force vector F_r can be broken into two components tangent and normal to the sail:

$$F_{rt} = -F_r \cos\Theta = -\sin\Theta \cos\Theta (SA/c) \tag{12}$$

$$F_{rn} = F_r \sin\Theta = \sin^2\Theta (SA/c) \tag{13}$$

As can be seen from Fig. 5, the components of the two forces tangent to the sail are equal and opposite, and cancel out, leaving only the two normal components. Thus, the total light pressure force F on a flat sail tilted at an angle Θ with respect to the sun-sail line is still normal to the back of the sail but smaller in magnitude by the sine of the tilt angle Θ due to the vector addition process:

$$F = F_{cn} + F_{rn} = (F_c + F_r)\sin\Theta \tag{14}$$

In addition, the light power available has been decreased by the $\sin\Theta$ of the sail tilt angle Θ by the decrease in effective area of the collecting area of the sail as shown in Fig. 4.

Substituting Eqs. (7) and (9) into Eq. (14) produces

$$F = 2\sin^2\Theta (SA/c) \tag{15}$$

Thus, the total light power force for a tilted sail is decreased by two factors of $\sin\Theta$ from a broadside-to-the-sun sail.

As is shown in Fig. 3, the desired acceleration direction angle β is related to the sail tilt angle Θ by the simple relation $\Theta = 90\ \text{deg} - \beta$. Therefore, $\sin\Theta = \sin(90\ \text{deg} - \beta) = \cos\beta$, and Eq. (15) can be expressed in terms of the desired acceleration direction angle β, rather than sail tilt angle:

$$F = 2\cos^2\beta (SA/c) \tag{16}$$

This is the well-known[6] basic force equation for the standard flat solar sail propulsion system.

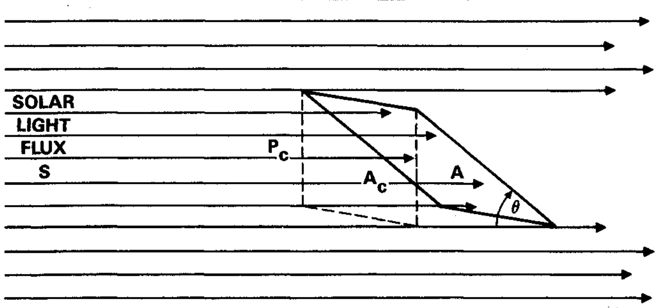

Fig. 4 Power collected by a flat tilted sail.

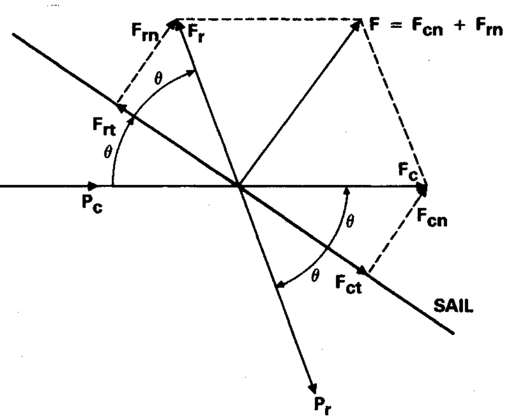

Fig. 5 Vector addition of solar sail forces.

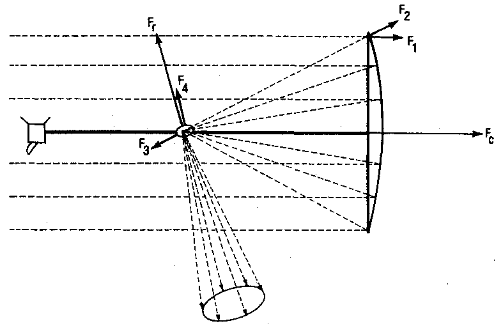

Fig. 6 Solar photon thrustor force diagram.

As long as the desired direction of travel is at angles that are in the directions away from the sun so that $\beta \sim 0$, then $\cos\beta \sim 1$, and nearly the full solar light pressure force is acting on the sail. But for certain applications,[8,9] where it is desired to obtain significant forces at right angles to the sun-spacecraft line, where β is approaching 90 deg, then the two factors of $\cos\beta$ reduce the available thrust drastically.

Solar Photon Thrustor System

The basic components of the Solar Photon Thrustor system are a light collector, a separate light reflector, and a connecting structure. The light collector is a large reflective surface similar in size and mass per unit area to that of the standard solar sails. These solar sails are hundreds of meters to kilometers in diameter and have masses per unit area of 10 g/m^2 or less, with the performance improving with decreasing mass-to-area ratio. The collector of the Solar Photon Thrustor faces the sun so as to always present a maximum area for collection of sunlight.

