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The E-sail will enable space travel and exploration with higher speed, better mass economy, and at less cost.

The Electric Solar Wind Sail (E-sail): Propulsion Innovation for Solar System Travel

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Pekka Janhunen

Sini Merikallio and
Pekka Janhunen

The electric solar wind sail (E-sail) is a novel propulsion concept that enables fast and economic space travel in the solar system. For propulsion it utilizes a continuous particle stream from the Sun (i.e., solar wind) by deploying long, electrically conductive charged tethers, which through electric force interaction are pushed by the charged solar wind particles, mainly protons (Janhunen et al. 2010). The E-sail thus provides constant thrust without fuel consumption, enabling more ambitious space missions than current technologies.

In this paper we explain how the E-sail works and review some advantages and challenges of the technology. We then describe some specific possibilities that it opens for solar system travel and exploration: asteroid mining of water and metal ores, support for a manned Mars presence, and the reduction of space debris.

The Electric Solar Wind Sail: Overview

The physical principle of the E-sail was discovered in 2004 (Janhunen 2004) and the technical concept in 2006 (Janhunen 2010a). The E-sail is currently

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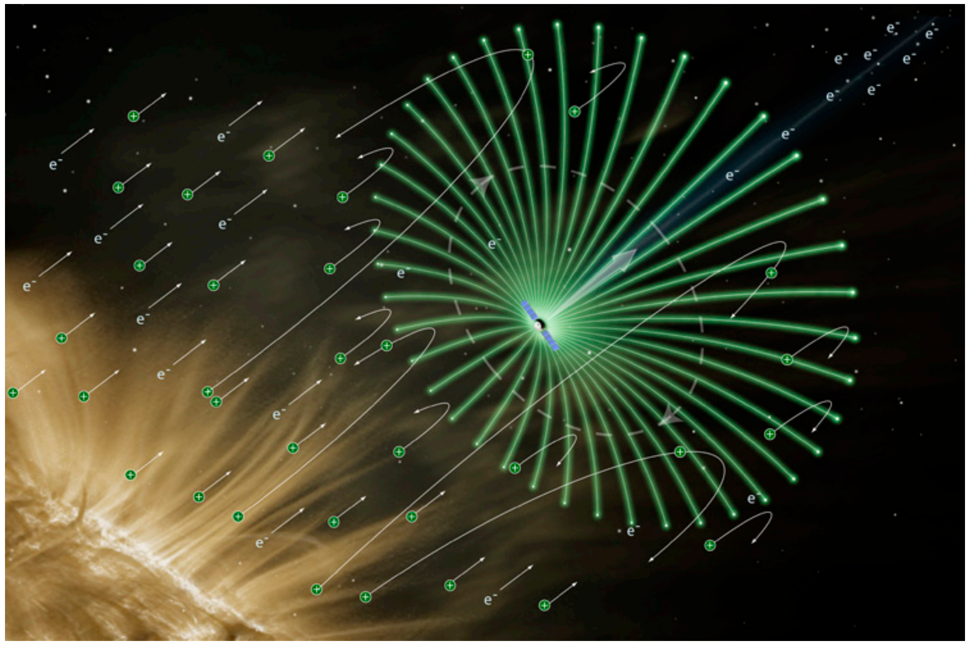

FIGURE 1 Artist's impression of an electric solar wind sail showing the spacecraft from which dozens of tethers (green) are deployed. The whole structure rotates in a cartwheel fashion around the spacecraft to keep the tethers centrifugally stretched. Also shown are solar wind particles (protons [+] and electrons [e−]) and their tracks affected by the electric charge of the tethers. The widths of the tethers and the size of the spacecraft are greatly exaggerated. Image by Alexandre Szames/Antigravite.

under development by the Finnish Meteorological Institute (https://www.electricsailing.fi/), NASA (the Heliopause Electrostatic Rapid Transit System, HERTS), and the European Space Agency (ESA; unpublished information).

