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Status report of the electric sail in 2009

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ABSTRACT

The electric sail is a new propulsion concept which uses charged tethers to extract momentum from the solar wind by Coulomb interaction. We give a status report of the electric sail as of October 13, 2009. We report progress during the last two years in plasma physical thrust estimation, tether manufacture methods, navigability, test mission planning and applications. The thrust estimates have gone up recently by a factor of about five, samples of final-type tether have been manufactured, accurate navigability of the sail in variable solar wind has been shown numerically, a CubeSat test mission for measuring the electric sail force in orbit is in Phase-A study and trajectory calculations for many classes of missions have been made. Using existing technology, it seems possible to build an electric sail of ~ 1 N thrust, ~ 100 kg mass and ~ 10 year lifetime. In terms of lifetime produced impulse per unit propulsion system mass, such a near-term and general-purpose device would be about 1000 times more efficient than a chemical rocket and about 100 times more efficient than a contemporary ion engine. This level of performance is enough to enable a host of important applications, such as in situ measurements in interstellar space, sample return from most solar system targets, non-Keplerian orbit probes for space weather forecasting and helioseismology and economical utilisation of asteroid resources.

1. Introduction

An electric sail (Fig. 1, [1,2,4]) is an innovative propulsion concept that, similar to a more conventional solar sail, allows a spacecraft to deliver a payload to some high-energy orbit without the need for reaction mass. The spacecraft is spun around the symmetry axis and the rotational motion is used to deploy a number (e.g., 50–100) of long, conducting tethers which are held at a high positive potential by an onboard electron gun, whose electron beam is shot roughly along the spin axis. The electric sail is similar to the magnetic sail [3] in its use of the solar wind momentum flux as a thrust source. The electric sail is similar to an ion engine in its use of electric power to generate thrust. Finally, the electric sail is similar to electrodynamic tether propulsion in its use of long, conducting tethers. Despite these similarities, however, the electric sail is a unique propulsion concept whose underlying physical principle (Coulomb drag interaction between charged tethers and the solar wind) differs fundamentally from other propulsion methods.

2. Thrust estimation

When a positively charged tether is placed in the solar wind, an electron sheath is formed which is pushed and distorted by the solar wind proton flow [2,4]. The positive potential forms an obstacle for solar wind protons so that a force which is proportional to the dynamic pressure of the flow ~ 2 nPa times the sheath width ~ 100 m times the tether length ~ 20 km is created. The force actually pushing the charged tether is the Coulomb force due to the asymmetric plasma charge distribution resulting from solar wind proton pile-up on the sunward side. The first

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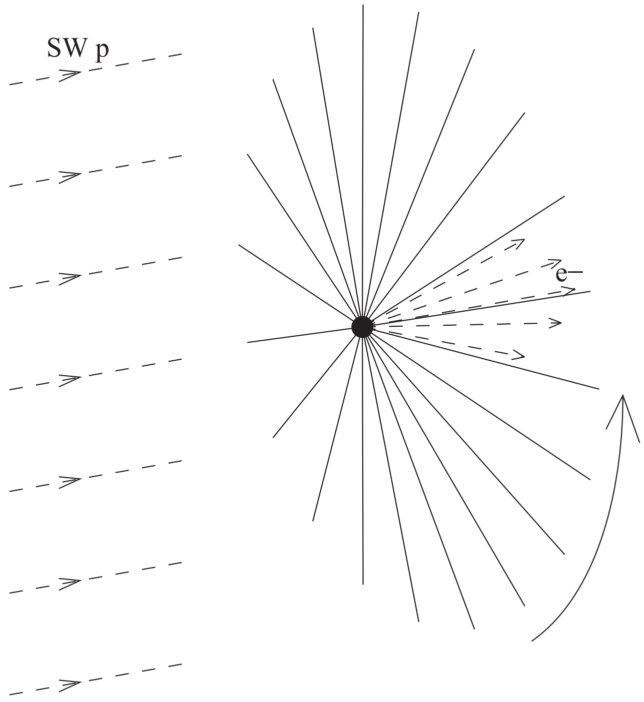

