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THE ELECTRIC SAIL - A NEW PROPULSION METHOD WHICH MAY ENABLE FAST MISSIONS TO THE OUTER SOLAR SYSTEM

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In this paper we give a status report of the electric sail concept which is a new (2006) propulsion invention. We consider the underlying physical principles, the technical implementation, its applications and the ongoing work.

Keywords: Electric solar wind sail, infinite specific impulse, high velocity increment

1. INTRODUCTION

Space propulsion is a long-standing and formidable problem which limits in an essential way the scale of space activity and our access to the solar system. To produce propulsion in empty space, one has to have a source of reaction mass and an energy source to accelerate that mass to high enough speed. A chemical rocket achieves both requirements by burning the fuel and producing a stream of exhaust gas. An ion engine does not rely on chemical energy, but instead uses solar or nuclear electric power to ionise and accelerate the propellant. Finally, a solar sail uses the radiation pressure of solar photons to eliminate both the need for an energy source and the need to carry onboard propellant. While theoretically appealing, constructing and deploying a solar sail with high performance remains technically a formidable task due to the extreme thinness of the membrane material needed. The electric sail is similar to the solar sail, but uses the solar wind dynamic pressure instead of the radiation pressure and the electric field produced by thin, conducting tethers as its sail, instead of a solid surface.

2. PHYSICAL PRINCIPLES OF ELECTRIC SAIL

The electric sail (E-sail) is a new propulsion invention [1] which is similar to the solar sail, but it uses the solar wind dynamic pressure instead of the radiation pressure. The electric sail is conceptually similar to Zubrin's magnetic sail [2] except that it uses an electrostatic field instead of a magnetostatic field for deflecting the solar wind proton flow and extracting momentum from it.

In its original form [1], the electric sail was envisioned as a large wire mesh (Fig. 1) whose mesh spacing is of the order of the plasma Debye length and which is kept in a high positive potential V_0 with an onboard electron gun. Such a mesh would form an impenetrable obstacle for solar wind protons for up to some threshold solar wind plasma density which also depends on the mesh potential. The positively charged wires attract electrons from the surrounding solar wind plasma. The resulting electron current is proportional to the total surface area of the wires and also proportional to $\sqrt{V_0}$ and must be expelled by the electron gun.

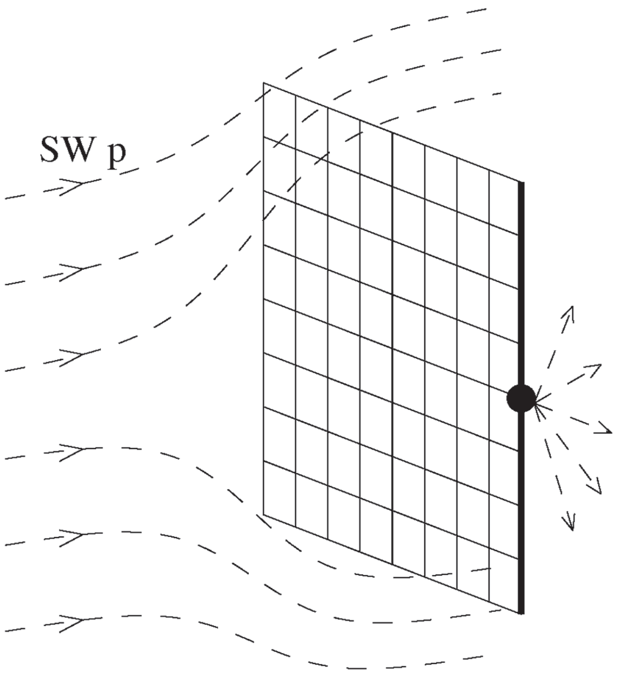

Fig. 1 The original idea of an electric sail as a large wire mesh whose mesh spacing is of the order of solar wind plasma Debye length [1]. This version would be difficult to deploy and the mesh spacing would be optimised for one particular solar wind density only.

3. TECHNICAL IMPLEMENTATION OF ELECTRIC SAIL

A wire mesh tens of kilometres across and with ~ 10 m mesh spacing, which was required in the original electric sail idea, would, in practice, be next to impossible to deploy in space. For this reason a deployable "toy" alternative was developed, and as such the construction principle of wire booms on spinning satellites was identified (Fig. 2). Gradually it became clear that the "toy" alternative, besides being deployable, could also be made guidable by a rather simple method and also met or exceeded the performance of the original idea. The latter prop-

