Interstellar Propulsion Concepts Assessment

Final Report

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NASA/Marshall Space Flight Center
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with

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Covering the Reporting Period From

19 March 1999 through 5 October 1999

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17 February 2000

Interstellar Propulsion Concepts Assessment

Objectives

NASA is investigating the feasibility of conducting extra-solar and interstellar missions over the next 10 to 50 years. An assessment of technologies supporting these near and far term objectives is required. To help meet these objectives the Principal Investigator was to assess the feasibility of candidate propulsion systems for the proposed "Interstellar Probe", a mission to send a spacecraft to the Heliopause at 250 AU and beyond.

Activities During Contract Period

During the contract period, running from the start of the contract on 19 March 1999 thorough 5 October 1999, the Principal Investigator (PI) participated in four meetings covering the subject of the contract effort. In addition, he communicated with a number of the meeting participants before and after the meetings via email, and carried out some independent analyses of his own, which will be summarized separately.

Interstellar Probe STD Team Meeting #1 - 15-17 February 1999.

Prior to the start of the contract, the PI had previously participated, at his own cost, in Meeting #1 of the Interstellar Probe Science and Technology Definition Team (ISP-STDT), which was held at JPL from 15-17 February 1999. The two propulsion concepts that had been downselected by the Interstellar Probe Propulsion Team, lead by Les Johnson of MSFC, were Nuclear Electric Propulsion and Solar Sail Propulsion. The PI joined the Solar Sail Propulsion subteam and participated in a number of telecons between the first and second meeting of the ISP-STDT. At the first ISP-STDT meeting, P. Weissman evaluated the possibility of imaging one of the 500 km diameter or smaller ice-covered "Kuiper Belt Objects" (KBOs) on the way through the Edgeworth-Kuiper Belt. Weissman assumed that science value would only be obtained if a well-resolved image of greater than 200 pixels across the image diameter could be obtained. He showed that this event was highly unlikely, unless a specific object were targeted, which would be difficult to do. As a result of his negative report, no visible imaging telescope was included on the strawman list of payload instruments. The PI objected, and pointed out that the density distribution as a function of diameter of the KBOs at different distances from the Sun was unknown. He was backed by Renu Malhotra, a KBO theorist, who pointed out that gathering such knowledge was important in developing models for of the growth of planets from the primordial dust disk. Using data estimates from Malhotra, the PI estimated that dozens or hundreds of KBOs could be detected by a small visible spectrum telescope during a flythrough of the Belt. Only one, or at most a few, pixels in the camera would be activated by each object, so that no "image" could be obtained, but there would be more than enough photons in that one pixel to ensure positive detection and enable tracking of the KBO as the probe passed it by. Because the probe was moving, the distance to the objects could be estimated by the rapidity at which the photon intensity rose and fell. The color could give an estimate of the albedo. Using those two pieces of information, an estimate of the diameter of the object could be obtained. This would result in a "census" of the KBOs as a function of object diameter and its distance from the Sun. The PI then attempted over the next few months to get someone in the visible space imaging field to work with Renu Malhotra, since she was a theorist, not an experimentalist, and had no interest herself in proposing a visible spectrum telescope to add to the strawman list of instruments. The PI also suggested that the KBO census could alternatively be obtained by a bi-static radar method. The Belt in front of the Probe trajectory would be illuminated by microwave energy, perhaps from the Aricebo radar transmitter system, with the weak return signals from the KBOs detected by a receiving dish on the Interstellar Probe. This idea has since been taken up by Richard Dickinson at JPL, who has since submitted a proposal to study the feasibility of the concept.

