Very Fast Solar Sails

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Abstract:

This paper is a presentation of some suggestions for development of a class of interplanetary and heliospheric lightsails that are very simple, very light, and, therefore, very fast. The suggestions are combinations of concepts put forth by Dyson, Forward, Drexler, Burke, Cotter, Colombo and others. It is suggested that the construction and deployment of sails with lightness number 10 is easily within the capability of our technology. Such craft could reach distances of 100 au within about four years. The problems, then, are how to communicate with the craft and how to attach to them any substantial amount of payload. Suggestions for distribution of payloads on the surfaces of the sails are put forward, and a workable scheme is offered for a deep-space retro-reflector, long the dream of Professor Colombo, that could make use of the Sun as a source of signal. The retro-reflector could facilitate the preliminary study of the density of the interstellar medium beyond the heliopause, within a few decades.

Discussion

One of the myths that has accompanied the paper development of the solar sail in the literature is that they are very slow, suitable only for very long trips to carry non-perishable supplies and equipment. There is a good reason for this myth. The value of scientific or life-support spacecraft is normally measured in the mass required to acquire certain traditional measurements, typically video images, or to support life for a given amount of time. Therefore, when analysts in the past have put forth designs for solar sailing spacecraft, the designs have been very heavily loaded with traditional instruments and power systems. For these designs, the characteristic accelerations of the spacecraft have been very low so as to trade time for payload.

In this paper, it is pointed out that solar sails need not be slow. Indeed, they can be designed to provide incredibly fast transfers for small payloads. Following suggestions by Forward, Dyson, and Drexler, we examine the limits of what can be done if payload mass can be reduced to a minimum. In some cases, the sail itself can be the payload, acting as an antenna or reflector for radiation generated near the center of the solar system. In such cases, spacecraft can reach 100 au in about 3.6 years. Such probes may permit the determination of the gravitational structure of the Öort cloud.

Review of Ideas for Solar Sails

This review is as much for the author as for the reader. Throughout a period of almost twenty years, the author has had an abiding interest in the ideas and applications of solar sailing. This interest has led to a compilation of many ideas and implementations of the light-sail concept. Since the demise of the Halley Rendezvous Project[1] in the late 1970's, conventional mechanisms have not been successful in developing this frontier technology that could enable "The Extension of Mankind into Cosmic Space" as Tsiolkovskiy[2] put it. This is not a criticism of the various institutions or individuals who have promoted solar sailing by bureaucratic methods -- it is a statement that these methods have been unsuccessful in raising the capital necessary to develop a self-supporting technology.

The first successful solar-sailing project will probably be financed by a forward-thinking company or wealthy individual who recognizes the long-term potential for intellectual and monetary profit available through the development of an efficient deep-space transportation system. Although the monetary profit may be secondary in the mind of the entrepreneur, any successful businessperson knows that, if your company runs in the red, you'll be out of business very soon, no matter how noble or beneficial your early dreams for the company or the project.

The myth of the solar sail as being useful only as a deep-space "cargo" vehicle or "slow-boat" has contributed to the lack of interest in its development within the various government agencies responsible for assessment of new technologies. In this paper, we describe a number of mechanisms for development of high-performance, potentially very fast solar sailing vehicles.

The Cassegrain Sail

One of the problems of solar sailing is the need to steer the sail in order to point the thrust due to solar radiation pressure in the desired direction. For a flat, or nearly flat sail, turning the sail yields a cosine squared loss in performance, one cosine comes from the decreased area of intercepted sunlight, and the other comes from the glancing incidence of the radiation pressure. Fig. 1 shows a way to get almost the full value of the solar pressure. The idea is to build a secondary mirror near the focus of the large parabolic reflector,A, that maintains its normal along the sun-line.