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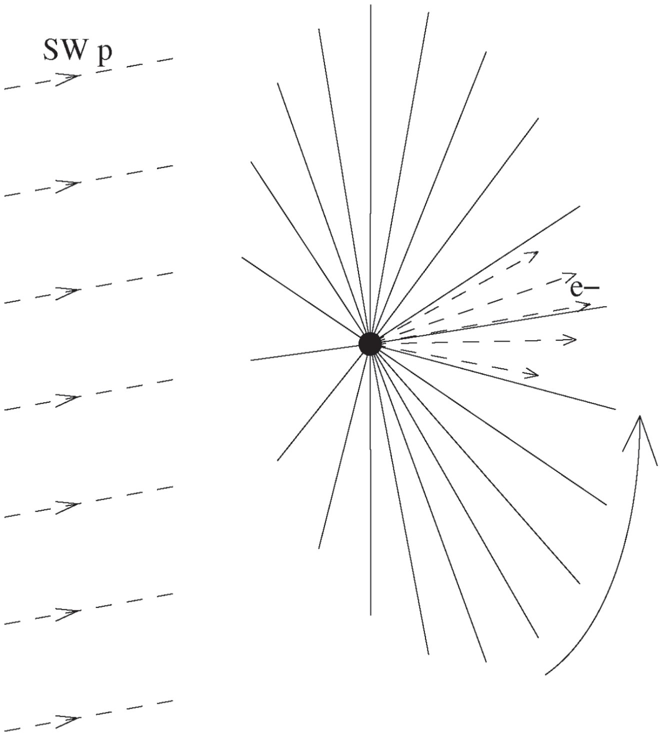

Fig. 2 Technically realisable version of the electric sail which consists of a set of rotating, charged tethers. Each tether forms an electric influence region around itself where solar wind proton trajectories are deflected and the tether experiences a push from the solar wind which depends on the tether's potential.

erty is due to the fact that the sail need not form an impenetrable surface for solar wind protons; it's enough if the sail wires are able to deflect them to some extent. Actually, the situation where the wires are so far apart that the protons always leak through between them is optimal because then there are never any superfluous wires so that all mass in the wires is in maximal use, and the situation remains the same over a wide range of plasma densities.

Thus, the practical electric sail consists of a number of long, thin, conducting tethers which are kept in a high positive potential by an onboard electron gun. In a full-scale mission the number of tethers is typically 50-100, their length 20 km, the tether potential up to +20 kV and the electron gun power needed to maintain it ~ 500 W. In order to be resistant to micrometeoroids, the tethers are made of multifilament Hoytether-type structure (Fig. 3, [4]). The Hoytether width is typically ~ 2 cm and it is made of 20 μm wires. With these numbers the electric sail gives ~ 0.1-0.2 N thrust at 1 Astronomical Unit (AU) distance from the Sun. The thrust force decays as $\sim 1/r^{7/6}$ where r is the distance from the Sun [3]. The tethers are kept stretched by rotating them with spin period of ~ 20 minutes. With these parameters the yield strength requirement due to the centrifugal force becomes 210 MPa, assuming copper wires and the worst case where micrometeoroids have broken all but one of the wires at a point which is close to the root of the tether. Metal wires are industrially available whose yield strength is 1 GPa and more so the strength requirement can be handled.

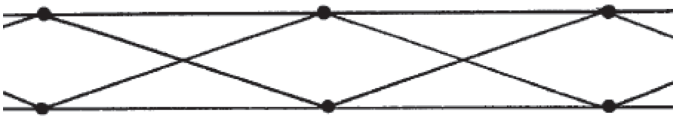

Fig. 3 Model of four-line micrometeoroid-resistant "Hoytether". The structure as a whole does not break if and when micrometeoroids cut some wires. The structure width is ~ 2 cm and the wire thickness ~ 20 μm.

The dynamic pressure of the solar wind is on average about 2 nPa at 1 AU distance from the Sun. This is about 5000 times less than the radiation pressure of the solar photons, which is the momentum source used by the solar sail. Thus at first sight it would appear that utilising the solar wind dynamic pressure with an electric sail is much more difficult than building a solar photon pressure sail with equal performance (acceleration, i.e. force per mass). However, compared to a solid, two-dimensional membrane surface, a charged, thin tether can be built extremely lightweight per effective sail area produced. This is because the effective "electric width" of a charged tether is about 20 m (a few times the plasma Debye length in the solar wind where the coefficient depends on the potential) which is of the order of million times larger than the physical thickness of the wire (20 μm). Thus it is not surprising that an electric sail can have at least on paper a higher performance than a currently deployable solar sail, even though it uses a thrust source whose areal density is 5000 times smaller.

A typical electric sail would take the electricity needed to power its electron gun from ordinary, modest-size solar panels. Like the solar sail, it has infinite specific impulse and the duration of the propulsive action is limited only by physical breaking of the equipment or manoeuvring of the spacecraft far from the Sun.

