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POSSIBILITIES OPENED BY ELECTRIC SOLAR WIND SAIL TECHNOLOGY

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The electric solar wind sail (E-sail) is a new propulsion technology which was invented in 2006 and which is developed by a European consortium. First flight experiments will be performed onboard Estonian and Finnish CubeSats in 2013-2014, and our aim is to fly a solar wind test mission in 2015-2016. Once developed the E-sail will reduce travel times and launch costs to solar system targets and enable qualitatively new types of non-Keplerian orbit missions. The E-sail taps the momentum flux of the natural solar wind for spacecraft propulsion with the help of long, charged tethers. The system produces a thrust vector which points away from the Sun, but which can be turned at will within an approximately 30° cone and whose magnitude can be easily adjusted. According to estimations, a 100-200 kg E-sail propulsion unit produces ~1 N of thrust at 1 AU and the thrust scales as $1/r$ where r is the solar distance. Small devices are also possible and have lower mass, the mass scaling is not necessarily linear. Possible applications of the E-sail include multi-asteroid touring, Kuiper and other distant object flyby, giant planet atmosphere probe, 2-year sample return mission from Mercury, remote sensing of Earth, Sun and planets from non-Keplerian orbits and the generic idea of data clippers to support transportation of large data volumes from solar system targets. With these applications, the Electric Solar Wind Sail has the potential to qualitatively change space exploration and to unlock the scientific and economical treasures of the solar system.

I. INTRODUCTION

The electric solar wind sail (E-sail) is based on using the solar wind momentum flux for spacecraft propulsion with the help of positively biased long and thin metallic tethers [1,2]. The tethers are kept stretched by centrifugal force (Fig. 1) and the positive voltage (+15-40 kV) of the tethers is created and maintained by an onboard electron gun pumping out negative charge from the system to balance the thermal electron current gathered by the tethers from the solar wind plasma.

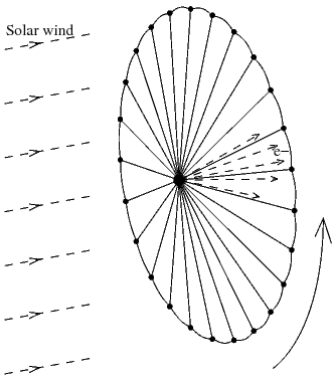

Fig. 1: Schematic figure of the spinning E-sail stabilised by auxiliary tethers and having a Remote Unit at the tip of each main tether

To prevent the tethers from colliding with each other the tether tips are connected by non-conducting auxiliary tethers. At the tip of each main tether there is an autonomous device (Remote Unit) commanded from the main spacecraft by a radio link. The Remote Unit contains two reels from which the adjacent auxiliary tethers are deployed as well as small thrusters for initiating the spin during deployment and possibly for adjusting the spin rate later during flight. For the Remote Unit thruster we have considered and are prototyping three options: cold gas thruster, field effect electric propulsion (FEEP) thruster and a small centrifugally stretched photon sail blade.

The main tethers used by the E-sail are made of three 25 μm and one 50 μm aluminium wire. The wires are bonded together using ultrasonic bonding at few centimetre intervals to create a few centimetres wide redundant and hence micrometeoroid-resistant tether [3]. Producing the tethers is the most particular and technically likely the most challenging part of constructing an E-sail.