Fig. 1. Technically realisable version of the electric sail which consists of a set of rotating, charged tethers. Each tether forms around itself an electric influence region where solar wind proton trajectories are deflected and the tether experiences a push from the solar wind which depends on the tether's potential.

plasma simulation based estimates of the electric sail thrust were based on the assumption that trapped electrons that necessarily form when the potential is turned on remain and contribute to the shielding of the tether charge [2]. Later, a natural electron scattering mechanism was identified which is able to remove trapped electrons in a few minute timescale typically [4], and it was found [4] that if trapped electrons are absent, then the electric sail thrust per unit length of tether is roughly five times higher than what was reported in [2]. The absence of trapped electrons is a standard assumption in most of the literature concerning electrodynamic tethers (e.g., [5]) and thus it seems to be justified at least most of the time in the case of electric solar wind sailing.

A simplified form of the thrust formula of [4] which is approximately valid in the solar wind is

$$\frac{dF}{dz} \approx 0.2(V_0 - V_1)\sqrt{\varepsilon_0 P_{\rm dyn}} \tag{1}$$

where V_0 is the tether voltage, $eV_1 = (1/2)m_i v^2$ is the bulk kinetic energy of the solar wind ions and $P_{\rm dyn} = m_i n v^2$ is the solar wind dynamic pressure. Often the V_1 term can be neglected in comparison to V_0.

Without trapped electrons, a 20 kV charged tether at 1 AU distance in average solar wind achieves ~ 500 nN/m thrust per length [4]. For example, an electric sail composed of 100 tethers 20 km long each would then achieve ~ 1 N thrust. Such tethers weigh 11 kg if made of 25 μm aluminium using the four-fold Hoytether construction [6] and the electron gun requires ~ 400 W power [2], so assuming that the whole propulsion system mass is

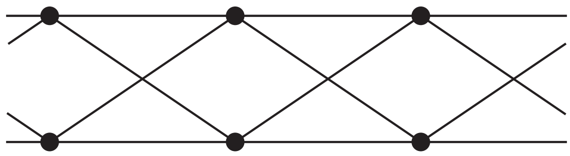

Fig. 2. Model of four-line micrometeoroid-resistant "Hoytether" [6]. The structure as a whole does not break if and when micrometeoroids cut some wires. The structure width is ~ 3 cm and the wire thickness ~ 25 μm. Sites where wire-to-wire bonding is needed are marked with dots.

less than 100 kg in this case appears to be justified. Such a device would give 1 mm/s^2 acceleration to a 1000 kg spacecraft of which 90% is payload. Alternatively, for a small probe of 50 kg total mass, the same acceleration would be provided by a small electric sail composed of only 10 tethers 10 km long each, with 50 mN total thrust at 1 AU.

3. Tether manufacture

For micrometeoroid resistance, multifilament tethers must be used (Fig. 2, [6]). The tether is made of ~ 25 μm Al–Si or other metal wire which is an off-the-shelf product of electronics industry. Producing the wire-to-wire bondings, however, is not trivial and new manufacturing methods were designed for this purpose using a commercial ultrasonic bonder machine with a special jig that holds the lower wire tightly in place when the upper wire is bonded to it with the ultrasonic bonding wedge [7]. The first successful bonds were produced with the jig in summer 2008 and work to refine, optimise and automate the process is underway at University of Helsinki.

The spinrate of the tethers must be selected so that the centrifugal force overcomes by about factor ~ 5 the solar wind force acting on the tether. At 20 km length, the single-tether solar wind force at 1 AU is ~ 10 mN so that the centrifugal force should be about 50 mN. In the worst case where all but one of the four Hoytether wires have been cut by micrometeoroids at some point along the tether near the tether's root, this loads the 25 μm aluminium by $\sim 30\%$ of its tensile strength.