Interstellar Probe STD Team Meeting #2 - 28-31 March 1999

The first meeting that the PI attended while funded by the contract was Meeting #2 of the Interstellar Probe Science and Technology Definition Team (ISP-STDT), held at JPL in Pasadena, California from 28-31 March 1999. At the meeting, Renu Malhotra estimated the space density of KBOs in the region from 30-50 AU radius from the Sun and 8 AU above and below the ecliptic plane. She estimated that KBOs with diameters around 100 km are spaced at distances of 1.5 AU. There would be 10-15 objects of this size passing within 1.5 AU of the Interstellar Probe as it traversed the Belt from 30 to 50 AU. KBOs with diameters around 5 km would be spaced at 0.1 AU. There would be 200 objects of this size passing within 0.1 AU of the Probe. KBOs with diameters around 1 km would be spaced at 0.02 AU and 1000 of these objects would pass within 0.02 AU of the Probe. Malhotra estimated that a 10-cm-diameter lens could see a 1 km object at 0.1 AU, thus there should be many thousands of counts of 1 km size objects in a census of the Belt. A high-speed replay of this multitude of objects streaming by the Probe during its journey through the Belt would produce a remarkable visual image for presentation to the general public. The most recent estimate of the number of KBO objects that would be counted by a typical small telescope is presented in Appendix A.

At this meeting, Charles Garner of JPL showed a number of candidate substrates for the aluminum film solar sail propulsion options. Most of these were the typical very thin polymer films, but one was a very low mass-per-unit-area carbon fiber mat. The solar sail trajectory selected in order to obtain the very high solar system exit velocities needed (>100 km/s) in order for the probe to reach 250 AU in 10-15 years, involves a close passage to the Sun. The high thermal and radiation environment near the Sun raised concerns about the survivability of the thin polymer films and even the aluminum film, since thin aluminum films agglomerate (form droplets) at temperatures above 800 K. This limited the closest distance of approach of the solar sail to the Sun, and therefore the solar system exit velocity. Out of this meeting, the PI revived an idea he had thought of earlier, Carbon Sails. It is described in more detail in Appendix C.

AIAA/MSFC/JPL Advanced Space Propulsion Workshop, Huntsville, AL - 5-8 April 1999

The second meeting that the PI attended while funded by the contract was the AIAA/MSFC/JPL Advanced Space Propulsion Workshop held in Huntsville, AL from 5-8 April 1999. The PI was primarily attending the Workshop to present papers on space tethers, so his travel expenses were paid by Tethers Unlimited, Inc. At the Solar Sails Session of the Workshop, the PI gave a presentation on Carbon Sails concept using the viewgraph charts in Appendix C.

Interstellar Probe SDT Team Meeting #3 - 17-19 May 1999

The third meeting that the PI attended while funded by the contract, was Meeting #3 of the Interstellar Probe Science and Technology Definition Team (ISP-STDT), held at JPL in

Pasadena, California from 17-19 May 1999. George Danielson of JPL presented a first cut design for a visible spectrum telescope suitable for a KBO census, using an all-beryllium Cassegrain telescope with an f/8 20 cm aperture. It would use a 1024 x 1024 HIT CCD detector which would use time delay integration, where the pixels are shifted across the array, to increase the effective exposure time on a spinning spacecraft. It would be a "smart" camera that would process three consecutive frames to remove star images, cosmic rays, hot pixels, and pixel to pixel sensitivity variation to produce only a count of detected KBOs. Unfortunately, Renu Malhotra was not in attendance to push for the science, and George Danielson was not able to come up with a good estimate for mass. As a result, the visible spectrum telescope for obtaining a KBO census was not placed on the "Strawman Scientific Payload" list, but was listed (with a question mark) on the "Additional Candidates" listing. In the opinion of the PI, when there are images to be obtained, then for maintaining public interest in supporting science missions, an imaging telescope should be manifested on every science mission.

The Team Chairman, Richard Mewaldt then brought up the topic of "What next?" What should be the next mission if this mission is successful? The mission selected was to "Break Out of the Local Bubble" at 3000 AU, with a goal of reaching 10,000 AU in 20 years. This would require an exit velocity from the solar system of 2400 km/s. In the opinion of the PI, it is conceivable that this might be done using solar photons with a carbon sail concept that starts very close to the Sun. Although carbon maintains its strength at temperatures well above 3000 K, it does start to sublimate with time in vacuum at much lower temperatures than 3000 K. Such a demanding mission scenario may require a sacrificial shield that will shade the carbon sail from the heat of the Sun until the sail is in its outward trajectory. Even then, the carbon sail may have to be designed to "gracefully degrade" as the carbon sublimates from the surfaces of the sail film and support structures, with the sail getting lighter and lighter with time. If the solar-photon-powered carbon sail is unable to obtain the necessary exit velocity for the 10,000 AU mission, then the mission can be accomplished using laser-pushed reflective lightsails. This laser-pushed-lightsail route would have the advantage of moving advanced propulsion right along the Roadmap toward true interstellar exploration -- missions to nearby star systems.

