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Recent advances in Electric Sail development

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Abstract. The electric solar wind sail is a newly invented way for using the solar wind dynamic pressure for providing thrust for a spacecraft. An electric sail spacecraft deploys long, thin, conducting tethers which are centrifugally stretched and kept in a high positive potential by a continuously working onboard electron gun. A positively charged wire embedded in solar wind plasma produces a Debye sheath around itself. Inside the sheath, the wire electric field repels solar wind protons so that they are deflected from their originally straight trajectories and thereby give some of their momentum to the wire. The solar wind dynamic pressure (on average 2 nPa at 1 AU distance) is about 5000 times weaker than the radiation pressure of the Sun, but since the wire's Debye sheath can be more than million times larger than the wire's physical diameter, the electric sail can be a mass-efficient method of spacecraft propulsion. If realised, the Electric Sail will be a significant and direct technical utilisation of a naturally occurring space plasma flow. We give an overview of the present status of the Electric Sail effort, reviewing its plasma physical basis and some technical aspects and potential applications. One application for the Electric Sail could be to implement the Interstellar Heliopause Probe, that is, a flight across the heliopause with less than 20-25 years of traveltime.

1. Introduction

The solar wind is a natural plasma stream which powers the aurora and other magnetospheric phenomena. The average solar wind density ~ 7.3 protons per cm^3 and speed $\sim$400 km/s amount to producing an average dynamic pressure of 2 nPa. Using this low density dynamic pressure as a source of spacecraft thrust was first considered in the 1980's when Zubrin and Andrews (1991) proposed the idea of magnetic sailing, that is, placing a magnet with large dipole moment on a spacecraft so that an artificial magnetosphere is generated which gets pushed by the solar wind. The magnetic sail would consist of a superconducting wire loop of tens of kilometres long which would carry high current. This arrangement is necessary in order to create a large enough dipole moment (current times loop area). A serious technical issues is then how to keep the wire loop in superconducting state without adding too much mass to the system. Unfortunately, cooling the wire by passive methods (coating) does not produce enough low equilibrium temperature for so-called high-temperature superconductors to work (Toivanen et al. 2004).

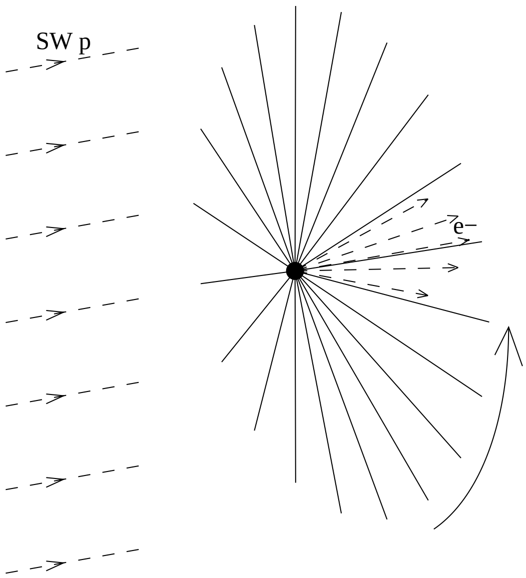

Figure 1. Schematic presentation of the electric solar wind sail deep-space propulsion method.

2. Electric sail

Since a magnetic field was found to be a technically difficult way of utilising solar wind momentum, perhaps a static electric field could be used. This idea was initially investigated by Janhunen (2004) and produced a theoretically promising result, although at that state it was not clear how one could implement the concept technically. This Electric Sail idea called for deploying tens of kilometres large wire mesh with $\sim$10 m spacing in the solar wind and keeping it stretched somehow against the solar wind pushing it. An onboard electron gun is used to keep the wires positively charged so that they repel solar wind protons, perturbing their trajectories and thereby tapping momentum from them. A breakthrough in this regard was achieved when it was realised that individual wires would work as well as a wire mesh and be far easier to deploy (Janhunen 2006). Centrifugal force could be used for deploying the wires and keeping them stretched (Fig. 1) as is done when deploying traditional wire booms in scientific spacecraft measuring the electric field by the double-probe technique (Mozer 1973). Micrometeoroids would break the thin $\sim$20 μm wires so that their lifetime would be too short in practice, but this could be avoided by using a multiline Hoytether construction for them (Hoyt and Forward 2001), Fig. 2. The multiline tethers can be made of thin aluminium or copper alloy wire by welding and stored on motorised, spinning reels from which they are deployed.