The possible applications of the E-sail are numerous and promising. It may be used to support manned Mars flight (Janhunen et al. 2015), tow an Earth-threatening 3 million ton asteroid to a more benign track (Merikallio and Janhunen 2010), or deliver a probe to Mercury within a year without any gravity assists (Quarta et al. 2010). It will be ideal for a cometary rendezvous (Quarta et al. 2016), fast planetary entry probe (Janhunen et al. 2014), or asteroid investigations and sample returns (Quarta and Mengali 2010a; Quarta et al. 2014). Travelling toward the edges of the Solar system, the E-sail will make it possible to reach the heliosheath in 15 years (Quarta and Mengali 2010b), a feat that took the Voyager spacecraft 27 and 30 years (Decker et al. 2008; Stone et al. 2005).

How It Works

Thrust for the E-sail is produced by the interaction of charged tethers with solar wind particles: deflected by the electric potential surrounding the tethers, the particles transfer some of their momentum to the E-sail. Solar wind consists mainly of hydrogen and helium nuclei, and a comparable number of electrons. All of these contribute to the thrust of the E-sail, although most of the wind's momentum is a function of the more massive positively charged particles.

Figure 1 shows an artist's impression of an E-sail design; the size of the solar wind particles and spacecraft is hugely exaggerated, and the numbers of tethers, protons, and electrons are not representative. Wire tethers are deployed from the spacecraft and their extension maintained by centrifugal force due to rotation of the whole system.

The produced thrust of an E-sail is inversely proportional to its distance from the Sun, F α (1/r) (Janhunen et al. 2010), in contrast to the traditional photonic solar sail, for which F α $(1/r^2)$. The reason behind this is that, with greater distance from the Sun and a corresponding attenuation of the solar wind, the effective area around the charged E-sail wires increases. In other words, the impact of the wire potential extends farther from the sail as the plasma density dwindles, resulting in better performance than with photonic sails, for which the area of the sail stays constant.

Advantages and Challenges

The E-sail requires no propellant, and discharging of the wires by the solar wind thermal electrons can be counteracted by an electron gun powered by solar panels of a modest size. To enable maneuvering and trajectory control, the E-sail thrust can be steered by controlling the voltage of individual tethers and thus changing the plane of the E-sail's rotation. At 1 astronomical unit (au) of distance from the Sun, approximately 2,000 km of E-sail tether are required to produce 1 newton (N) of thrust. This can be achieved with, for example, 100 tethers, each 20 km long, spun out centrifugally from the spacecraft. There are no technological showstoppers in sight for producing an E-sail like this.

Space is dense with tiny dust particles that threaten the integrity of the E-sail. The risk of this micrometeorite impact is mitigated by weaving the E-sail tether into a 2–3 cm wide mesh-like structure of several wires so that isolated damages in constituent wires do not jeopardize the whole (Seppänen et al. 2011).

E-sail tethers need to be lightweight, conductive, resistant to micrometeoroid impacts, and able to withstand the tension and pull created by the centrifugal acceleration. The number and lengths of the tethers can vary. Their diameter is restricted by the need to limit surface area so as not to generate excessive thermal electron current. Such current would need to be cast off by the electron gun, the use of which decreases performance by increasing power system energy consumption.

Given mechanical (tensile strength, surface area, and weight) and availability (workability and industrial supply) requirements, the material currently under consideration for the tethers is 25–50 µm diameter aluminum alloy wire. Each kilometer of the tether weighs 10 g (Seppänen et al. 2013), resulting in a total tether mass of just 20 kg for a 2,000 km E-sail. The whole propulsion unit—including supporting structures, electron guns, power systems, and design margins—weighs 50–200 kg (Janhunen et al. 2013), far less than the weight of currently used propellant technologies. These features give the E-sail a significant advantage, especially in sample return missions and campaigns with many targets.

In the future, carbon nanotube technology might further enhance the E-sail by allowing the manufacture of longer, more lightweight yet durable and conductive tethers (Lee and Ramakrishna 2017; Monthioux et al. 2017).

Asteroid Mining: Rocket Fuel from Water

The E-sail will permit very low cost freight carriage in the solar system and thus enable affordable asteroid mining operations. It can be used for the transportation of mining equipment to asteroids and return of the mined products. One E-sail can make several trips to and from asteroids during its estimated 10 years of life. The technology can be easily multiplied and operations could proceed on several asteroids simultaneously.