50th IAF Congress, Amsterdam, The Netherlands - 4-8 October 1999
The fourth and last meeting that the PI attended while funded by the contract effort was the 50th International Astronautical Congress held in Amsterdam, The Netherlands from 4-8 October 1999. This involved only a short trip across the English Channel from the PI's residence in Scotland, UK. Since the PI was primarily attending the Congress to give papers on space tethers, his travel expenses were paid by Tethers Unlimited, Inc. At the IAF Congress the PI participated as Acting Secretary in a Saturday meeting of the Interstellar Exploration Committee of the International Academy of Astronautics, as the Committee elected new members and officers, finalized the plans and agenda for the Interstellar Exploration Sessions at the present Congress and the next Congress. On Tuesday, the PI attended the Interstellar Exploration Session and participated in the discussion.

Kuiper Belt Object In-Situ Sampling Mission
In May 1999 the MSFC Contract Technical Representative requested the PI to be on the Technology Development Subteam of the Kuiper Belt Object In-Situ Sampling Mission Team led by Emma Bakes. This would be a mission that would first fly by and drop a sampling probe

on one or more Centaur objects. The Centaurs are large reddish objects with orbits between Saturn and Neptune that are felt to be similar to KBOs. The mission would then continue on to the Kuiper Belt to rendezvous with, land on, then drill for, obtain, and analyze in place, a deep core sample from a KBO object.

This mission, because of the rendezvous and landing requirement, cannot be done with a solar sail. It can be done using nuclear electric propulsion (NEP), and the Team-X group at JPL carried out a first cut design for the mission based on using NEP. This nuclear propulsion option, however, was categorically rejected by the Origins Theme science review panel at NASA Headquarters. The PI has invented an alternate non-nuclear propulsion concept, which if detailed analysis proves is feasible, will allow the mission to proceed without the use of <u>any</u> radioactive power sources on the mission. This new propulsion concept, Solar Concentrator Heat-to-Electric Ion Propulsion, is discussed in Appendix B.

APPENDIX A

Kuiper Belt Object (KBO) Census

At the second meeting of the Interstellar Probe Science and Technology Definition Team (ISP-STDT), held at JPL in Pasadena, California from 28-31 March 1999, Renu Malhotra gave an estimate of the space density of Kuiper Belt Objects (KBOs) in the donut-shaped region with a radius of 30–50 AU from the Sun and 8 AU above and below the ecliptic plane. She estimated that KBOs with diameters around 100 km would be spaced at distances of 1.5 AU, KBOs with diameters around 5 km would be spaced at 0.1 AU, and KBOs with diameters around 1 km would be spaced at 0.022 AU. Although imaging a KBO at high resolution was quickly determined not to be possible, the PI suggested a simple count, or "census" of the objects in the Kuiper Belt as a function of distance from the Sun might be useful. At the third meeting of the ISP-STDT, George Danielson of JPL presented a first cut design for a visible spectrum telescope suitable for a KBO census, using an all-beryllium Cassegrain telescope with an f/8 20 cm diameter aperture. It would use a 1024 x 1024 HIT CCD detector which would use time delay integration, where the pixels are shifted across the array, to increase the effective exposure time on a spinning spacecraft. It would be a "smart" camera that would process three consecutive frames to remove star images, cosmic rays, hot pixels, and pixel to pixel sensitivity variation to produce only a count of detected KBOs. The estimated number of objects that would be detected by a 20 cm diameter telescope during the Kuiper Belt flythrough as a function of object diameter was calculated by the PI and is given in the following table:

Kuiper Belt Objects Counted During a Kuiper Belt Flythrough

KBO radius (m)	Detection Range (km)	Spacing (km)	Number In View At Any Instant	Total Number in Flythrough
(100 km) 100,000	(3AU) 14,000	(1.5AU) 7,000	16	45
(10 km) 10,000	1,400	780	11	400
(1 km) 1,000	140	100	5	1,300
100	14	12	3	6,600
10	1	2	1	34,000

It is not expected that any of the objects would be close enough to activate more than a few pixels, so no "images" would be obtained. What would be obtained is a sample "census" of the Kuiper Belt, or a count of objects as a function of brightness and 3-D position in the Kuiper Belt. The range to the object can be obtained independently of the brightness of the object, since small nearby objects will move rapidly with respect to the background stars, while larger distant objects with the same observational brightness will stay in view much longer.