A baseline full-scale E-sail would contain 100 tethers, each of which is 20 km long. Such a propulsive device would weigh 100-200 kg and would produce ~1 N thrust at 1 AU. The thrust scales as $1/r$ where r is the solar distance. The reason for such scaling (which decays slower with r than for photonic solar sails) is that the solar wind dynamic pressure which pushes the sail decays as $1/r^2$, but the plasma Debye length scales as r and for fixed bias voltage the virtual sail area seen by the solar wind proton flow is proportional to the total tether length multiplied by the solar wind plasma Debye length. The thrust vector direction can be controlled by ~30° in any direction by tilting the sail (because the thrust vector upon a single tether is along the component of the solar wind velocity perpendicular to

the tether, the thrust vector turns less than the sail's spin plane and hence larger than ~30º tilting of the thrust vector may not be feasible). The tilting of the sail's spin plane is accomplished by fine-tuning the tether voltages differentially in a synchronous way with the rotation and hence altering the solar wind forces acting on them. The magnitude of the thrust can be controlled freely between zero and a maximum value which depends on the hardware (tether length, maximum electron gun voltage and power etc.) and the instantaneous solar wind density and velocity. The thrust magnitude control is actuated by changing the current and voltage of the electron gun.

Because the E-sail thrust vector can be controlled in both magnitude and direction (although the latter in a somewhat limited way), it can be used for spiralling inward or outward in the solar system by tilting the sail to brake or accelerate the spacecraft's orbital motion around the sun, respectively. If the payload is lightweight, the outward spiralling motion can approach straight line motion i.e. rapid acceleration (which decays as ~1/r) out of the solar system. For inward motion, however, a natural limitation stemming from Kepler's laws applies that the minimum transfer time for moving to much closer solar distance than the starting orbit is proportional to the heliocentric period of the starting orbit (i.e., 1 year if starting from Earth and going inward, 12 years for moving from Jupiter distance to Earth, etc.). Hence the E-sail enables arbitrary and rather fast transfers in the inner solar system as well as fast one-way trip to the outer solar system (how fast, depends on the E-sail size and payload mass). A speedy return from the outer solar system is not possible with a pure E-sail, however; although in applicable cases a fast return may be possible using a gravity assist manoeuvre with a giant planet [4].

I.I E-sail technical development status

As of this writing (September 6, 2012), the longest continuous piece of main tether that has been manufactured is 120 m. The tether factory is automatic and designed to be scalable to at least one kilometre continuous length. Cold gas and FEEP versions of the Remote Unit technical readiness level five (TRL-5) models have been designed and their construction is ongoing. Opening the tether from the reel has thus far always been successful when it has been tested after tether production with realistic tether tension pull force. Different ways of reeling the tether have been explored and were not found to be critical for a successful unreeling.

The ESTCube-1 1U CubeSat mission is planned to be launched in March 2013. ESTCube-1 will demonstrate deployment of 10 m long tether in polar LEO orbit and will measure the expectedly micronewton scale E-sail force acting on it. The tether voltage is 500 V. The Aalto-1 3U CubeSat mission will fly in 2014 and will host an improved version of the E-sail experiment (in addition to other scientific instruments unrelated to the E-sail) containing a 100 m long tether.

II. E-SAIL APPLICATIONS

We present example applications for E-sail propulsion technology. Our emphasis is on near-term, low to moderate cost missions and on missions of paradigm shifting nature. The treatment of generalisations is also exemplary rather than exhaustive.

II.I Multi-asteroid touring

Many asteroids are hard to reach with chemical rockets and ion engines. This is due to their low mass providing no gravitational slingshot effects and often significant orbital eccentricities and inclinations of the orbits. Because the E-sail can provide continuous thrust whose duration is limited only by physical breaking down of the equipment, it is very well suited for asteroid missions. In the main belt, an E-sail mission could make close inspection of 5-8 asteroids per year in flyby mode or 1-3 in rendezvous mode. By rendezvous we mean settling to the asteroid's orbit for prolonged close inspection. The E-sail would also be suited for asteroid sample return, asteroid mining and even deflection of orbits of Earth-threatening asteroids [5].

II.II Outer solar system object flybys

The E-sail can boost small and moderate mass payloads at high speed to outer solar system. Because of high travel speed, only flyby is possible in practice. The outer solar system hosts a large and growing number of objects (for example Kuiper belt objects, Centaur objects and Jupiter Trojan asteroids) whose detailed study is difficult without flyby missions. One possibility would be to build a number of relatively small and identical flyby probes, each destined to a different outer solar system target. Such probes could be launched flexibly either together or as piggybacks with other missions: since the E-sail is not delta-v limited, any escape orbit launch can be used for launching any E-sail probe regardless of its target in the solar system.