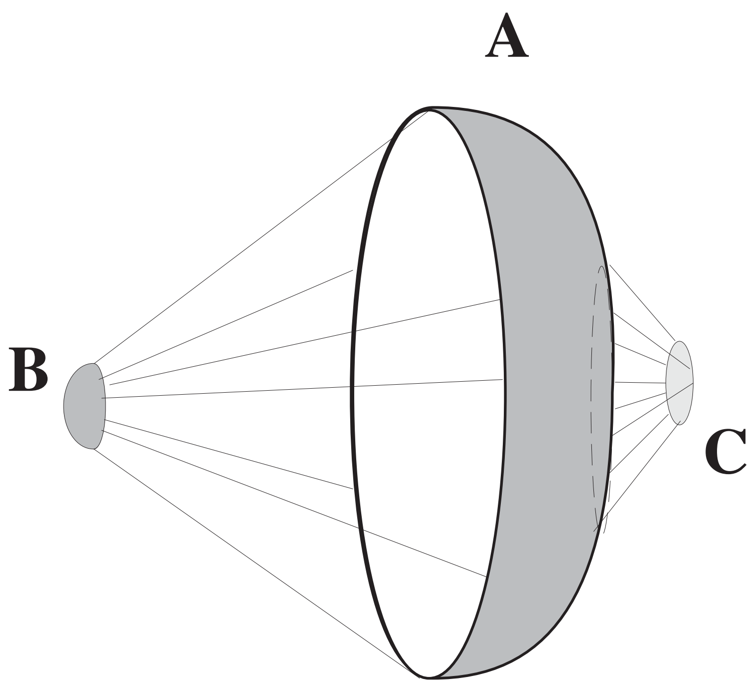

Fig. 1 Cassegrain Sail with Secondary and Steering Mirrors

The secondary mirror B (much smaller than the mainsail) directs all the reflected sun-light to an even smaller, and more controllable, steering mirror, C, placed near the center of mass of the entire system. Now the reflected light can be directed at almost any angle with respect to the sun-line without the need for moving the mainsail. But the thrust vector must still be outward. If, for example, we try to get an inward thrust by removing the steering mirror, the momentum of the outgoing light is identical with the momentum of the incoming light (assuming perfect mirrors) and the net force on the sailcraft will be zero.

This concept was discovered by the author in 1978 but was not published. Later, in communications with Dr. Forward, the author learned that Forward had also discovered the idea and included it as part of his "photon thruster" concept[3] for levitating comsats above and below the equator. In subsequent discussions, Forward pointed out that the idea had been described in Polyakova's excellent book[4]. The concept was discovered prior to 1971 by A. P. Skoptsov [5].

Some form of this concept will almost certainly be used in the giga-ton interplanetary freighters of the 22nd century. The maximum use of the light pressure and the nearly complete control of the reflected momentum, without requirement for steering the mainsail (and the usual cosine loss associated with steering a flat sail) will probably offset the obvious technological problems of thermal stability for the secondary and steering mirrors.

Super Sails

Dyson[6], Forward[7], Drexler[8], and others have identified mechanisms and manufacturing techniques that will provide the materials for super sails -- sails with lightness numbers of 10 to 30 or 40. Lightness number is Richard MacNeal's[9] phrase for the ratio of the light-pressure acceleration to the gravitational acceleration. Thus, a lightness number 10 sail would be able to produce an acceleration of 60 mm/s^2 at 1 au.

Drexler has demonstrated manufacturing techniques that can produce films of aluminum as thin as 500 Å (5x10^{-8} m). Dyson and Forward have suggested tuned (microwave) and perforated (optical) sails that can reduce the mass of the solid film sails by at least a factor of 10. Because the suggested perforations are of the order of the wavelength of the most intense sunlight, approximately 65% of the light is reflected in spite of the holes that greatly reduce the mass of the sail material.

These sails are truly gossamer structures, with total sail loading values of from 0.15 to 0.015 g/m^2. Here, sail loading follows the definition of J.L. Wright[10], where sail loading was defined as the total spacecraft mass (in grams) per unit area of intercepted sunlight (in m^2) with the sail oriented normally to the sun-line. Wrinkle-shadowing, isotropic losses, and other reflectivity degradations led Wright to adopt a simple formula for characteristic acceleration (at 1 au) of

$$a_c(\mathrm{mm/s^2}) = [8\ (\mathrm{g \cdot mm/m^2 \cdot s^2})]\ /\ \sigma(\mathrm{g/m^2})\ ,$$

where σ is the sail loading as described above. In the following sub-sections, we shall discuss the spinning sail, the electrostatic sail, and the variable density sail.