In addition to relatively rich heavy metal ores in asteroids, our interest was raised by another reserve: an abundant number of water-bearing asteroids on near-Earth orbits (Elvis 2014) that can be readily accessed by the E-sail (Quarta 2014). The water can be separated from the asteroid material by using a two-part container (figure 2) in which the water is evaporated from the asteroid regolith in the first chamber and then pressure driven into the other chamber to condense into ice (Janhunen et al. 2015). The temperatures of the containers can be controlled by their surface albedos and infrared emissivities (i.e., coating by colored metal or white paint) or by using additional shades, heat pumps, or solar-powered heat elements. Once filled, the second container can be separated and hauled to the orbit of the Earth or anywhere else.

The resulting water can be split into hydrogen and oxygen, which form a potent spacecraft fuel when liquefied. This process requires electricity, which in space is readily available via solar panels. Currently all

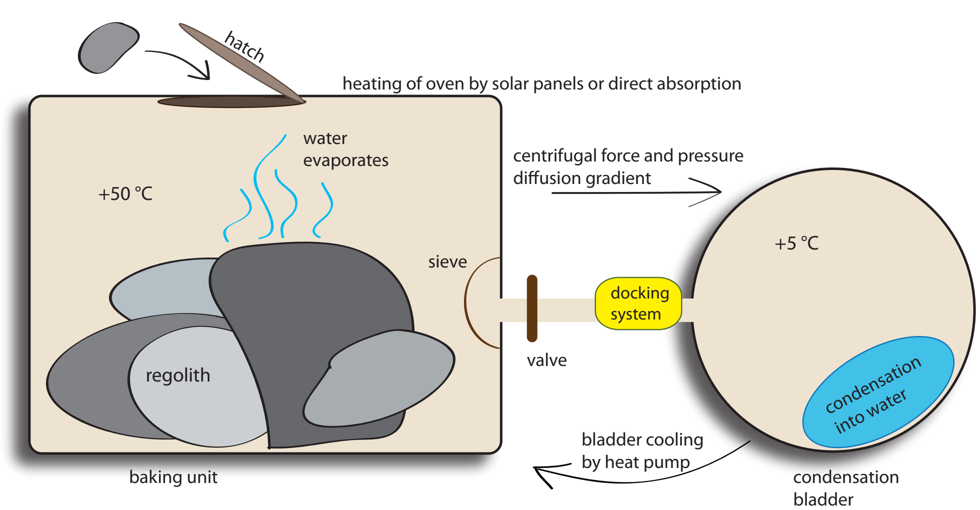

FIGURE 2 Illustration of a two-chamber unit that can be used in situ to extract water from asteroid regolith. Asteroid material is heated in the first chamber (left) so that water in the material vaporizes. Pressure gradient drives the water vapor into the second chamber (right), where it cools and condenses.

the fuel used by a spacecraft has to be lifted from the surface of the Earth and carried throughout the mission, requiring enormous fuel mass fractions. As an example, NASA's Juno mission to Jupiter, launched in 2011, had a liftoff mass of 3,625 kg, of which propellant accounted for more than 2,000 kg. We have come up with an approach to address this challenge, as described in the next section.