II.III Giant planet atmosphere probes

Similarly to boosting a probe to the outer solar system, the E-sail can also send a probe into atmospheric entry course of a giant planet. The Galileo probe made accurate measurements of the Jovian atmosphere which constrained the models of solar system evolution. There would be a high scientific value in getting similar measurements also from the other three gas giant planets. The E-sail could be used to send four probes (or five, if we also want to cover Titan) to the giant planets to measure their atmospheres with

identical instruments. For reduced development costs the probes could be identical, or alternatively the heat shields could be tailored for each planet to leave more room for the instruments. Again, the probes could be launched either together or as piggybacks with any escape orbit launch.

Table 1 summarises the travel time from Earth to each of the giant planets using 1 N E-sail for different payloads. The 'payload' is here defined to be the total mass minus the assumed E-sail subsystem mass of 100 kg.

	Jupiter	Saturn	Uranus	Neptune
500 kg	1.0	1.7	3.1	4.6
1000 kg	1.6	2.8	5.3	8.0
1500 kg	2.5	4.6	9.6	14.9

Table 1: Travel time in years to the giant planets using 1 N E-sail for three payload masses

II.IV Sample return from Mercury

An E-sail capable of 1 mm/s² acceleration at 1 AU and having thrust scaling as $1/r$ can take a spacecraft to Mercury rendezvous in 9 months [4]. A return trip would take similar time. To apply this capability to Mercury sample return might require relatively large total mass (maybe of order 2 tonnes) because of a required lander with retrorockets, etc., and consequently one E-sail might not be enough to carry everything if a speedy mission is desired. Would this be the case, the carried items could be divided between two E-sails e.g. in the following way. One E-sail spacecraft goes to Mercury's orbit, jettisons the sail and lands on the surface by braking rockets (delta-v 4.3 km/s due to escape speed). It takes a small sample and puts it in a return capsule which is launched to low Mercury orbit by a chemical rocket (delta-v 3 km/s). Another E-sail spacecraft arrives from Earth and releases a separate catcher spacecraft which makes a rendezvous with the sample capsule in Mercury orbit and propels itself back to the E-sail mothercraft for rendezvous and docking. The second E-sail then returns to Earth's vicinity and grounds the sample e.g. by separating the capsule in a hyperbolic reentry trajectory.

If an E-sail with 1 mm/s² characteristic 1 AU acceleration is used, the sample return from Mercury takes less than two years. For a given E-sail size, allowing longer mission time would increase the maximum carried mass approximately linearly. For operation in the thermal environment encountered at Mercury, the presently developed aluminium E-sail tethers [3] might have to be replaced by other materials such as copper. Extra development work required by such wire material change would be expected to be straightforward.

II.V Non-Keplerian orbits

Because the E-sail can produce continuous thrust, it can be used to "float" a spacecraft against a weak gravity field on a non-Keplerian orbit [6]. Potential applications of such orbits are numerous. In Earth's vicinity one could stay on the sunward side of the Earth-Sun Lagrange L1 point to monitor the solar wind, yielding a longer warning time for space weather forecasting than the present ~1 hour of Lagrange point probes SOHO and ACE. The same region of space could also be used as a vantage point for monitoring Earth's vicinity for new mini-moons and other near-earth asteroids: from Earth or Earth orbit such observations are difficult because they would involve optical telescope viewing in the sunward direction. Also, a probe could be set to orbit the sun in an orbit which is artificially lifted above the ecliptic plane. From such orbit there would be a permanent view to sun's polar region which would be good for helioseismological observations. As a planetary science application, a probe could be lifted above Jupiter-Sun Lagrange L1 point. Such probe could monitor the solar wind incident on Jupiter's magnetosphere while having a view to Jupiter's polar aurora. The role of the solar wind as driver for Jupiter's aurora is not clear and to resolve the question requires simultaneous measurements of the planet's aurora and the solar wind in front of the planet. A similar science case and reasoning applies to the other giant planets as well.