A high-speed replay of this multitude of objects streaming by the Interstellar Probe during its journey through the Belt would produce a remarkable visual image for presentation to the general public. If the year-long passage were compressed into a one-minute video, it would look like you were driving through a blizzard.

At present, the visible spectrum telescope for a KBO census is not on the primary list of instruments for the Interstellar Probe mission since a 20-cm diameter telescope aperture requires a 5 kg instrument. The total science payload mass available is only 25 kg and there are a dozen instruments selected ahead of the KBO telescope. Since there is a plethora of data expected for this experiment, consideration should be given to cutting the size and mass of the telescope for the KBO Census experiment and accepting the resulting cut in number of objects counted.

APPENDIX B

Solar Concentrator Heat-to-Electric Ion Propulsion

In May 1999 the MSFC Contract Technical Representative requested the PI to be on the Technology Development Subteam of the Kuiper Belt Object In-Situ Sampling Mission Team let by Emma Bakes. This would be a mission that would first fly by and drop a sampling probe on one or more Centaur objects. The Centaurs are large reddish objects with orbits between Saturn and Neptune that are felt to be similar to KBOs. The mission would then continue on to the Kuiper Belt to rendezvous with, land on, then drill for, obtain, and analyze in place, a deep core sample from a KBO object.

This mission, because of the rendezvous and landing requirement, cannot be done with a solar sail. It can be done using nuclear electric propulsion (NEP), and the Team-X group at JPL carried out a first cut design for the mission based on using NEP. This nuclear propulsion option, however, was categorically rejected by the Origins Theme science review panel at NASA Headquarters. The PI has invented an alternate non-nuclear propulsion concept, which if detailed analysis proves to show is feasible, will allow the mission to proceed without the use of <u>any</u> radioactive power sources on the mission. This new propulsion concept is called: Solar Concentrator Heat-to-Electric Ion Propulsion.

NEP (nuclear electric propulsion) and RTG (radioactive thermal generator) propulsion use radioactive materials to produce heat, which in turn is used to generate electricity, which in turn is used to operate the spacecraft instruments and electric propulsion system. The PI proposes that we use the same heat-to-electricity subsystem, the same radiator system, and the same electric ion propulsion system that is in the NEP design. The heat source, however, would be solar photons collected by a very large solar-sail-like structure that has sufficient curvature to act as a light concentrator. The PI admits that such a sail is going to be large, and difficult to build, aim and use. It may or many not be heavier than the nuclear reactor and its shield. Fortunately, a great deal of design and hardware development has gone into DoD and NASA studies of the solar concentrator heated hydrogen rocket (Solar Thermal Rocket). Large inflatable solar concentrators have been built and have achieved concentration ratios of 10,000 to 1. With the new sail materials now available at JPL, and with this applicable solar concentrator technology available, the design problems of a solar concentrator heat-to-electric ion propulsion system should be solvable.

The NEP reactor in the ISP design has an output of 600 kWt (kilowatts thermal) to achieve 180 kWe (kilowatts electric). The full 180 kWe is needed by the propulsion system in order to bring the spacecraft to a halt at a Kuiper Belt Object out at 40 AU in a reasonable period of time. The solar flux at 40 AU, however, is only 0.84 W/m^2. To collect 600 kWt of solar heat at 40 AU will require a solar light concentrator with a diameter of about 1 km. Although large, this is not impossible, since solar sails of this diameter are under consideration for the Interstellar Probe Mission. Once rendezvous has been accomplished, the 180 kWe of electrical power on the mother ship will be more than enough to transmit the data back to Earth at high data rates. That amount of power available is also enough to consider the possibility of beaming power from the spacecraft to the drilling rig, thus eliminating the need for a nuclear RTG to supply the drilling power. Actually, since the drilling portion of the effort requires only the mechanical rotation of a shaft, that rotary power can probably be supplied by a storable propellant version of a chain-saw engine. Beamed power may still be needed to run the down-hole sample analysis equipment and the data transmission subsystems, although batteries may also be sufficient for this short duration power requirement. Eliminating all nuclear components from the mission will make it much easier to sell.