The collecting surface is shaped into a lens-like form that will concentrate the sunlight into a smaller area. The concentrated sunlight then goes to a smaller reflecting surface of minimal size and mass, which reflects the sunlight in a direction such that the net light pressure force on the whole system is in the desired direction. In addition to the light collecting system and the light reflecting system, there will be some sort of structure to connect the two portions of the Solar Photon Thrustor to each other, to the payload, and usually (but not necessarily) to some sort of control system.

The embodiment of the Solar Photon Thrustor system shown in Fig. 1 is repeated in Fig. 6 with the addition of extra force arrows to show the detailed method of operation. As is shown in Fig. 6, as the sunlight strikes the collector mirror, there is a force F_1 exerted on the collector mirror by the light pressure from each ray of sunlight. Note that all of these forces F_1 are in the *same* direction. Together, they add up into the large collected light power force vector F_c shown in Fig. 6. Note that the collected light power force vector F_c is centered

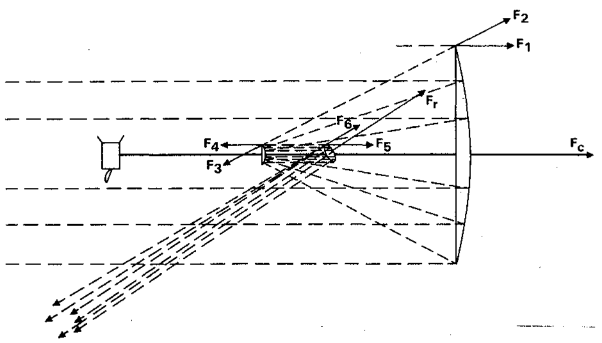

Fig. 7 Dual reflector solar photon thrustor.

at the center of the collecting sail, and if the mast is aligned along the sun-spacecraft line, the collected light power force vector passes through the center of mass of the spacecraft, which lies along the mast.

When the light reflects off the curved surface of the collector mirror, each ray exerts a force F_2 on the sail. These forces are in different directions, but instead of trying to keep track of all of them, note that when the reflected light ray that caused the force F_2 back on the collector mirror hits the reflector mirror, it causes a force F_3 that is equal and opposite to F_2. If the structure connecting those two points is stiff enough (or better yet, all the forces are symmetric about the axis of the combined system), then, for every force F_2 there is an equal and opposite force F_3. The net result is that there is no net force or torque on the spacecraft due to these paired forces. (In reality, there will be some force pairs that produce a small residual net force or torque, but these can be taken care of by the control system.)

The reflecting optics can either be a single mirror suitable for reflecting the sunlight in a direction away from the sun, such as is shown in Fig. 6, or a double mirror system suitable for reflecting the sunlight in a direction toward the sun, as shown in Fig. 7. In the dual reflector mirror system of Fig. 7, it can be seen that F_2 is canceled by F_3, and F_4 by F_5, so that all internal light pressure forces are self-canceling if the optical paths are designed to be symmetric about the optical axis of the system.

After the light reflects off the final reflecting mirror, there is one more increment of light pressure force. This is F_4 in Fig. 6, and F_6 in Fig. 7. All of these forces combine into the net reflective light pressure force F_r. If the final reflecting mirror is positioned properly, the net reflective light pressure force F_r will pass through the center of mass of the spacecraft.

Thus, after all of the collection and reflection processes, the net forces that result are the collected light power force F_c and the reflected light power force F_r. If the reflectance of the mirrors has been kept high, then the magnitudes of these two forces are nearly equal. If the design and operation of the Solar Photon Thrustor system has been proper, then both of these forces pass through the center of mass of the total spacecraft. For the case where the radiation pressure force from the collected light and the radiation pressure force from the reflected light are equal in magnitude and pass through the center of mass of the structure, the force diagram simplifies to that shown in Fig. 8. The collected light power force vector F_c is always in the direction away from the sun. If the collector is oriented broadside toward the sun, the magnitude of the force is given by

$$F_c = SA/c \tag{17}$$

which is just Eq. (3).

If it is desired to have the spacecraft accelerate in a direction that is at an angle β off from the sun-spacecraft line, then as is shown in Fig. 8, the component of this force along the desired acceleration direction angle β is just

$$F_{cd} = \cos\beta (SA/c) \tag{18}$$

If the mirrors in the reflector optics system are good, then the magnitude of the reflected light power force F_r is equal to the collected light power force

$$F_r = F_c = SA/c \tag{19}$$

As the force diagram in Fig. 8 shows, to achieve the desired direction of *total* thrust at some desired angle β, the reflected sunlight should be sent off at an angle of 180 deg -2β. The light pressure force from the reflected light is therefore at an angle β on the other side of the desired acceleration direction. The component of this light pressure force in the desired acceleration direction is

$$F_{rd} = \cos\beta (SA/c) \tag{20}$$

The net force produced along the desired acceleration direction is then just the sum of the two components:

$$F = F_{cd} + F_{rd} = 2\cos\beta (SA/c) \tag{21}$$

By comparing Eq. (21) with Eq. (16), we find that the Solar Photon Thrustor system produces an improved amount of propulsive force over the standard flat solar sail propulsion systems. The improved level of thrust is proportional to $\cos\beta$, where β is the angle between the sun-spacecraft line and the desired direction of acceleration.

