SUMMARY:

We know that there are lot of money wasted for Space mission every year all-around the world. From past experience we learnt all those missions have only 50% possibility of success. So we thought of saving worlds money & achieving a milestone in space propulsion by our new concept of solar sail for space Sail.

A Space Sail is an interstellar kite that could power interstellar flights beyond our Solar System. We are developing a rigid-yet-lightweight carbon fiber material that could be used to build just such a giant space sail. One day we’ll be able to launch the biggest, fastest interstellar probe ever towards exotic destinations beyond our Solar System.

The thin reflective sails, made of composite materials, would span 440 yards. That's twice the diameter of the Louisiana Superdome. Sunlight falling on the sail would push the probe out of the Solar System and across our Milky Way galaxy. This can also be used for robot missions to distant stars and then, later, for human travel.

APPLICATIONS FOR SOLAR SAILS INCLUDE:

- Exploration of the solar system and beyond
- Delivery of science instruments/observatories and return of samples
- Maintenance of special 'artificial' orbits for observations, etc.
- Delivery of large cargos and people to research stations and settlements
- Serving as concentrators of solar energy and reflectors for communications
- Protection of Earth and other planets by asteroid deflection, shielding, warming, and illumination.

INTRODUCTION:

Space sailing and light sailing are the general terms for sailing in space using large reflectors for propulsion. Solar sailing is based on the use of pressure from sunlight reflecting off of a large, low-mass sail to produce a force, which results in acceleration of the ship. Solar sailing ships can carry cargo and people throughout the solar system at a fraction of the cost of other propulsion methods. Laser sailing and beam sailing refer to sailing by means of beamed energy which impinges on sails to provide propulsion.

Where Are the Ships?

JPL estimated the cost of the first production unit of an 820-meter solar sail at $65 million, for use in 1982. A second unit would cost a bit less, and could have been produced by about 1984. Adding some electronics to make it functionally independent might have pushed the cost to around $70 million. If launched in 1986, it could have completed six round trips to Mars by this time, delivering a total of...
nearly 20 tons of cargo. Those voyages would have been done without propellant or rebuilding of the ship, other than normal maintenance. With the success of that ship, it would have been reasonable to have built a 2000-meter sailing ship, perhaps by 1990. The larger ship could have made four round trips by this time, delivering potentially 100 tons of cargo to Mars.

Those same ships could still be operating. With the same kind of excitement people had a hundred years ago when they welcomed ships such as Flying Cloud back to their home ports from voyages to distant places, people today could follow the progress of the ships from Mars, past a couple of asteroids, then into Earth’s gravity field, before easing into a parking orbit for a stay of a few months before their next voyage to Mars.

**USING SUNLIGHT - SOLAR PRESSURE:**

Maxwell's equations of electromagnetic radiation imply that light carries momentum, as does the quantum theory of light. By Newton's Second Law, changing the momentum of light by reflection results in an applied force and, by his Third Law, a reactive force acts upon the reflector, as shown in the figure. The resultant force is perpendicular to a perfect flat reflector.

This force is what drives a sailing ship.

The solar intensity $W$ at 1 AU is 1367 W/m². The pressure $P$ on a flat perfect reflector is given by:

$$P = 2W \cos^2 \alpha - 1R^{-2} = 9.120 \cos^2 \alpha R^{-2}, \ \mu N/m^2$$

Where $c$ is the speed of light, $R$ the distance from the Sun's center in AU, and $\alpha$ is the angle between Sun and sail normal.

Using an efficiency factor, $\mu$, typically about 0.90, pressure, characteristic acceleration, and sail loading, $\sigma$, are related by:

$$ac = P \times \mu \div \sigma = 9.120 \times \mu \div \sigma = -8.28 \div \sigma, \ mm/s^2$$

Sail loading is total mass divided by sail area, given in g/m², and is also called areal density.

An aluminum coating is probably the best choice for the reflective surface. It provides a reflectivity of 0.88 to 0.91 across the visible spectrum.