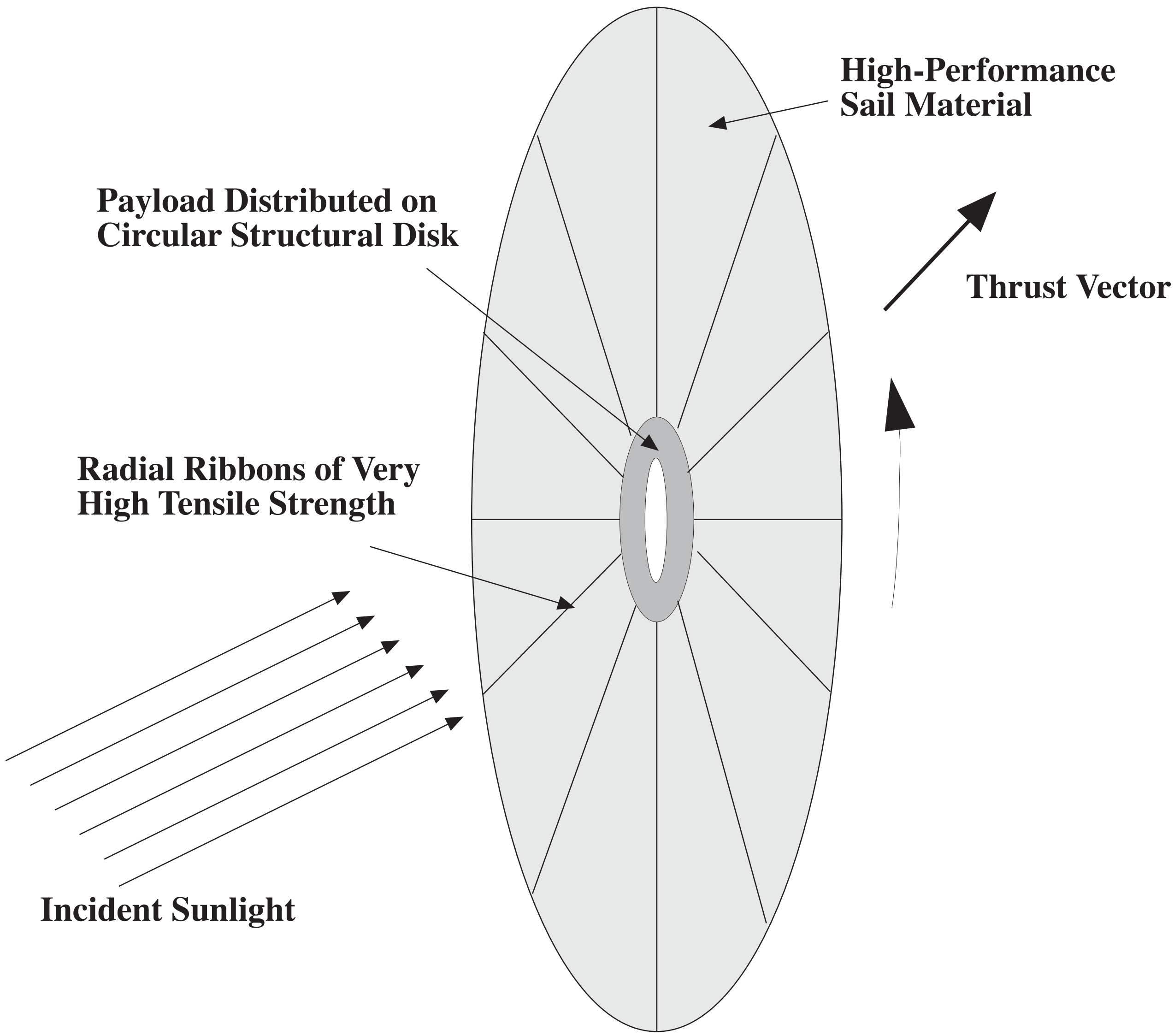

Fig. 2 A 200 meter Spinning Sail (Lightness Number 1)

Spinning Sails

This is the simplest and most natural of the super-sails. It is a spinning disk as described by T. Cotter[11]. In this configuration, the structural mass is greatly reduced because the centrifugal force of the spinning mass will hold open the mass of the sail disk to intercept the sunlight. The maximum size of the spinning sail is limited only by the tensile strength of the radial supporting wires or ribbons perpendicular to the spin axis of the sail. All elements of the spinning sail (except perhaps a small circular rim near the spin axis) are in pure tension and are capable of sustaining enormous stress in the outward radial direction. Fig. 2 is a diagram of a 100 meter radius spinning sail made of 500Å aluminum foil and Kevlar™ ribbons for radial structural support. The sail material for such a vehicle would weigh only about 5000 grams.