4. Navigability

The solar wind which is the thrust source of the electric sail is naturally highly variable, unlike for example the solar photon radiation field which is the thrust source of ordinary solar sails. Thus it is not clear *a priori* that the electric sail can be navigated accurately enough to be feasible to use it as the main or sole propulsion system for planetary missions. However, there are two mechanisms which efficiently damp the variations of the electric sail thrust even when the solar wind parameters (density and speed) vary strongly [8]. The first mechanism is due to the fact that the electron sheath width has an inverse square root dependence on the solar wind electron density. Thus when the solar wind density drops, the thrust becomes lower because the dynamic pressure decreases, but the simultaneous widening of the sheath partly compensates for it. The second mechanism arises from the natural desire to run the electric sail electron gun with the maximum power available from the solar panels. When the solar wind electron density drops, so does the electron current gathered by the tethers, so that one may then increase the electron beam and tether voltage without increasing power consumption. When both mechanisms are taken into account and the simple maximum power strategy is used, the obtained thrust is proportional to $n_0^{1/6}$ where n_0 is the solar wind density, i.e. the dependence of the thrust on the solar wind density is weak.

Fig. 3 shows an example 10-day period of measured solar wind data when the density and speed variations were large. Under high maximum voltage (40 kV), the resulting variations in the thrust (panel c) are much weaker than in the solar wind itself. The situation is further improved by the fact that in reaching a planetary target such as Mars, it is the average thrust over at least a one month timescale that matters, not daily thrust values. Furthermore, if one modifies the maximum power strategy so that some electric power capability is kept in reserve, then the likelihood becomes high that the planned thrust level goal can be reached. One can also design the trajectory so that nearly maximum power is used in the beginning phase of the mission, but when approaching the target, more power is left in the reserve. In this way, if a prolonged period of weak solar wind should occur in the initial phase of the mission, this can be corrected for later by using the power margin provided by the designed power envelope. When all these considerations are put together, the conclusion is that the navigability of the electric sail is essentially as good as that of any other propulsion system such as an ion engine [8].

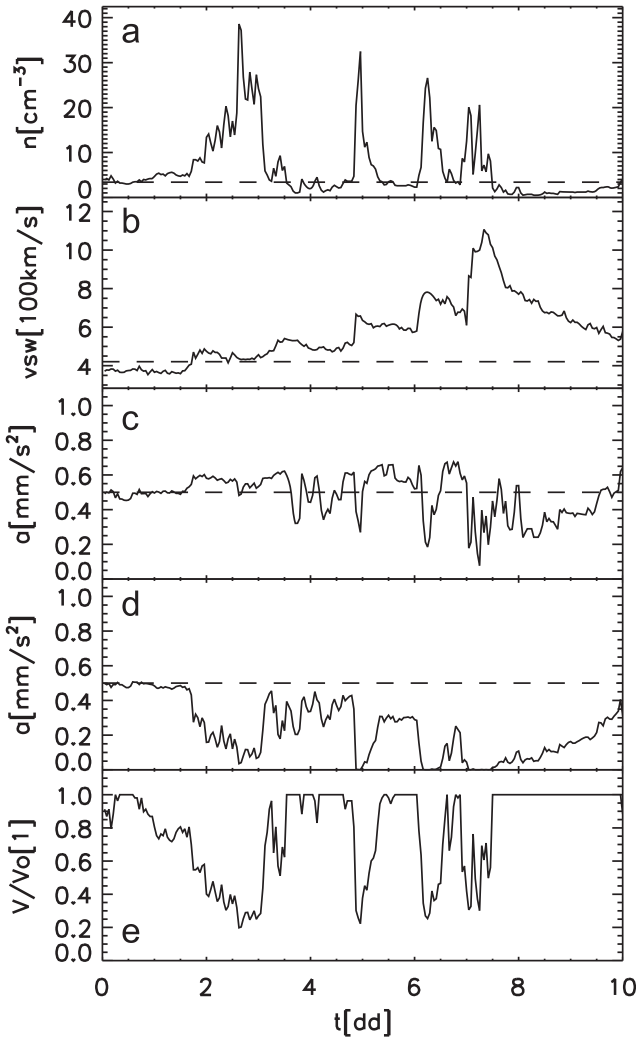

Fig. 3. Solar wind density (a) and speed (b), resulting electric sail acceleration with 40 kV (c) and 10 kV (d) maximum voltage, as well as voltage variation compared to maximum (e), over a 10-day period when solar wind showed large variations [8].