A ship can have multiple sails, each with different orientations. Each sail has some curvature in it. Using finite element analysis, the local pressure on parts of sails can be integrated to determine the total force and moments acting on the ship. A resulting approximation of the force versus its angle theta, valid for a square sail, is:

$$F = F_0 \left( 0.349 + 0.662 \cos(2 \theta) - 0.011 \cos(4 \theta) \right)$$
Sailing Motion:

Sailing motion is determined by $\theta$, the angle between the solar radial and the ship’s total force vector. A positive $\theta$ generally adds energy and causes outward motion. A negative $\theta$ generally reduces energy and causes inward motion. The projection of the acceleration vector onto the velocity vector determines the actual change in energy in the local gravitational field. A sail does not extract energy from or put energy into the reflected light to accomplish its sailing.

If the reflection does not extract energy from or inject energy into the photons, how does the sailing ship gain or lose energy? The reflected photons have the same energy flux they had prior to the interaction, but a different momentum vector. It is this altered momentum vector that gives the ship an accelerating force that allows it to work against the gravitational field to gain or lose energy within the field. The absorbed photons are the energy lost from the impinging flux. The absorbed energy is re-radiated from the sail, with some helping and some hindering the ship’s motion.

Some Minor Effects:

The solar wind, charged particles streaming out from the Sun, also exerts a force on a sail (or any other object in space). However, the wind pressure is smaller than solar pressure by a factor of 5000 to 10,000 and is usually ignored when calculating trajectories for sailing ships.

When a solar sailing ship has a component of motion toward or away from the Sun, the wavelength of the incident light is slightly altered by the Doppler Effect. This causes a minor change in the power density of the incident light, but is so small that it is ignored.

The aberration of sunlight is the result of a body’s lateral motion relative to the source of the light. This means the light does not appear to come precisely from the center of the Sun, but at a very small angle (typically less than 0.01°). The angle is so small that it is ignored in trajectory calculations.

Solar pressure calculations for a sail usually assume that the light from the Sun comes from a point source. However, the Sun is a large body with a diameter of 1.4 million km (860 million statute miles). If precision is needed for trajectory calculations close to the Sun, its actual diameter should be taken into account.

VOYAGES AND ORBITS:

Inner Solar System: The Interplanetary Shuttle

The following table includes some sailing ship capabilities in the inner solar system, showing payload in metric tons and trip times for two ship sizes. Sailing ships can complete these voyages and return to Earth for subsequent voyages, operating as an Interplanetary Shuttle. Sailing ships are expected to have useful lives of roughly 30 years, during which they consume no propellant.

It can be seen from the table that a small fleet of five 2-km ships could deliver 200 tons or more to Mars every 26 months. This would be the most economical of all methods of supporting an outpost or settlement on Mars.
Mars:

Ships can depart for Mars at every opposition. A representative trajectory profile is shown at right. The ships can arrive at speeds that allow sailing into orbit. They can also make faster transfers, in less than half the time for a rendezvous, at speeds low enough for aerodynamic braking for entry into Mars orbit or direct descent to the surface. On the return trajectories, the ships cruise through the asteroid belt making typically two encounters and return to Earth in less than two years. The ships then have time for servicing and taking on passengers or cargo for the next departure opportunity, approximately 26 months after the previous departure.

Trip times to Mars vary with the payload for a given sail area. A 2000-m ship could carry 25 tons to Mars in 130-150 days, or 70 tons in about 300 days. The propellant needed to send 70 tons to Mars by chemical propulsion would cost over $1 billion if carried into orbit by an expendable launch vehicle.

Pluto Mission:

The space science community places a high priority on a mission to Pluto before its atmosphere freezes out around the year 2020. Sailing ships could make this a good mission at low cost. A ship with an ac of 1.50 mm/s² (5.52 g/m²) could leave Earth orbit in early 2008 and arrive at Pluto by mid-2015; a ship with an ac of 1.25 mm/s² (6.62 g/m²) could leave Earth orbit in early 2007 and arrive at Pluto also by mid-2015. The trip times increase somewhat with later departures. These two ships could reach Pluto before 2020 even if their departures were delayed by about 4 years.