Solar Photon Thrustor Components

The light collecting mirror of the Solar Photon Thrustor is a collecting surface made of lightweight, metal-covered, plastic film with a spherical curvature. A spherical surface takes the nearly parallel light rays from the sun and concentrates them down at a focal point that is at one-half the distance to the center of curvature of the collector lens. In Fig. 6, the diameter of the collector mirror was drawn equal to the focal distance order to make the different parts of the structure easier to see. The ratio of the focal distance f to the diameter d of a lens or mirror is called the f number of the lens. With a focal distance equal to the diameter, the f number of the mirror is $f/d = 1$. Such a mirror is called an f/1 lens.

Small f/1 lenses have been made by L'Garde, Inc., for the Solar Thermal Rocket program of the Astronautics Lab at Edwards Air Force Base. They have a measured solar concentration ratio of 10,000:1. The present mirrors are made of fairly heavy plastic film since they must withstand significant accelerations and torques. A picture of the prototype is shown in Fig. 9.

Low f-number mirrors are not needed for the Solar Photon Thrustor. The use of high f-number mirrors would ease the tolerances and lower the costs. The high f-number mirrors would be almost flat. They would not need inflation pressure to hold their curvature, but could make do with the light pressure force itself to form the desired curvature.

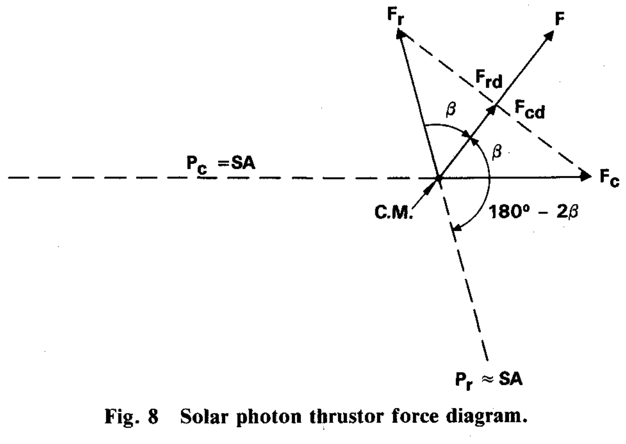

Fig. 8 Solar photon thrustor force diagram.

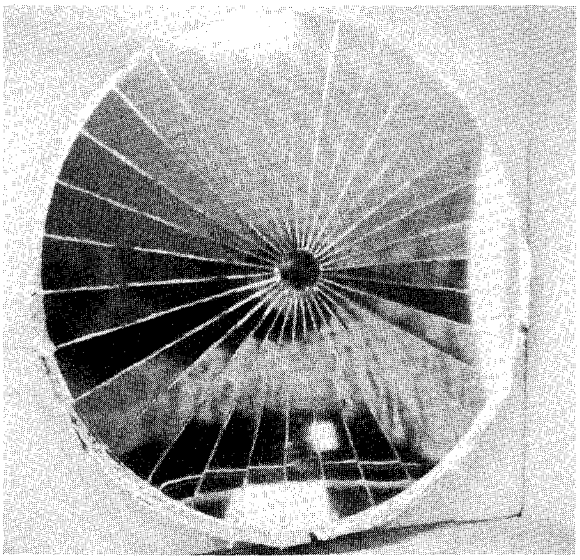

Fig. 9 Prototype inflatable solar concentrator.

High solar power concentration ratios are also not needed for the Solar Photon Thrustor. An easily reached concentration ratio of 100:1 means that the area (and therefore the mass) of the reflecting optics will be 1% of the area (and mass) of the collecting optics and therefore a negligible portion of the total spacecraft mass.

Note in both Figs. 6 and 7 that by tilting the reflecting mirror, the sunlight can be reflected in any desired angle off the axis formed by the sun-spacecraft line, whereas rotation of the whole spacecraft around the sun-spacecraft line allows direction of the reflected sunlight in azimuth around the sun-spacecraft line.