The PI has since learned that others have looked at similar concepts. A decade ago, in the paper, "Optics and Materials Considerations for a Laser-Propelled Lightsail", Paper IAA-89-664, 40th Congress of the International Astronautical Federation, Malaga, Spain, 1-12 October 1989, Dr. Geoffrey A. Landis proposed a laser light beam concentrator photoelectric ion propulsion system. More recently, Dr. Robert H. Frisbee at NASA/JPL did a first cut analysis of a solar concentrator photoelectric electric ion propulsion system that uses an inflatable-structure or solar-sail type of sunlight collector/mirror to intercept and focus the weak sunlight at 40 AU onto conventional solar photoelectric cells. These then produce electricity for an electric ion propulsion system. As Frisbee points out, the real issue here is the required areal density (grams per square meter) of the solar concentrator mirror. In order to keep the mass low enough that there is minimal impact on the overall propulsion system mass (and specific mass, or kg per kW of electricity), the mirror areal density needs to be on the order of 1 gram per square meter for a 1-km diameter mirror. This makes the concentrator mirror close to being a larger-diameter version of the Interstellar Probe solar sail.

On the next page is a printout of the Excel spreadsheet generated by Frisbee, which shows a comparison of a Solar Concentrator Photoelectric Electric Ion Propulsion system with a Nuclear Thermoelectric Ion Propulsion System. The Solar Concentrator Photoelectric option is assumed to have a solar array power system specific mass of 15 kg/kWe and a solar power to electrical power conversion efficiency of 20%. The concentrator mirror areal density is 1 gram per square meter, or a specific mass of 6.6 kg/kWe. The total specific mass of the entire system is thus 21.6 kg/kWe. This is compared with the Nuclear Electric Propulsion system, which Frisbee estimated as 16 kg/kWe at 100 kWe, assuming a 30% efficiency in conversion of heat to electricity.

There are two ways for the Solar Electric Propulsion system to match or better the Nuclear Electric Propulsion system in specific power. It should be possible to make the photoelectric array quite a bit smaller and lighter because it doesn't have to intercept the sunlight directly, and most solar cells work well with moderately concentrated sunlight. Also, the inflatable-structure or solar-sail mirror isn't load bearing, as it is in a solar sail, so it may be possible to reduce its areal density and thus its specific mass.

The PI strongly recommends that a high-specific-impulse, low-thrust Solar Concentrator Electric Ion Propulsion system, either a Thermoelectric or a Photoelectric version, be studied as a replacement for Nuclear Thermoelectric Ion Propulsion for difficult deep space missions. Such studies could be carried out by the Advanced Propulsion Group at JPL, who have analyzed similar systems in the past.

KBO RENDEZVOUS SEP MISSION

Robert H. Frisbee, JPL

Assume use of Inflatable Optics or a Solar Sail as a mirror to collect and focus the required amount of sunlight intensity on the solar array