Characteristic acceleration required for equilibrium position. Characteristic acceleration required for equilibrium position.

Planet-Synchronized Positions (Natural and Artificial Lagrange Points)

Every pair of mutually orbiting bodies has a set of five gravitational equilibrium points (Lagrange points) in their system. These are illustrated here using the nomenclature established by Lagrange and Euler.
An early solar sail investigator pointed out that a solar sailer kept facing the Sun follows an orbit equivalent to one around the Sun with no sail and a reduced solar mass, that is, the sail’s radial acceleration 'cancels' some of the Sun’s gravitational pull. For the pedantically oriented, this means these orbits are precisely Keplerian (Kepler’s laws apply precisely). Some of the currently in vogue use of non-Keplerian is in fact incorrect. The equation is simply $GM' = GM - ac(1\text{AU})^2$, where consistent units must be used. When a ship with $ac = 5.93 \text{ mm/s}^2$ faces the Sun, the Sun has 'no mass' because the Sun's gravitational field is balanced exactly.

This insight led to Wright discovering artificial Lagrange points in the regions of the natural Lagrange points and other points around Earth, where a sailer can remain synchronized with Earth's motion around the Sun.

The natural Lagrange point establishes the outer limit. Venus might establish a practical inward limit because of its passage by the Sun-Earth line every 19 months, or it might be practical to keep an Earth-synchronized sail at points even inside of Mercury's orbit.

Other regions exist where a sail can be kept synchronized with Earth or other planet. These balance points exist all around planets except for certain zones. Sails placed in these positions can be used for illumination, heating, observation and communications. A map of the terrestrial regions is shown in the figure at left in conventional radial-tangential-normal coordinates. The ac values are the local field values normalized to 1 AU and adjusted by $\cos^{-2}$ of the angle.
Asteroid Resources:

A typical Earth-approaching asteroid comes close to Earth, but also travels out to the inner regions of the asteroid belt. Sailing ships offer the most economical method of recovering resources from asteroids or short-period comets. If a 2-km ship was assigned to bring a resource load from such an asteroid to Earth, the load mass can trade off against trip time.

As an example case, with a 2-km ship, a return load of 160 tons takes about five years, based on numerical simulation. Allowing for maintenance and the outbound trip, a ship could return with 160 tons about every seven years. Three ships could be linked to carry 500-ton loads in the same time. Rendezvous trajectories to Apollo, Amor, and Aten class asteroids can often be done in as little as three months.

Mined material could be brought to Earth orbit for use as structural material, manufacturing stock, and inert shielding of orbital facilities for long-term habitation. Cost of transportation for resources to Earth orbit when operating with the large loads is estimated to be less than $400/kg, which is two orders of magnitude less than the cost of delivery by an expendable launch vehicle.

Asteroid Deflection:

A sailing ship can deflect an asteroid or comet by pulling it, using a bridle which attaches to physical poles embedded at the rotational poles of the body. Deflecting a small body is a challenge dependent upon navigational capability. Before towing begins, the body should have a navigational package installed which may include transponders, celestial navigation, and multi-spacecraft positioning, similar to GPS but on a solar-system scale. As an example, a 0.1 m/s velocity uncertainty leads to a positional uncertainty of roughly 16 Mm (2.5 Earth radii) 5 years in the future. Bad navigation at the start of towing could increase the risk of collision instead of reducing it.

A 2-km sailing ship can deflect a 10-m asteroid by 20 Mm (3 Earth radii) with an action time of 1 month. A 100-m asteroid requires four 2-km ships, or one 4-km ship, pulling for 12 months to achieve the same deflection. Deflecting a 1000-m asteroid (2 billion tons) by 20 Mm in 5 years requires a team of about 43 4-km ships, or 173 2-km ships.

SHIP DESIGNS:

Only one large, intensive design effort has been done on sailing ships to date. In 1976 and 1977, a square sailer and a helio-gyro were designed for a rendezvous with Halley’s Comet. The square sailer had a single sail 820 m on each side. The helio-gyro had nearly the same total sail area in its 12 blades.
A simple chain of logic says that if an 820-m sailer can be built, so can one of 1000 m. In fact, the designers of the square sail said the same basic design could be extended to 2000 m. This range, 1 to 2 km, is important for moving people and payloads to other planets. These ships could help, and possibly enable, economical development of the solar system.