The question of how to guide the spacecraft is solved by inserting potentiometers between each tether and the spacecraft so that the potential of the tethers are possible to control individually. One can then use an algorithm rem-

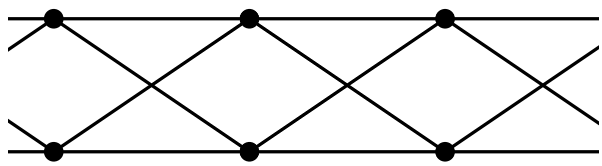

Figure 2. A four-wire Hoytether. Wire bonding sites are shown by dots.

iniscent to flying a helicopter to turn the tether spinplane and thereby alter the thrust vector obtained from the solar wind (Janhunen 2006). The maximum thrust vector alternation (coning angle) is estimated to be $\sim 30^{\mathrm{o}}$. This level of thrust vectoring is enough to make the electric sail very useful for many types of manoeuvring in the solar system (Mengali et al. 2008a,b).

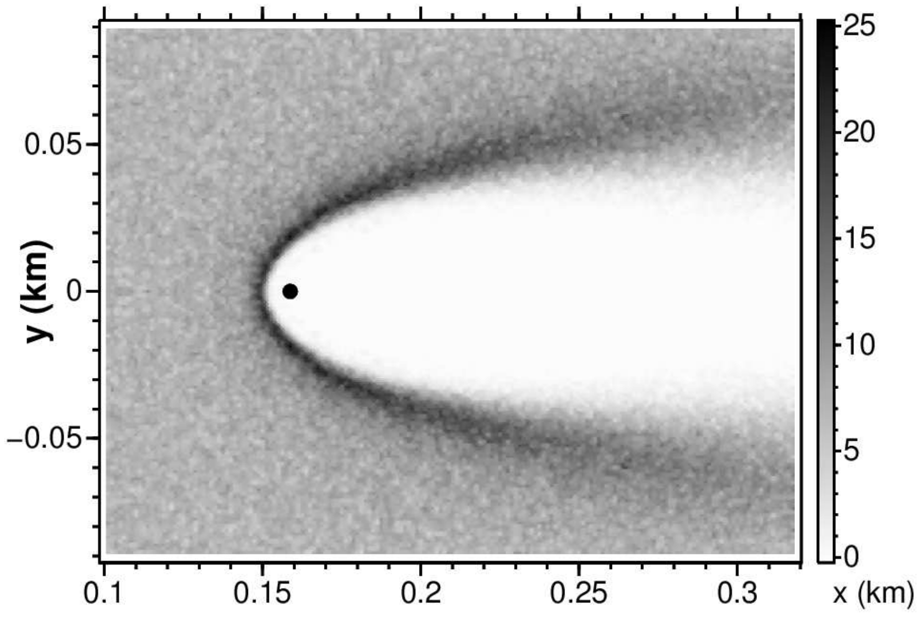

Figure 3. Particle-in-cell (PIC) simulation of solar wind (arriving from the left) interacting with a positively charged tether (dot). Proton density in cm^{-3} is shown in greyscale.

Self-consistent plasma simulations were performed to evaluate the level of thrust obtainable from a charged wire or tether embedded in solar wind flow (Janhunen and Sandroos 2007). The resulting thrust per unit length of tether is of the order of 50-100 nN/m in average solar wind conditions at 1 AU distance from the Sun when using a tether voltage of 15-20 kV relative to the plasma. The thrust is independent of any solar wind magnetic field because it is a result of the piling up of solar wind protons on the sunward side of the positively charged obstacle (tether). The force acting on the tether is the Coulomb force produced by a local antisunward electric field resulting from the proton pileup which pushes the positively charged tether in the antisunward direction (i.e., flow direction). Figure 3 shows a snapshot of particle-in-cell simulations of (Janhunen and Sandroos 2007).

The electric sail thrust decreases with radial distance r roughly as $1/r^{7/6}$ (Janhunen and Sandroos 2007). This exponent comes about because the thrust is proportional to square root of the electron pressure $P_e = n_e T_e$ and $n_e \sim 1/r^2$ and $T_e \sim 1/r^{1/3}$ according to observational studies (Sittler and Scudder 1980). Typical parameters of a full-scale electric sail might be number of tethers 50-100 and length of each tether 20 km, resulting in 2000 km total tether length which at 1 AU produces 0.1-0.2 N thrust. This thrust can give acceleration 0.5-1 mm/s^2 to a spacecraft whose total mass is 200 kg, of which the mass of the electric sail tethers is less than 10 kg and the whole electric sail propulsion package (solar panels, power system, electron gun, tether reels, controls and tether direction sensors) is 50-100 kg.