The thrust produced by the solar wind on the tether has been predicted by simulation and theory [3]: at 1 AU distance it is typically 50-100 nN/m and it depends on the solar wind conditions (density and speed) and the tether potential (increasing the potential increases the thrust). For explicit orbital calculations with the electric sail, see the companion paper [5].

Between the spacecraft and each of the tethers there is a potentiometer (tunable resistor) which allows each tether to be in a slightly different potential. Because the thrust magnitude depends on the tether potential, this gives a way to control the thrust experienced by each tether individually. The whole tether spinplane can be turned by modulating the potentiometer settings by a sinusoidal signal which is synchronised to the rotation period. The phase of the signal determines the direction into which the spinplane turns and its amplitude determines how fast the turning occurs. A mechanical simulation program has been written to demonstrate this.

It might happen that due to slight inhomogeneities in the solar wind stream and small mechanical or electric differences between the tethers, one of the tethers start to rotate with slightly higher or lower angular speed than the other tethers. If let to continue, this state of affairs would sooner or later lead to a collision of two neighbouring tethers. At worst such a collision could produce a chain reaction and a complete mixup of the tethers, thus it must be avoided. A way to avoid it is to slightly reel in or out the offending tether in order to slightly increase or decrease its angular speed, respectively. For this purpose the direction of each tether should be monitored during flight and at least the root of the tether must be of a type which allows continuous fine-tuning of the length, i.e. reeling in and out in space multiple times.

Although the spin period is long, the large length of the tethers causes the angular momentum of the deployed system to be fairly large. There are different approaches for obtaining this initial angular momentum. The most straightforward deployment procedure is to use a pair of small chemical rockets mounted on tips of rigid booms of some tens of metres long for producing torque. The spinup fueltank, booms and rockets can be jettisoned after the deployment is complete, so they do not affect the performance of the final flying package, although they do increase the mass which must initially be launched from the Earth. The needed fuel is inversely proportional to the length of the spinup booms.

Another solution ("Windmill") is to make certain spinplane turning manoeuvres simultaneously with synchronised reel in/reel out procedures during the deployment while the electron gun is turned on. This allows one to obtain most of the angular momentum from the solar wind so that only a much smaller amount of initial spinup fuel is needed. For this to work, however, one must be prepared to reeling in and out the tethers multiple times at an arbitrary point.

Yet another approach to initiating the spin is to have two identical electric sail spacecraft initially mounted together to a common axis ("Siamese Twins"). A small electric motor on the axis is enough to cause countering rotation, after which one deploys the tethers on both spacecraft in an identical way. The only difference between the spacecraft is the sense of their rotation. After deployment is complete, the spacecraft are slowly separated, after which we have two deployed and spinning spacecraft. This approach requires highly symmetrical and accurate mechanics in order to avoid the closely spaced, counterrotating tethers from colliding.

We envision that in the first electric sail missions one would use the straightforward spinup propulsion method and leave the "Windmill" and "Siamese Twins" solutions for later experimentation and study.

4. APPLICATIONS OF ELECTRIC SAIL

Specifically, the electric sail would enable missions in the following classes.

1. Flight out of the Solar System into interstellar space, out of the influence region of our Sun (the heliosphere). Although traditional techniques (chemical propulsion combined with solar and planetary gravity assists, nuclear electric propulsion or solar sail) can be used to reach the heliopause within 25-30 years, the electric sail could reach the target in a much more attractive time span of 15 years. Furthermore, the mission could potentially be rather cheap because the hardware is lightweight (no need for heavy-lift booster rocket). ESA calls this mission the Interstellar Heliopause Probe (IHP).
2. Rapid flyby mission of any target in the Solar System. This is a variation of the previous one, where one selects a specific target and pays more attention to accurate navigation to make a close flyby. For example, there are many objects in the Kuiper belt that have never been imaged in situ.
3. An off-Lagrange point solar wind monitor, i.e. a spacecraft that hovers between Sun and Earth and measures the solar wind. The traditional technique (used e.g. in SOHO) is to place the probe at the Lagrange L1 point. The most accurate and reliable method to predict space weather is to measure the solar wind and its magnetic field before it impacts Earth's magnetosphere. The drawback of the Lagrange point is, however, that it takes only ~ 1 hour for the solar wind to travel from there to Earth's magnetosphere, i.e. one gets only about one hour of warning time in terms of space weather forecasting. This is inconveniently short for many operational purposes. With the electric sail one could place the spacecraft somewhere else, for example four times farther from the Earth than the Lagrange L1 point, so that one would get a four-hour warning time. A technical detail is that because the probe would be heavily charged when propulsion is on, one would have to alternate between solar wind monitoring phases and propulsive phases, for example 5 min each. This is not a problem since one can turn off propulsion simply by turning off the electron gun, after which the tethers get neutralised in about 30 seconds and ion measurements start to give meaningful results.
4. Other missions in the inner solar system, for example studying the Sun at close range or fetching samples from asteroids. Using the electric sail would not make these missions faster, but it might cut their costs significantly because no propellant is needed.