The structural elements or "ribs" of the disk would add, perhaps 10 kilograms (only because the sail is so small), and the payload would contribute the lion's share of the total mass. Assume a payload of 27 kg to yield a total mass of, say, 42 kilograms. The sail loading for such a vehicle would be about 1.337 grams/m^2 and would develop a characteristic acceleration of about 6 mm/s^2 at 1 au. This is a lightness number 1 sail that, effectively, turns off the solar gravitational field. It will leave the Earth's orbit on a straight line and continue outward on a line tangent to the Earth's orbit at 30 km/s. If it remains pointed toward the sun, it will reach 100 au (thought to be the boundary of the heliopause) in about 16 years. It will reach Pluto's orbit in about 6 years with a whopper antenna 200 meters in diameter.

The careful reader will have noticed that we have made no provision for controlling the attitude of the spinning sail. There are many possible ways to do this; increasing the sail area by 40% and using a 45° fixed angle to the sun-line is one way to ensure dynamic performance and still maintain a substantial cross-sectional view of the sail when it reaches the outer limits of the solar system. Another possibility is the use of small ion thrusters, operated from the spacecraft power supply, to slowly torque the sail around to keep it pointed toward the sun. Methods for offsetting the spacecraft center of mass from the sail spin axis could provide a slow torque to reorient the sail but at the expense of simplicity.

With a payload ratio as assumed above, the sail cannot benefit much from perforation to lower the mass of the sail material. Even if the sail material weighed nothing, the spacecraft would still weigh 37 kg and the overall lightness number would still be approximately 1. A 100 meter radius sail with a 27 kg payload is not really a "hot" sail. Let's see what happens with a bigger sail.

Imagine a sail with a radius of 1000 meters, made of the same 500Å aluminum foil as before. The mass of the sail material is now 424 kg and we assume a 50% factor for structural members made of very high tensile strength material. Now add a payload of 100 kg. - - enough to support some conventional instruments and a reasonable data rate. The total mass of 736 kg yields a sail loading of 0.234 g/m^2 and an acceleration of 34.15 mm/s^2. The lightness number of this vehicle is 5.7; it will follow an hyperbolic trajectory corresponding to a "repulsive gravity" of 4.7 times the normal solar gravity. The excess speed of this hyperbola will be about 96 km/s or about 20 au/year. The spacecraft will reach Pluto's orbit in about 2 years and the heliopause in about 5 years.

What happens, in this case, if the sail is perforated to decrease its mass to 10% of the original 424 kg? And what if the structural mass is reduced from the original 212 kg to 100 kg? (The structural mass is not reduced by the same percentage so as to provide mass to support the higher acceleration loads at the payload attach points.) Now the total vehicle is only 242 kg. The total sail loading is (242000 g/3.1416 x 10^6 m^2) = 0.077 g/m^2. This yields a characteristic acceleration of 77.9 mm/s^2 or about 6.7 km/s/day. Here we have used $a_c = 6/\sigma$ to account for the loss of light pressure through the perforations and due to reradiation. Even with the reduced effective pressure, however, the lightness number is about 13. Thus, in only 5 days, the solar radiation pressure will add almost as much ΔV as the initial speed of the Earth (and the spacecraft) around the sun. Notice that, in this case, there is no need to control the vehicle spin-axis. In the recent words of J.L. Wright, "It would be like shooting at the planets with a rifle." The spacecraft will reach Mars's orbit in about 3 weeks; it will reach Pluto's orbit in about 15 months; and it will reach the heliopause (100 au) in just over 3 years, less than one U.S. political administration.

Electrostatic Sails

It was the author's privilege to be a part of the near re-birth of solar sailing at the Jet Propulsion Laboratory during the late 1970s. One of the most interesting ideas put forward at that time was the suggestion by J.D. Burke[12], that very thin films of radioactive paste containing good beta emitters (e.g. Ce_{137}) could be painted or deposited on a thin substrate of aluminum or other material. The natural ejection of electrons by the radioactive element would tend to charge the entire sail and cause it to deploy itself and remain open by the repulsive forces of the positive charge left after the exodus of the energetic electrons.