5. Cubesat test mission

The electric sail's designed environment is the free solar wind, but the electric sail effect (force acting on a charged wire or tether by a plasma stream) can be measured already at low Earth orbit (LEO). At LEO one can use the velocity difference between the satellite and the nearly stationary ionospheric plasma to simulate the solar wind. The ionospheric plasma is up to 10^5 times denser than the solar wind and the ion mass (O+) is 16 times higher, but on the other hand the relative speed is only 7 km/s instead of 400 km/s, so the dynamic pressure at LEO is $\sim$500 times higher than in the solar wind. The sheath width is some centimetres instead of 100 m as in the solar wind so the thrust per unit length at LEO is $\sim$5 times less than in the solar wind, being $\sim$1 μN for 10 m tether.

The ESTCube-1 is a 1 kg Estonian nanosatellite (http://www.estcube.eu) obeying the CubeSat satellite standard. Its planned launch is 2012. The satellite will measure the electric sail effect in orbit for the first time by deploying a 10 m spin-stabilised tether and charging it to +200 V using a 0.5–1 W electron gun. The satellite's orbital velocity vector will lie in the spin plane. One can measure the electric sail effect by turning the tether voltage on always in the same phase of the spin and measuring the resulting change of the tether's and satellite's spinning rate. For example, one can always turn on the voltage when the tether is spinning against the plasma flow so that the electric sail force tends to brake the spin of the tether. Changes in orbit are also expected to be detectable. The geomagnetic field at LEO will slightly modify electron motion inside the sheath (an effect which is not present in the solar wind), but this is not expected to produce an important effect for the electric sail thrust.

6. Applications

Ways to calculate pure electric sail trajectories to planetary and asteroid targets have been analysed [10,11]. The "standard" $\sim$1 N electric sail could be useful in four different tasks: (1) providing a fast one-way ride for a small payload ($\sim$200 kg) at $>$50 km/s out of the solar system [12], (2) providing a relatively fast trip to a giant planet orbit for $\sim$500 kg payload, using a chemical orbit insertion burn near the planet [9] and possibly also E-sailing and/or ED tethering in the giant planet's magnetosphere, (3) providing a back and forth sample return trip for a ~ 1000 kg payload in the inner solar system (at most the main asteroid belt distance) [10], (4) providing a non-Keplerian orbit for special purposes such a off-Lagrange point space weather monitoring or off-ecliptic solar orbit for helioseismological measurements [13]. Solar wind plasma measurements are not possible at the spacecraft when the E-sail is on, but since the neutralisation time of the tethers is only ~ 30 s at 1 AU, interleaved propulsive and measurement phases can be used in solar wind monitoring. Its main limitations for travelling in the solar system are that it does not produce much thrust inside planetary magnetospheres (because there is no solar wind there) and that because its thrust vector is always more or less pointing radially outward from the sun (the thrust direction can be altered by $\sim 30^\circ$), a return from the outer solar system in reasonable time is not possible by using the electric sail alone. Return from a giant planet orbit is possible, however, by performing an impulsive chemical rocket burn near the giant planet so as to eject the spacecraft towards the inner solar system [9]. In this strategy, the electric sail tethers must be engineered to survive the impulsive acceleration. Another option is to use a separate electric sail during the return trip which is deployed after the impulsive burn.

Scientifically, the above possibilities would enable e.g. sample return from many solar system targets with reasonable cost and the first in situ measurements in the interstellar space. Commercially, utilisation of asteroid resources such as water could become economical by using electric sails as a "logistic chain" for returning material from asteroids to Earth orbit. This is so because the impulse per mass unit produced by the electric sail over its lifetime may be ~ 1000 times higher than for a chemical rocket and ~ 100 times higher than for a contemporary ion engine (e.g., 1 N thrust over 10 years lifetime per 100 kg propulsion system mass gives 3000 km/s impulse over mass figure of merit, compared to 3 km/s for space-storable chemical propellant). In the role of an asteroid material tug hauling heavy payloads, the sail remains all the time near 1 AU so that the lifetime impulse is not limited by the sail travelling too far from the sun.

7. Conclusions

Unless some currently unforeseen technical or physical difficulties will emerge and prohibit the realisation of its currently held potential, the electric sail technology is on its way to markedly improving our access to the solar system. For the electric sail, space is not empty, but a radially flowing plasma stream in which one can fly and manoeuvre almost at will and for arbitrarily long periods without propellant or other consumables .

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