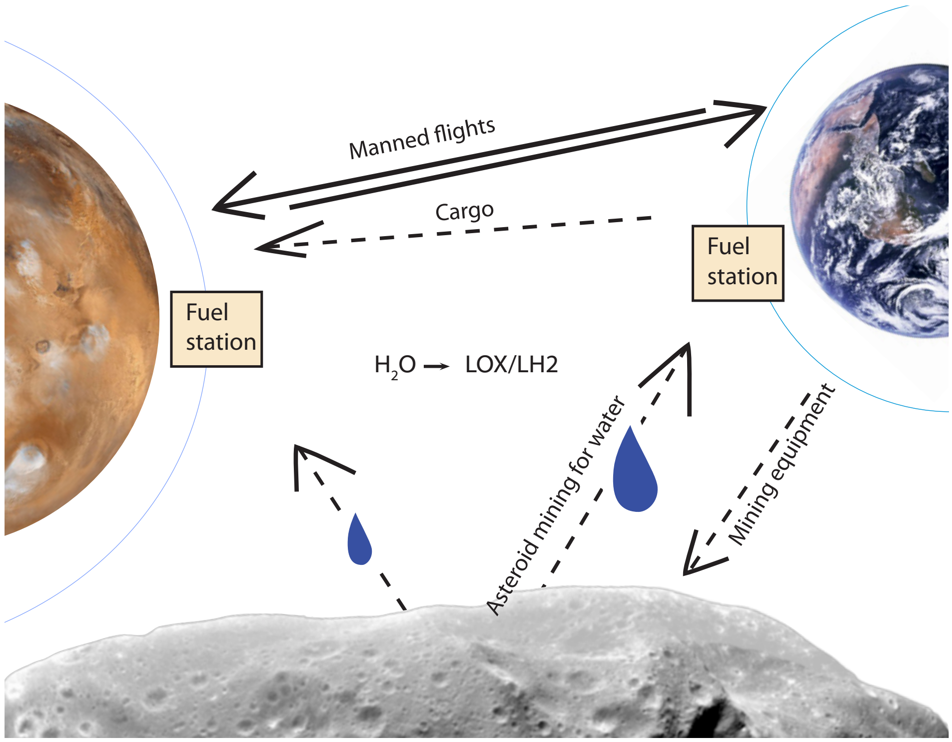

FIGURE 3 Schematic presentation of E-sail–facilitated Manned Mars Initiative (EMMI). At the heart of EMMI are asteroid mining operations: water from an asteroid (bottom) is transported to the planetary orbit and refined into liquid oxygen/liquid hydrogen LOX/LH2 fuel, which can be used for transportation to and from Mars. Pictures of the planets and asteroid surface are by NASA and not presented at scale.

EMMI: Manned Mars Flights Facilitated by the E-sail

In 2015 we proposed the E-sail–facilitated Manned Mars Initiative (EMMI; Janhunen et al. 2015). The idea behind EMMI is to mine water from asteroids and bring it to space-based "gas stations" in the orbits of Earth and Mars where it can be turned into rocket fuel. Such stations—with two on the way to/from Mars (figure 3)—can significantly facilitate manned Mars exploration in the near future.

Orbital fuel tank refills will allow for smaller tanks and thus considerably lighter spacecraft. Moreover, the spacecraft that lifts passengers and cargo from the surface of the Earth into orbit can be different from that which taxis between Earth and Mars. This will reduce the design requirements of both vehicles, as the one carrying passengers from Earth will not need to have capabilities for long-term life support, and the traverse shuttle will not need to survive atmospheric entry and launch vibrations and thermal loads. In addition, the availability of virtually free fuel on the Martian orbit will increase mission safety and enable speedy returns when necessary.

The asteroid-extracted water can also be used in life support as a source of potable water and even oxygen for breathing. Thick water layers around manned spacecraft and surface habitation modules can function as a radiation protection shield during the long traverses between Earth and Mars.

These spacecraft can be operated at a fraction of the current estimated Mars colonization costs: once in place, the EMMI is estimated to run on a budget comparable to the maintenance costs of the International Space Station (ISS). Moreover, launchers used for setting up EMMI can be of the same scale as those used for building the ISS.

Plasma Brake

A spin-off from the E-sail technology, a plasma brake, can be used to bring small satellites down from their orbits at the end of their viable life (Janhunen 2010b, 2014; Orsini et al. 2018). It can be attached to existing satellites and space debris with, for example, harpoons. Advantages of the plasma brake are low weight, potentially low cost, and high safety, as it can be operated without any volatiles, explosives, or inflammables.

A plasma brake payload is currently flying on a low Earth orbit (LEO) CubeSat mission, the Finnish Aalto-1, and waiting to be tested using a short (100 m)

E-sail tether (Kestilä et al. 2013). It is important to note that the relative speed of the spacecraft and ionosphere (~7 km/s) is not comparable to the solar wind speed (~400 km/s). However, as the tether voltage is varied in sync with the rotation of the satellite, the E-sail effect will be observable in changes in the CubeSat's rotational speed.

With Aalto-1, researchers are looking forward to verifying, and measuring, the E-sail force in real space environment.

Summary and Discussion

The design, production, and testing of electric solar wind sail prototypes are making good progress. E-sail technology could be available for solar system research within 10 years and, if successful, may revolutionize the way space travel and exploration missions are conceived and executed. The E-sail will enable affordable continuous manned Mars presence, considerably decrease travel times in the solar system, make it possible to tackle space debris, and help facilitate asteroid mining operations. The E-sail thus holds great promise for accessing both scientific and economical treasures of the solar system.

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