Although this concept opens up questions of interaction of the charged sail with the solar wind and the magnetic bumps and wiggles of the solar system, it is one of those ideas that may yield a major reduction in structural mass for solar sails. Such sails would eliminate the need for structural ribs or ribbons to take up the stress due to rotation of the sail. The difficulties would be those of radioactive effects on the electronics of a distributed payload, control of the sail attitude during a solar "storm," and collapse of the charge during passage through clouds of electrons.

These imagined difficulties are ones that could be thoroughly investigated by a group of dedicated graduate students with access to a good physics lab and a 50 kilogram canister on a Shuttle, Ariane, or Proton launch.

Variable Density Sails

Another of the ideas that came to the author's attention in the late 1970s was the substance of the Master's Thesis of R. Hyde[13]. Hyde was a student of T. Edelbaum who died just prior to a major solar sailing symposium at the CalTech Jet Propulsion Laboratory in Pasadena. Edelbaum was one of the major supporters of solar sailing and other forms of power limited propulsion. His death was a great blow to those of us who were so enthusiastic at that time.

Hyde's thesis dealt with the possibility of constructing sails with continuously variable density across certain portions of the sail, so as to create lateral pressures that would hold the sail open, obviating the need for major structural members.

This is a tough problem, not easily analyzed on the back of an envelope. It is one with subtle interactions of light pressure, inertial reaction forces on structures, and the effects of nearly constant solar radiation pressure on membranes of variable density. One can only speculate as to the exotic solutions that may become available if future solar sail designers consider the use of variable mass sails. These devices open up the possibility of very thin sails that do not require structural mass.

As an addendum to the possibilities of variable mass sails, the author wishes to introduce the concept of a very high performance mainsail with "steering tugs" that have just enough capability to hold the sail open against the inertial forces that would tend to collapse the sail at the attach points of the payload held in pure tension by long lines of very high tensile strength material. Fig. 3 is a cartoon of such a system. The additional performance required of the tugs will depend upon the amount of payload and the acceleration developed by the mainsail. The drawing is not suggested as a design for today's technology but only as a possibility for the future and to stimulate the reader's imagination. Conceptually, the "tri-sail with steering tugs" is a model of a sail with sections of variable performance.