It might be possible to apply artificial heating of the electron population which is trapped by the electric field of the tethers to effectively increase the electron temperature and thereby increase the effective Debye length, electron sheath extent and thrust level (Janhunen and Sandroos 2007). In the best case the thrust per unit tether length could eventually become several times higher than the above estimates. While not easy to study theoretically because of the complicated 3-D geometry, electron heating should not be difficult to test observationally in space, if and when an electric sail test mission is flown.

At the moment of this writing (September 2008), the technology status of the electric sail is as follows [see also Janhunen (2008b)]. A suitable electron gun design has been created as well as the first version of a numerical simulator of spinning tether mechanics. Welding together of thin metal wires has been demonstrated in a way which can be scaled to automatic serial production. Ideas exist on how to reel the tethers reliably. Several straightforward ways of implementing the tether direction sensors needed by tether control algorithms have been identified. Plans for low-cost testing and measurement of electric sail propulsive thrust in solar wind crossing highly elliptic Earth orbit have been drafted. Concepts have also emerged on how to test and measure the single-wire electric sail effect in the laboratory.

3. Applications

The electric sail does not work inside planetary magnetospheres because the solar wind cannot enter them and it cannot be scaled to very high thrust level because at $\sim$ 100 km tether length the tensile strength and conductivity of commonly used metals start to present problems. However, other limitations for its use are now known to exist. The electric sail could be used for scientific planetary and asteroid missions with clearly smaller launch masses and therefore less cost than what is possible to achieve with other methods. It would be uniquely well suited for missions where one wants to keep the spacecraft on a non-Keplerian orbit indefinitely. Such non-Keplerian orbits could be used, e.g., for monitoring the solar wind between Earth and Sun at somewhere else than the Earth-Sun Lagrange L1 point or for orbiting the Sun with an off-ecliptic trajectory so as to gain a permanent view to its polar regions e.g. for helioseismology studies (G. Mengali et al., manuscript in preparation).

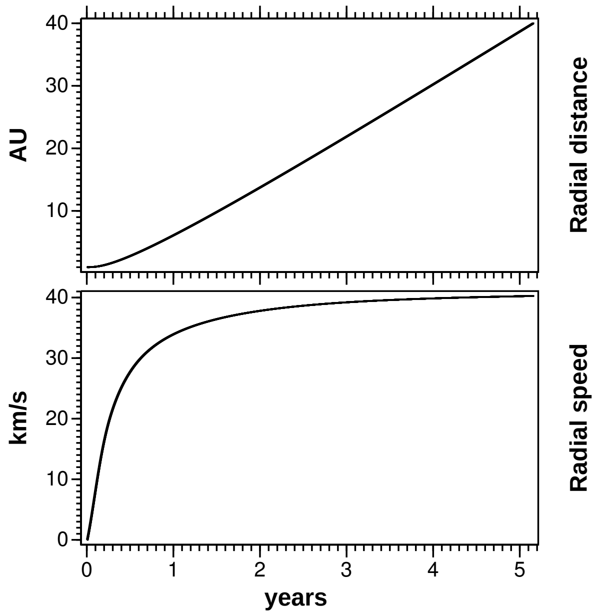

Figure 4. Radial distance and radial speed as a function of time in a sample calculation where a probe is propelled out of the solar system with the electric sail.

Last but not least, the electric sail could propel a small, lightweight spacecraft at high speed out of the solar system, to reach the boundary of the heliosphere and measure *in situ* the properties of the interstellar space (plasma, neutrals, dust, cosmic rays, magnetic field and waves) with less than 25 year traveltime. Figure 4 shows the result for 150 tethers of 60 km length each, 140 kg payload and 314 kg total mass. This mission is able to reach the heliopause at 200 AU in 24 years, assuming no boost from artificial electron heating (Section 2, last paragraph).

3.1. Using electric sail tethers as dust detectors

The electric sail tethers could probably be double-used to provide scientific measurements during the cruise phase, in addition to providing propulsion. The thrust obtained from the tethers gives information about the solar wind dynamic pressure. Perhaps more importantly, the long and charged tethers might also be usable as large-area dust detectors. When a dust particle hits a tether wire, it produces a small, expanding plasma cloud. Due to its conductivity, the plasma cloud locally modifies the capacitance of the tether and produces an electric signal which spreads to other parts of the tether. The hits of dust particles could therefore be detectable by accurately monitoring the potential of the tethers at the spacecraft end.

4. Conclusions

The electric sail is a newly invented method of potentially using the solar wind dynamic pressure for an important technical purpose, namely to produce propellantless thrust for a spacecraft and thereby enable exploration of the solar system with unprecedented flexibility and effectiveness. No major technical or scientific roadblocks or issues are currently known that would preclude the implementation of the electric sail. Omitting technical details, this paper is intended as providing a brief 'snapshot' of the present status of the electric sail invention.

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