4.1 Orbital Fuel Factory Application

All the above applications are for scientific or monitoring missions. We can also envision at least one potential commercial application, namely an orbital fuel factory. The fuel factory's goal is to provide rocket fuel at high Earth orbit which is based on asteroid water and which is cheaper than bringing the corresponding amount of fuel from Earth by traditional booster launching. The fuel factory concept has four distinct parts:

1. A water-mining robot at an icy asteroid (or old cometary nucleus). The robot applies moderate heating to the asteroid soil and collects the outgassing water vapour in a tank or bag where it is left to condense or freeze.
2. A set of electric sail transfer spacecraft that carry the mined water ice to high Earth orbit. According to our present estimates, if given about 5 years of time, a 100 kg electric sailcraft could bring a 2 ton load from an asteroid to high Earth orbit if the asteroid is at most at Martian orbital distance.
3. A solar-powered fuel factory at high Earth orbit which turns water to cryogenic fuels (liquid hydrogen and liquid oxygen) using electrolysis. Being far from the Earth and its harmful infrared emission, the cryogenic liquids are possible to store behind sunshields.
4. A reusable cryogenic rocket vehicle capable of refueling at the factory and performing different orbit transfer services for customer payloads in Earth's magnetosphere. Alternatively, to avoid cryogenics and separate fuel factory, the water could be used directly by an a solar-powered electrolysis rocket spacecraft, if rapid orbital changes are not required.

The economicality of the fuel factory rests on the high payload fraction (~ 20) of the electric sail "logistics chain" from the asteroid to high Earth orbit. As far as we know, the other components of the fuel factory concept represent known space technology. With the fuel factory, one can benefit from the mass efficiency of the electric sail also in those applications which require impulsive thrust (e.g., landing to large bodies), large payloads (e.g. manned Mars flight) or intramagnetospheric orbits (nearly all commercial space activities). Thus, although the electric sail produces only weak thrust and does not work in Earth's magnetosphere, its benefits could eventually be felt in essentially all space activities if the fuel factory application is realised. For example, the fuel factory might be used for making the construction of large-scale solar power satellites more economical [7].

5. PROJECT STATUS IN MAY 2007

At this moment (May 2007), the following are known about the realisability and technical readiness level of the main components of a spinning electric sail.

1. At least one manufacturer can produce high-quality 20 µm copper alloy wire at 20 km continuous length whose tensile strength of more than 1 GPa is quite adequate for an electric sail raw material.
2. Different techniques of bonding aluminium and copper alloy wires together to produce the 4-line or other type of "Hoytether" are under investigation.
3. Different ways of reliable reeling of the tether have been conceptualised. Whether or not one can reel in and out in space repeatedly at arbitrary point remains to be studied. If the answer is positive, it will make certain other design considerations somewhat simpler, for example the "Windmill" spinup strategy then becomes possible.
4. A design for a suitable electron gun already exists and meets the electric sail requirements well.
5. Two completely independent numerical codes for simulating the dynamics of the rotating tethers have been written. The possibility to turn the tether spinplane controllably using potentiometer modulation have been numerically demonstrated (thus far in constant solar wind). The efficiency of a tether length fine-tuning algorithm which is designed to keep the tethers from colliding with each other has been similarly demonstrated as well.
6. At least two different strategies for measuring tether directions (necessary input for the control algorithms in full-scale electric sail mission) have been identified. Preliminary reasoning and estimates indicate that at least one of the strategies should work as a practical direction sensing method without too large mass and power overhead.

6. CONCLUSIONS

The electric sail is a new and potentially revolutionary deep space propulsion technique which is at the moment undergoing rapid technical development. From the operational viewpoint, the electric sail is like a solar sail, but, when considering high performance levels, it is expected to be easier to construct and deploy. The most important limitation of the electric sail is that it cannot produce thrust in Earth's magnetosphere because there is no solar wind there.

It seems at the moment that building the electric sail will be only moderately challenging. The most challenging parts are in producing and reeling of the long, thin and conducting tethers. Naturally, new technical problems may emerge during the course of the work, but we would be somewhat surprised if one of them would develop into a real "show-stopper" issue. At the moment our main concern is how to find a level of funding for the effort which does not unnecessarily delay or constrain the necessary technical development work. A companion paper ("Considerations of electric sailcraft trajector design", see also [6]) presents quantitative examples of flight times to the outer solar system of electric sail missions.

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