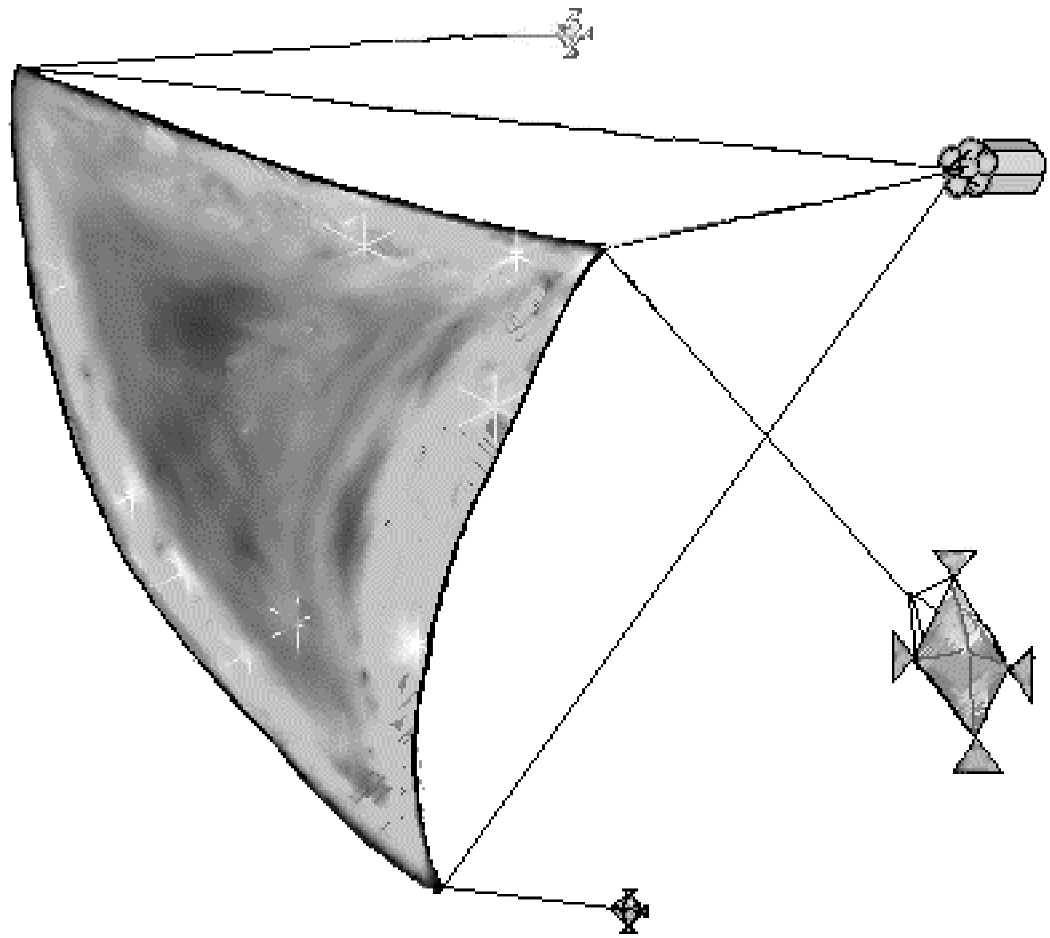

Fig. 3 "Tri-Sail with Steering Tugs"

Building A Lightness Number 10 Sail

The problems of handling and deploying such gossamer structures, while difficult, are not insurmountable. And the benefits to deep space transportation are almost incalculable. The solar sail is truly a "Frontier" transportation system that makes use of resources (light pressure) at the frontier for its fuel and propellant alike. If our civilization survives the transition from home planet to space, it will probably survive at least until our star burns out. In the meantime, everything we can do to provide efficient transportation within our solar system will contribute to the survival of our species. That should be worth some midnight oil to figure out how to build high-performance sails.

It is generally assumed that high-performance sails will have to be built in space and that the sail factory will have to be operated by humans in space. Neither of these assumptions is necessary. First, as we shall see, there are techniques for manufacturing gossamer structures on Earth and deploying them from conventional launch vehicles. Second, even if sail factories are built in space, they need not be directly operated by astronauts. Telerobotics and automation technology are sufficiently advanced that gossamer sails could be constructed in space by operators on Earth.

But an orbital factory would require a substantial commitment of capital; what about looking for ways to manufacture the sails on Earth and launching them from conventional spacecraft? The following suggestion is one made by William Carroll of the CalTech Jet Propulsion Laboratory and reported to me by J.L. Wright (c. 1978).

There are materials, like DuPont's Mylar™ that break down in the presence of ultraviolet light. There are other plastic-like materials that sublime in vacuum. Carroll's suggestion was to find a material upon which the metal sail can be deposited by conventional techniques used in very-large-scale-integration computer electronics. Then, when the substrate is exposed to vacuum or sunlight, it remains intact for a few minutes, and then promptly disintegrates into molecules, leaving the very thin metal and its structural ribbons already deployed, spinning, and ready to launch. It may be possible to manufacture a special film, using the techniques of polymer chemistry (or perhaps the new aerogels), that will have exactly the desired characteristics of stability for a fixed amount of time, and then very rapid disintegration and separation from the metal foil.

Other technologies, like sub miniaturization, so successful on the Earth, can be applied to the problems of distributing the payload over the surface of the sail, mitigating the need for excess structural mass near the payload attach points.

Needles and Whirlygigs

There is a type of solar sail that is capable of very high lightness number - - the type for which the sail is itself the payload. Imagine a needle made of aluminum, 500 Å in diameter, and 10.7 cm long. Imagine, further, that the needle is set spinning about an axis normal to the needle's length and oriented along the sun-line. This is a terrific solar sail, even without perforation. The sail loading is 0.106 g/m^2 and the characteristic acceleration is 75.41 mm/s^2 at 1 au - - a lightness number of 12.6 without perforation. A trillion (10^{12}) of these needles would weigh only 540 grams.

The reason for the chosen length is to suggest that the needles would resonate at 10.7 cm, one of the principal lines of the solar spectrum. In this way, one could use the sun as a transmitter of a unique signal at a very specific frequency and, by correlating the known variations of the sun's 10.7 cm flux with the Doppler-shifted signal received on Earth from the "cloud" of needles, one could track a sufficiently large cloud well past the known limits of the solar system.