Solar Power (kW/m^2 at 1 AU) =	1.35	
Typical SEP Array		
Specific Mass (kg/kWe)	15.00	
Specific Power (W/kg)	66.67	
Efficiency	0.20	
Specific Area (m^2/kWe)	3.70	
Areal Density (kg/m^2)	4.05	
For Electrical Power (kWe) of:	100.00 <- Enter this value	
Sunlight Power @ 20% eff. (kW)	500.00	
Array Area (m^2)	370.37	
Array Mass (kg)	1,500.00	
Mission Parameters	End of Initial Acceleration Phase	KBO Rendezvous Phase
Distance (AU)	10.00	40.00
R^2	100.00	1,600.00
1/R^2	1.0000%	0.0625%
For a 100 kWe System:		
Area Required at 1 AU (m^2)	370.37	370.37
Circle Diameter (m)	21.72	21.72
Area Required at Distance (m^2)"	37,037	592,593
Circle Diameter (m)	217.16	868.63
Assume Inflatable Optics or Solar Sail Mirror (Sunlight Collector/Reflector)		
Areal Density (grams/m^2)	1.00 <- Enter this value	
Reflectivity	90% <- Enter this value	
Collector/Reflector Area (m^2)	41,152	658,436
Collector/Reflector Diameter (m)	228.90	915.61
Collector/Reflector Mass (kg)	41.15	658.44
Coll/Refl Specific Mass (kg/kWe)	0.41	6.58
Total Power System Specific Masses (kg/kWe)		
Solar Arrays	15.00	15.00
Mirror	0.41	6.58
Total KBO SEP Power Specific Mass	15.41	21.58
Total KBO NEP Power Specific Mass	16.00	16.00

APPENDIX C

Carbon Sails

The PI has invented a sail structure design that could greatly improve the performance of the solar sail option for a deep space probe such as the Interstellar Probe Mission, where the solar sail passes close by the Sun to obtain the necessary Solar System exit speed. Instead of making the solar sail with a light-reflecting surface of low-melting-temperature aluminum, he proposes to make the sail with a light-absorbing surface of high-sublimation-temperature carbon film, backed by the carbon fiber substrate being developed by Charles Garner at JPL. The PI carried out a brief analysis of this "Carbon Sail" concept and showed that such a structure has the potential to achieve a solar system exit velocity of greater than 1000 km/s. This is 10 times better than the estimated solar system exit velocity for an aluminum film sail. The details of the results are summarized in the charts that follow. The material in this Appendix was presented at the AIAA/MSFC/JPL Advanced Space Propulsion Workshop held in Huntsville, Alabama from 5-8 April 1999.

It should be emphasized that absorbing sails are not a replacement for reflective sails except under certain conditions. Absorbing sails work best where the desired sail trajectory is directly away from the light source, and the desired accelerations and velocities are so high that the sail has to be operated at its thermal limit. These conditions, however, are exactly those that apply to the solar sail propulsion method for high-speed extra-solar missions such as that of the Interstellar Probe Mission. Absorbing sails may also pay off in the interstellar propulsion scenario, which would use high power lasers to push a lightsail to the velocities required for rapid interstellar flight. By using a carbon lightsail capable of operating at high temperatures, a given amount of laser light power can be concentrated on a smaller sail, allowing higher sail acceleration levels, shorter laser operational times, smaller transmitter apertures, lower sail mass, and lower laser power and cost. If rendezvous at the target star is desired, magnetic sails could then be used to stop in the target star system.

Because the generic lightsail propulsion method can be extrapolated from extra-solar missions driven by solar photons to interstellar missions using laser photons, the PI recommends that the lightsail propulsion option for the Interstellar Probe Mission be chosen over the nuclear electric propulsion option. In addition, the PI recommends that further study be made of the pros and cons of using a carbon sail instead of an aluminum sail, for both the Interstellar Probe Mission beyond the Heliosphere and for true interstellar missions to the nearer star systems.

CARBON SAILS

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SAIL ACCELERATION FROM LIGHT PRESSURE

FORWARD UNLIMITED

Light power P on sail of mass M produces acceleration a

$$a = \frac{2\eta P}{c M} \qquad (\eta = \text{reflectivity})$$

["Roundtrip Interstellar Travel Using Laser-Pushed Lightsails", J. Spacecraft **21**, 187-195 (1984)]

SAIL ACCELERATION FROM LIGHT PRESSURE

FORWARD UNLIMITED

Light power P on sail of mass M produces acceleration a

$$a = \frac{2\eta P}{c M}$$ **WRONG!**

["Roundtrip Interstellar Travel Using Laser-Pushed Lightsails", J. Spacecraft **21**, 187-195 (1984)]

Correct equation is:

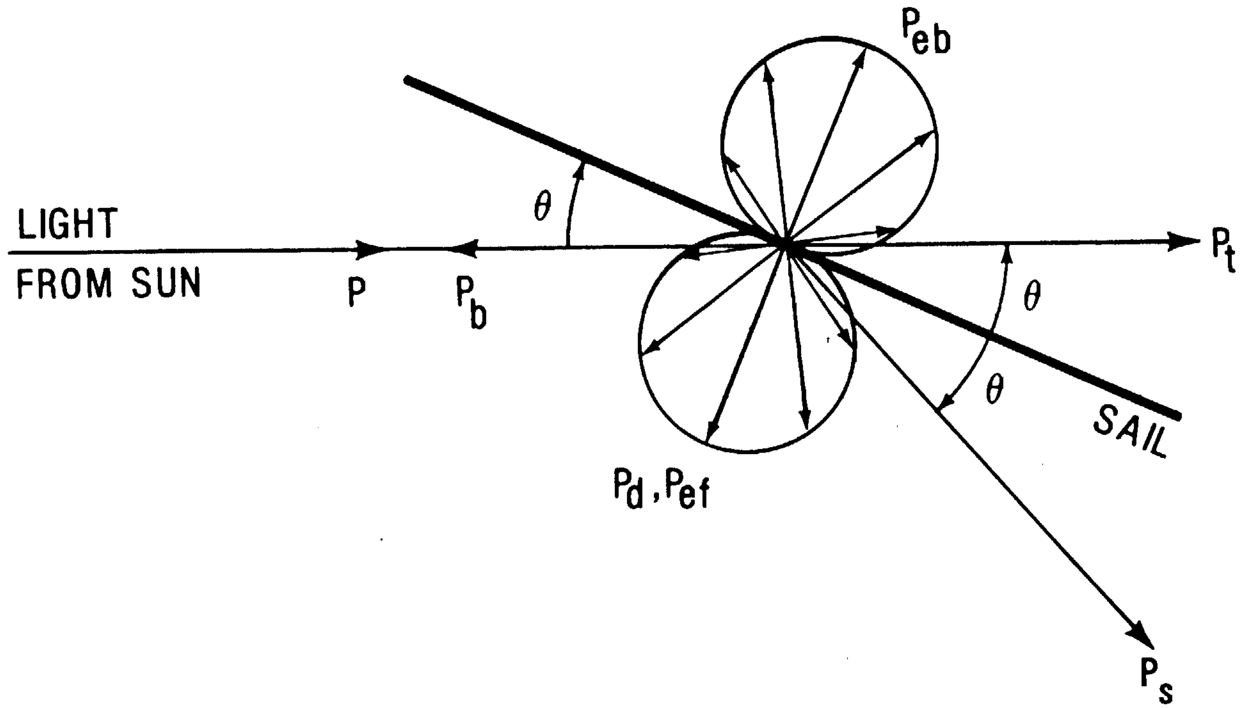
$$a = \frac{[(1-\tau) + \eta] P}{c M} = \frac{[2\eta + \alpha] P}{c \rho A t}$$

Since $\eta + \tau + \alpha = 1$

For Aluminum, reflectivity $\eta = 0.85$ & absorptivity $\alpha = 0.15$
$2\eta = 1.70$ while $2\eta + \alpha = 1.85$

DISTRIBUTION OF POWER IN A GREY SAIL

FORWARD UNLIMITED



SAIL ACCELERATION FROM EMITTED INFRARED POWER

FORWARD UNLIMITED

- **Absorbed light power is re-emitted as infrared power**
- **Emitted power creates acceleration forces on sail surfaces**
- **Emitted radiation diffuse - usually Lambertian (cosine)**
- **Integrated force 2/3rds of normally-directed radiation**
- **Full equation for sail acceleration is:**

$$a = \frac{\{2\eta + \alpha[1 + \frac{2}{3}(\varepsilon_F - \varepsilon_B)]\}P}{c\,\rho A t}$$

"Grey Solar Sails", J. Astronautical Sciences **38** 161-185 (1990)

- **Usually emissivity similar on front and back**
- **Tailored emissivity can improve performance**