A 1-km ship could have been built and put into operation during the 1980’s, and could have been followed by a 2-km ship in the 1990’s. Instead of sending one or two costly small spacecraft to Mars at each opportunity, these ships could be carrying tens of tons per trip. The whole economics of exploring and developing Mars could be changed through the use of these low-cost and economical ships.

**Boom-Supported Sails:**

Ships that do not spin are said to be 3-axis stabilized, that is, they have means of controlling their orientation about 3 axes. These ships must use booms or other devices to hold the sails open. A variety of designs have been proposed, but the most structurally efficient are ships with 4 booms. Six boom configurations are also structurally efficient.

Several types of booms can be used.

The most favored are:

**Composite booms** which can be coiled onto a drum for stowage and deployment. These have circular or lenticular cross sections.

**Open-truss booms** which coil into a canister. These are triangular in cross section and can have about a 100:1 extension ratio.

**Inflatable booms** which are very simple and of low mass. These need to have some means of becoming rigid without relying on gas pressure for long-term use.

The square-sail design done at JPL in 1976 used open-truss booms and a mast. Numerous stays were used in the design to stabilize the structure while keeping the booms as light as possible. This was a complex, but efficient structure. The mass of the mast, booms, and stays was approximately 20% of the mass of the sail. The design achieved a sail loading (areal density) of about 6.6 g/m² excluding the payload.

**Spin-Stiffened Sails:**

Sails can be spun to achieve their necessary rigidity through centrifugal action rather than relying on booms. The two basic types are a disk sailer using sail panels with non-parallel sides and the helio-gyro that uses sails as long, un-tapered blades.

The disk sailer is expected to have the lowest mass of perhaps any sailing ship. If the sail can be made sufficiently thin, this type of sailer could possibly achieve an areal density of less than 1 g/m².

The helio-gyro was found to require substantial edge tendons along the blades to withstand the centrifugal forces. The result was that the helio-gyro is not as mass
efficient as the square sailer, but it was favored because of its deployment simplicity compared to the square sailer.

**Sail Designs:**

Triangular sails will have less of a wrinkling problem than a square sail. Being attached with three lines, they can be adjusted to provide full attitude control for the ship.

Pressure on a sail induces curvature in it. The parameters of curvature are shown in the figure at right. A representative degree of scallop is about 2% of the span of the edge.

Determination of the curvature under actual sailing conditions requires a finite-element analysis of the sail loads, actual pressure, and structural deflections. This will allow determination of what built-in curvatures should be in a sail.

The outer edges of a sail must be reinforced, especially near the attach points. Rip stops should also be used across the sail membrane. Production seams will usually provide rip-stop protection in one direction, so rip stops need be added only in the other direction.

**SAILING OPERATIONS:**

**Smart Lines:**

As with maritime ships, lines are essential for a wide range of uses. One difference is that some lines may be very long and need to be self-guiding. A maneuverable grappling device can be used at the end of a line to place or pick up payload containers, to secure a ship to a structure such as a station, or to pick up samples from an asteroid or comet. These smart lines will be an essential part of sailing operations. Lines a few hundred kilometers long may be used to move a ship from a space station to an orbit farther out where it could begin sailing. Other lines, called stays, may be used as rigging among mast and booms or for connecting to other parts of a ship's structure.

**Low Earth Orbit:**

A sailing ship can have its structure completed and sails unfurled either at a station or after it has been started on its way by some other means, such as a rocket. For reliability, the choice of using a space station is the better one. If a sailing ship is completed in low Earth orbit beneath the radiation belts, it will usually require some assistance in moving to an orbit farther out, away from Earth's atmosphere, before it can begin sailing. This appears to be a relatively minor disadvantage compared to the advantages of operating directly from a station in low Earth orbit. The first large sailing ships may then be completed at the International Space Station or at a similar facility, possibly one dedicated to the operation of sailing ships.