II.VI Data clippers

Besides for returning physical samples from heavenly bodies, the ability of the E-sail to move relatively freely in the solar system could be utilised by returning science data stored in memory. The rationale for such E-sail "data clippers" is as follows [7]. For a given type of mission, the amount of resulting science grows with the amount of data returned. Building instruments that produce a lot of data (high resolution images of planetary surfaces, for example) is not difficult nowadays. More and more, the bottleneck in the amount of science that can be done is simply the bandwidth of the data downlink. While bigger space and ground segment antennas, larger transmitting power and employment of higher radio or even optical frequencies can be used to increase the bandwidth, doing so is challenging without increasing the mission's total budget. At the same time, memory technology is rapidly improving and flash memories will soon allow compact onboard storage of so large datasets that downloading them from large distances by contemporary data links would no longer be feasible.

After recording the data, the E-sail data clipper could travel back to Earth's vicinity for downloading the data over a relatively short distance using inexpensive ground segment antenna. This is a powerful, generic

concept which can potentially be applied in many different missions in many different cost categories and variants. In the low end cost category, a small CubeSat sized spacecraft could explore e.g. the asteroids and return to Earth's vicinity at the end with its memory full of data, downloadable by low-cost ground segment facilities.

The E-sail combined with the data clipper idea could alter the present paradigm of solar system science by allowing large amounts of data to be returned from distant targets while having low costs in the space segment, ground segment and operations.

III. CONCLUSIONS

We presented examples applications of E-sail technology.

The E-sail is well suited for all kinds of asteroid missions because it allows in principle an unlimited delta-v capability so that the spacecraft can e.g. visit as many asteroids as one wants during a mission (in a bit similar way as a Mars rover proceeds from rock to rock, for example). For the outer solar system, a straightforward way to use the E-sail is to employ it as a booster for one-way missions, effectively superseding expensive direct chemical boost and slow Earth-Venus gravity assist manoeuvring options. The E-sail boosting could be used basically by any outer solar system probe, including Kuiper belt flyby and giant planet atmospheric entry probes. Sample return from Mercury would be enabled by the E-sail, and the mission duration would possibly be less than 2 years. The E-sail also enables various non-Keplerian orbits in the vicinity of Earth and other planets. We mentioned applications of such orbits to space weather, near-earth asteroid finding and Jupiter and other giant planet auroral science. Last but not least, the powerful concept of data clippers was discussed which utilises the E-sail's capability to return back to Earth's vicinity. Data clipper E-sail missions could carry back potentially large amounts of scientific data from distant targets at low cost, without the expenses of large ground antennas.

For reducing costs of solar system missions, the following aspect of the E-sail is worth noting: Any E-sail probe, regardless of its target, can be launched with any escape orbit launcher, either alone or together with other E-sail or traditional probes. This is in marked contrast with the present paradigm where we typically use the launch vehicle's upper stage for producing the needed interplanetary kick (extra delta-v beyond escape orbit). The present paradigm is expensive and inflexible because it does not allow probes destined to different targets (Mars, Jupiter and asteroids, for example) to share the same launch.

It is probably no exaggeration to conclude that the E-sail has a potential to change the paradigm of solar system exploration in the future. The keys are high efficiency and performance, a new type of launch flexibility and (in many cases) the possibility to return home with samples or large data volumes. The E-sail can be enabling technology both in challenging high-end missions as well as in the low-cost category.

Our future activities include the ESTCube-1 and Aalto-1 CubeSat missions in 2013 and 2014, respectively, as well as preparations for a solar wind test mission.

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