In addition to the collecting mirror, which contains a good fraction of the mass of the Solar Photon Thrustor, and the much smaller reflecting mirror (or mirrors), there is also a control system, and a structure to tie the mirrors together and to the payload. In Fig. 6, the main structure is a simple mast. At one end is the payload (greatly exaggerated in size in the figure), at the other end is the collector mirror. In a typical optimized spacecraft, the collector lens will have a mass about equal to that of the payload, so that the center of mass of the combined system will be at about the halfway point. The reflector mirror system is then placed at the center of mass point along the mast. In operation, the payload and Solar Photon Thrustor are launched as a compact package. The collector mirror is unfurled, the mast extended, then the reflector mirror deployed. Light torques are used to align the system toward the sun; then the reflector system is used to give the whole spacecraft the desired acceleration vector.

Alternate Configurations

The configurations shown in Figs. 6 and 7 are not the only ones possible. There are other obvious reflecting optics arrangements that would allow the pointing of the reflected sunlight beam in any direction without rotation of the spacecraft. Such arrangements are well known in the field of high-power laser-beam directors. There are also other obvious optical arrangements that can allow separate control of the acceleration direction applied to the center of mass of the spacecraft and the torques around the center of mass of the spacecraft.

The collector could be on the sun side of the spacecraft and the payload on the other. The collected light would be partially collimated by a curved relay mirror and transmitted through an axial hole in the collector mirror to the deflector mirror located at the center of mass of the spacecraft between the collector and the payload. (See Fig. 39 in the book by Polyakhova[5] describing the work by Skoptsov.[4])

The collector could be a reflective fresnel lens consisting of alternate rings of reflecting material and nothing. Although a fresnel lens has different focal lengths for different wavelengths of light, if the f number of the lens is high enough, most of the light will pass through a relatively small area where it could be deflected by a mirror placed at that point. Such a reflective fresnel lens would have two focal points, one on the sun side for the reflected light that hit the reflective rings and one on the other side for the transmitted light that passed through the empty rings. Such a system would have two deflector mirrors, one on each side of the lens. If the payload were at the center of the collector lens, then the deflector mirrors would be on opposite sides of the spacecraft center of mass, and the net thrust would be through the center of mass of the spacecraft.

The Solar Photon Thrustor is not limited in its operation to the use of photons from the sun. It could be designed to obtain propulsive thrust from the radiation pressure force of electromagnetic photons of any kind. These photons could be in any portion of the electromagnetic spectrum and from any source, natural or man-made. Some specific examples would be thrustors designed to travel on microwave or laser beams from powerful transmitting systems on Earth or in space.

Since microwave and laser beams are coherent electromagnetic radiation, different structures are feasible for the collectors and reflectors. Phase fresnel lenses consisting of alternate rings of thin plastic and nothing could replace the reflective surface mirrors or fresnel lenses. Phase holograms in thin plastic would be more sophisticated versions of these discrete fresnel lenses and could be used in both the collector and director systems.

The electromagnetic radiation does not have to stay in its original form. For example, the collector could collect sunlight and concentrate it on a thermal boiler system. The heat generated could be used to make microwave, laser, or other useful coherent radiation, which would be beamed down to Earth. The waste heat from the process would be radiated away into space. Both the beamed coherent power and the radiated waste heat would produce propulsive force of comparable magnitude to the collected light. By proper design of the whole system, the beamed power and waste heat, along with the collected light, could provide the propulsion needed by the system. Similar concepts, where sunlight is concentrated onto solar cells to make electricity to make microwave power, or where coherent radiation of one form is converted into another using parametric mixing of electromagnetic radiation in nonlinear materials, all can be combined with the general concept of the Solar Photon Thrustor so that the power handling process produces useful propulsive thrust as a byproduct.

Minimum Operational Altitude

Moss[10] has shown that a properly designed and operated Solar Photon Thrustor can be launched at significantly lower altitudes in the Earth's atmosphere than a flat solar sail. For example, at low solar activity, the minimum launch altitude for a solar sail is 630 km, whereas for a Solar Photon Thrustor it is 460 km, which is reachable by the Space Shuttle from a Vandenberg launch.

The Solar Photon Thrustor would be placed in an orbital plane perpendicular to the Earth-sun line. These near polar orbits would provide continuous solar illumination and therefore maximum acceleration. The required orientation of the collector in this orbit is tangent to the direction of motion and results in minimum cross-sectional area for aerodynamic drag. The estimated time for the Solar Photon Thrustor to raise its orbit from the launch altitude at 460 km to the nearly drag-free environment at 1000 km is only 4 days.

Summary and Conclusions

A new type of light pressure propulsion structure that gives improved performance over the standard flat sail light pressure propulsion systems has been proposed. The standard flat sail light pressure propulsion systems suffer a decrease in their effective light collection area when they are tilted to travel in a direction other than directly away from the sun. In contrast, the Solar Photon Thrustor maintains its collecting area pointing directly at the sun, thus always collecting the maximum amount of light power. A separate, low mass sail then redirects the collected light in the proper direction to achieve the desired net spacecraft thrust direction.

Acknowledgments

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