ABSORPTIVE SAILS

FORWARD UNLIMITED

- **Incident light either reflected, transmitted, or absorbed**

$$\eta + \tau + \alpha = 1$$

- **If all light is absorbed**

$$\eta = 0, \quad \tau = 0, \quad \alpha = 1$$

- **Then acceleration on sail is**

$$a = \alpha\ [\ 1 + 0.67\ (\varepsilon_F\ -\ \varepsilon_B\ )\}P/Mc$$

- **If IR emissivity on front is much higher than on back**

$$a = 1.67\ P/Mc$$

- **Which is almost as good as a perfectly reflecting sail**

$$a = 2.00\ P/Mc$$

TEMPERATURE LIMITED SAIL ACCELERATION

FORWARD UNLIMITED

- Sail acceleration limited by temperature limit of sail material
- Light power absorbed in sail must be re-emitted
- Emitted power depends on emissivity and temperature

$$P_E = \alpha P_I = (\varepsilon_F + \varepsilon_B)\, A\, \sigma T^4 \qquad (\sigma = 56.7\ \mathrm{nW/m^2\,K^4})$$

- Temperature limited acceleration of grey sail

$$a = \frac{\{2\eta + \alpha[1 + \tfrac{2}{3}(\varepsilon_F - \varepsilon_B)]\}\,(\varepsilon_F + \varepsilon_B)\,\sigma T^4}{c\,\alpha\,\rho\,t}$$

- Temperature limited acceleration of absorptive sail

$$\eta = 0,\ \alpha = 1,\ \varepsilon_F = \varepsilon_B = 1$$

$$a = \frac{2\sigma T^4}{c\,\rho\,t}$$

LEVITATION DEMONSTRATION

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- Levitate small sail in laboratory in one gee
  - Spectacular demonstration to get press attention
  - Useful for studying sail material degradation
  - Might aid in studying sail design stability questions
- Aluminum film reflective sail
  - Agglomerates (forms droplets) at $T > 800K$
  - $t = 20$ nm (70 atoms), $\eta = 0.85$, $\alpha = 0.15$
  - Maximum acceleration possible only 0.22 gees
- Carbon film absorptive sail ($\eta = 0$, $\alpha = \varepsilon = 1$)
  - Maintains strength up to $T \sim 3000K$
  - Max acceleration = 70 gees with $t = 20$ nm, $T = 3000K$
  - One gee lab levitation with $t = 270$ nm, $T = 2000K$
  - Levitation power 1 kW for 2.5 cm diameter sample

CLOSE SOLAR PASSAGE FLYOUT INTO INTERSTELLAR SPACE

FORWARD UNLIMITED

- Carbon sail 20 nm thick (0.05 gm/m^2)
- Add 20 nm aluminum coating (0.1 gm/m^2)
- Use as reflective sail to escape from Earth
- Use as reflective sail to cancel Earth orbital speed
- Drop into Sun for close passage at 6 solar radii
- Near Sun aluminum evaporates, leaving carbon sail
- Carbon sail reaches 2000K at 6 solar radii
- Acceleration level reaches 14 gees
- Gravity of Sun only 0.8 gees
- Trajectory nearly a straight line outward
- Solar System escape velocity > 1000 km/s (c/300)

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13. ABSTRACT *(Maximum 200 words)*

NASA is investigating the feasibility of conducting extra-solar and interstellar missions over the next 10 to 50 years. An assessment of technologies supporting these near and far term objectives is required. To help meet these objectives the Principal Investigator assessed the feasibility of candidate propulsion systems for the proposed "Interstellar Probe", a mission to send a spacecraft to the Heliopause at 250 AU and beyond. During the contract period, the Principal Investigator (PI) participated in four meetings covering the subject of the contract effort. In addition, he communicated with a number of the meeting participants before and after the meetings via email, and carried out some independent analyses of his own on: 1) The use of high temperature absorptive carbon light sails instead of low temperature reflecting aluminum light sails to obtain high solar system escape velocity trajectories for extra-solar and interstellar probe missions. 2) The count rates for a Kuiper Belt Object census using a small visible light telescope during a flythrough of the Kuiper Belt by the Interstellar Probe. 3) A Solar Concentrator Heat-to-Electricity Ion Propulsion system as a non-nuclear replacement for a Nuclear Reactor Heat-to-Electricity Ion Propulsion system for a Kuiper Belt Object rendezvous mission.

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