**Spirals:**

Sailing ships can spiral in toward a planet or away from it. They can escape from a planet or sail into a capture orbit from
interplanetary space. The time required operating from orbits at lunar distance and interplanetary space is typically 1 to 2 weeks. Operating between low Earth orbit and interplanetary space would typically take 4 to 6 months.

**Interplanetary Cruise:**

Sailing ships can be steered by several means, primarily by vanes or adjusting the orientation of the sails. This latter approach appears to be the easiest to implement. Sails will typically be attached by three lines. Letting out or taking in the lines in an independent manner allows a sail to be reoriented. This results in a torque on the ship, which causes it to turn to a new orientation. The orientation of a ship determines the direction of its acceleration.

While cruising in interplanetary space, the ships turn slowly. Turning rates of about 1 deg/day are typical. The ships will have very capable onboard computers so that any ship could sail itself to its destination. Control centers on Earth will monitor the progress and condition of the ships.

<table>
<thead>
<tr>
<th>Payload, tons</th>
<th>6</th>
<th>25</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accel (ac), mm/s²</td>
<td>0.4</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Areal density, g/m²</td>
<td>20.7</td>
<td>8.3</td>
<td>5.5</td>
</tr>
<tr>
<td>Mars transfer, days</td>
<td>330</td>
<td>130</td>
<td>100</td>
</tr>
<tr>
<td>Payload cost, $/kg</td>
<td>8300</td>
<td>710</td>
<td>2000</td>
</tr>
</tbody>
</table>

**Operating Costs:**

JPL estimated the cost of the first production unit of an 820-meter solar sail at $65 million, for use in 1982. A second unit would cost a bit less, and could have been produced by about 1984. Adding some electronics to make it functionally independent might have pushed the cost to around $70 million. From this, a very rough estimate of $50 to 100 million seems reasonable for a 1-km ship design in steady production, and $70 to 150 million for a 2-km ship. These unit costs could be amortized over 15 to 30 years of operations.

Commercial charter rates might be roughly $10 to 25 million annually for ships in this size range. For a two-year voyage, the commercial shipping charges could be roughly $20 to 50 million, which for a 25-ton load averages $1 to 2 million per ton. The table shows rough estimates of shipping costs for cargo taken to Mars by a 2-km ship.

**Shipping companies:**

Commercial shipping companies will begin operations with interplanetary ships as soon as a commercial market exists. One could exist in the near future if NASA, ESA, and other space organizations purchased interplanetary transportation in the same way as they purchase launch services. Private organizations, most likely ones associated with the development of Mars, could also be part of the market for sailing ships. Several companies, including General Astronautics, are likely to offer shipping services on a charter basis, much like maritime shippers on Earth.

**ACTIVITY AND HISTORY:**

This section describes the history of the invention of space sailing and related events on the theory of light. It appears that Jules Verne may have been the first to recognize the space sailing concept in 1865, although Johannes Kepler might have preceded him with the idea around 1610.

**ISSAC NEWTON** published his three laws of motion in 1687 (Principia). His Second Law equates a motive force to a change in momentum, which is the principle used in determining the force resulting from the
reflection, absorption, and emission of radiation. His Third Law equates that to a propulsive force on a sail.

**JAMES BRADLEY** measured the aberration of starlight as an angle of 20" (= 0.006 deg) in 1728 and used Romer's data to explain the effect as being due to the orbital motion of Earth.

**JAMES CLERK MAXWELL**, in 1864, published his theory of electromagnetic fields and radiation, which shows that light has momentum and thus can exert pressure on objects. His work provides the theoretical foundation for sailing with light pressure.

**SVANTE ARRHENIUS** published Worlds in the Making in 1908, in which he predicted the possibility of solar pressure distributing life spores across interstellar distances, the concept of panspermia. He apparently was the first scientist to state that light could move objects between stars.

**FREDERIK TSANDER** published his solar sailing work in 1924, the first technical publication on the subject. He identified several useful configurations and made calculations of interplanetary trajectories by solar sailing spacecraft. He coined the term "solar sailing". He also showed the optimal method of transfer between circular orbits before Hohmann and showed how spacecraft could perform gravity-assist maneuvers.