There are many things to be worked out for such a scenario: ensuring that the spin-axes of the needles point along the sun-line as the cloud recedes from the sun: finding the right metal: developing a reliable, automated launching mechanism. If one could work out the technology to use lithium (as suggested by C. Wiley[14]) instead of aluminum, one could gain another factor of 5 in lightness number and the cloud would reach Pluto's orbit in less than 7 months. Perhaps the needles could be designed as reverse whirlygigs that would translate some of the solar pressure into rotational motion and stabilize the spin axis along the sun-line.

Dr. Forward[15] recently suggested that thin films of metal may become superconducting at temperatures higher than the usual laboratory values. If the cloud begins to superconduct, the signal received at Earth would be greatly amplified. What about Buckytubes, tubular structures of carbon 60 molecules that may become superconducting at normal deep space temperatures? They might make an excellent cloud.

Applications

The needle-cloud suggestion is a combination of two of Professor Colombo's favorite ideas - - a deep-space retro-reflector and the solar sail. If the idea still appears feasible after careful study of the signal-reflecting properties of such a cloud, it could provide a valuable and inexpensive tool for study of the gravitational structure of the outer solar system. Careful analysis of the dispersion and elongation of such a cloud (consisting of needles of two separate densities and two distinct resonance frequencies but equal lightness number) could reveal the density of the interstellar medium beyond the heliopause.

The author has not worked out the numbers for the mass of needles required to return a discernible signal from the sun; the requirements may turn out to be infeasible. In that case, it would be better to use the 1000 meter (lightness # 12.6) spinning sail and take along a power source, a transmitter, a very simple pointing control system, and a few particles and fields instruments.

Other applications include the use of the high-speed sail technology for quick reconnaissance trips within the solar system. Such missions might include a launching mechanism for a solar probe that does not require the long trip to Jupiter. This was another of Colombo's suggestions - - a light-pressure "drag-chute" that would remove most of the angular momentum from the probe's Earth-launched heliocentric trajectory.

Other applications will come to light if young people begin to study this powerful propulsion technology. As the technical problems are worked out, some students will recognize new and important applications that make use of the untapped 254 million trillion megawatts constantly radiated into the Universe by our little star.

Conclusions

It has been suggested that the development of very high-performance light-sails is easily within the capabilities of our technology. Such sails could be used in a variety of experiments to study the gravitational and magnetic structure of the outer solar system, as well as to enhance the performance of the well-documented applications for interplanetary transportation. It was pointed out that such sails can reach Pluto's orbit, carrying a 100 kg science payload, in about one year and could reach the outer limits of the solar system within about 4 years.

A suggestion was made for a very simple, and relatively inexpensive "retro-reflector" made of thousands of trillions of needles to form an immense "cloud" of tiny antennae that could reflect the unique signal produced by the sun at particular lines in the solar spectrum. Such an experiment might reveal the magnetic and gravitational structure of the "heliopause" - - the supposed region near the shock wave caused by the interaction of the sun's magnetic field with the interstellar medium. Such an experiment might uncover facts more astonishing than the discovery of the Earth's Van Allen radiation belts. The time scale of the trajectories is much less than that required of most governments to establish and obtain funding for deep-space projects.

Acknowledgments

Throughout the paper, reference was made to Professor G. Colombo, his suggestions, and his dreams for the application of clever ideas to study our celestial environment and to aid in the expansion of our civilization into space. The ideas and philosophical attitudes of Professor Colombo continue to live in the mind of the author, and many of Colombo's colleagues. It is the author's wish that the spirit of Giuseppe Colombo shall continue to live and be acknowledged for as long as our species shall survive. Among the many others to whom the author is indebted for inputs to this work are, in particular, J. Wright, L. Friedman, E. Polyakova, R. Forward, R. Garwin, C. Maccone, and A. Sukhanov. This work was supported by internal funding from ACTA Consulting Group. Accommodations for the presentation and conference were graciously provided by Politecnico di Torino, Alenia Spazio S.p.A, Institute for Scientific Interchange, and Club Two-Thousand A.D. The author is extremely grateful for the opportunity to present this paper at the Centro di Astrodinamica *Giuseppe Colombo*.

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