**CARL WILEY**, writing as Russell Saunders, described the concept of solar sailing in "Clipper Ships of Space", published in Astounding Stories in 1951, the first U.S. publication on space sailing. His "light-jammer" configuration resembles a parachute, being a magnesium hemisphere 80 km in diameter and 0.15 um thick.

**JEROME WRIGHT** published Solar Sailing: Evaluation of Concept and Potential in 1974, beginning the modern solar sailing activity. He discovered artificial balance points using sails around planets in 1974-75. His development of a method to rendezvous with Halley's Comet led to the first substantial solar sail development work, done at JPL in 1976-77. He led the construction of the first prototype solar sail.

**CONCLUSION:**

Old-fashioned booster rockets need so much fuel that they can't push their own weight beyond the Solar System into interstellar space. Space sails, on the other hand, require no fuel. Imagine the wind pushing sailboats across water on Earth. The thin reflective space sails would be propelled through space by sunlight, microwave beams or laser beams.

With excitement a hundred years ago when people welcomed ships such as Flying Cloud back to their home ports from voyages to distant places, people today could follow the progress of the ships from Mars, past a couple of asteroids, then into Earth's gravity field, before easing into a parking orbit for a stay of a few months before their next voyage to Mars. **In no time a new era of space sail journey is awaiting to dawn.**

**SPACE SAILING GLOSSARY:**

- \( \alpha \) - angle between the incident light and the ship's reference axis or the normal to a flat reflector

- areal density - the mass divided by the sail area, expressed in g/m², typically using sail mass, sail+bus mass, sail+bus+payload mass, or membrane mass before fabrication into a sail
**boom** - a linear structural element that holds a sail(s) open, typically extending from a ship's center or from a mast

**characteristic acceleration** - the acceleration a sailing ship would experience at 1 AU from the Sun while facing the Sun, used as a reference of performance, abbreviated as ac

**disk sailer** - a ship with a circular plan form, often without compression members and relying on stiffening by means of rotation

**Doppler effect** - a shift in wavelength caused by relative motion of a body toward or away from the source of the radiation or sound

**Earth synchronous** - Sun-centered orbital motion where a sail or other craft maintains a constant position relative to Earth

**gravity assist** - an encounter at hyperbolic speed with a body of substantial mass which results in turning the velocity vector of the spacecraft, typically used to change orbit energy, size, eccentricity, inclination, or orientation

**heliogyro** - a rotating sailer using long blades for sails; the blades twist to control the ship

**light pressure** - pressure on a surface obtained by changing the momentum of impinging light (or other electromagnetic radiation)

**light sailing** - travel in space using light pressure for propulsion of a sailing ship

**mast** - a linear structural element perpendicular to the plane of the sails

**planet synchronous** - Sun-centered orbital motion where a sail or other craft maintains a constant position relative to a planet

**rigging** - the set of lines giving strength and stability to a system of sails, booms, and mast(s) (if included)

**sail** - a thin, often large, often membranous structure used for propulsion or attitude control of a ship, spacecraft, or other space structure

**sail loading** - see areal density

**sailer** - a sailing ship; a ship using sails

**sailor** - a crew member on a sailing ship; a person working on space sailing ships who would, with no hesitation, sign on as a crew member if an opportunity was available

**solar pressure** - light pressure obtained by using unaltered light from the Sun or other star

**solar sailing** - travel in space using solar pressure for propulsion of a sailing ship

**solar wind** - the flux of particles emitted by a star, mostly electrons and protons traveling at a few hundred meters/second at 1 AU, carrying less momentum than sunlight

**space sailing** - travel in space by means of pressure on sails

**sphere of influence** - the roughly spherical volume of space centered on a planet where its gravity dominates that of the central star

**square sailor** - a sailing ship with an overall square form

**stay** - a rigging line

**Sun synchronous** - Sun-centered orbital motion where a sail or other craft maintains a constant position relative to a point on the Sun

**swingby** - see gravity assist
θ - angle between the resultant force vector and the radial from the light source

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