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CONSIDERATIONS OF ELECTRIC SAILCRAFT TRAJECTORY DESIGN

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ABSTRACT

Outgoing optimal (minimum time) trajectories for electric sail spacecraft are calculated. The study includes trajectories for reaching a distance of $100\ \mathrm{AU}$ from the Sun, escape trajectories, and missions aimed at obtaining a flyby with Uranus or Neptune. The results are parameterized as a function of the electric sail acceleration at $1\ \mathrm{AU}$. Using an electric sail of modest complexity, the attainable flight-times are quite attractive. Because no gravity assists are used, the mission trajectories investigated do not suffer of complications such as rare launch windows. Missions with coast arcs (in which the propulsion is switched off at some point) are also analyzed, because they might be needed for outgoing missions which include the Pioneer anomaly study.

Keywords: Electric sail; Mission design; Trajectory optimisation

1. INTRODUCTION

The electric sail is a new propulsion concept [1,2] whose present status is described in a companion paper "The electric sail - a new propulsion method which may enable fast missions to the outer solar system". The subject of this paper is to show the results of trajectory calculations to the outer solar system using the electric sail model described in Ref. [2]. The results are obtained using an indirect approach whose details are described in Ref. [3].

2. TRAJECTORY RESULTS

We first consider the problem of reaching a distance of $100\ \mathrm{AU}$ from the Sun as quickly as possible using a given electric sail configuration. The electric sail performance is parametrised by its mean propulsive acceleration $a_\oplus$ at a distance $r = r_\oplus \simeq 1\ \mathrm{AU}$, that is, in the proximity of the Earth. Fluctuations in the solar wind that cause deviations from the mean value are not taken into account. Their effect is heavily smoothed out because of the long flight time and, furthermore, one can compensate for them by active tuning of the spacecraft's electron gun which is used to generate the system voltage. Due to the complexity of an accurate solar wind modeling, the impact of its fluctuations on the mission performance could be investigated using a Monte-Carlo approach. However, such an analysis is beyond the scope of this paper

At a generic distance r from the Sun, the electric sail acceleration is given by [2]

$$a = a_\oplus \left(\frac{r_\oplus}{r}\right)^{7/6} \tag{1}$$

When optimal trajectories are sought, it is important that the sail plane may be tilted in such a way that the thrust force vector forms an angle α with the radial solar wind direction (the Sun-spacecraft line, see Ref. [3]). The largest practically usable angle α_{max} is not accurately known, even if it is estimated to be in the range

a_{max} ▪ $[20, 30]\,deg$. The thrust force on a tether is always along the component of the solar wind velocity vector which is perpendicular to the tether. A simple geometric argument shows that the thrust angle a is approximately equal to one half of the sail plane inclination angle. We refer to a as the cone angle.

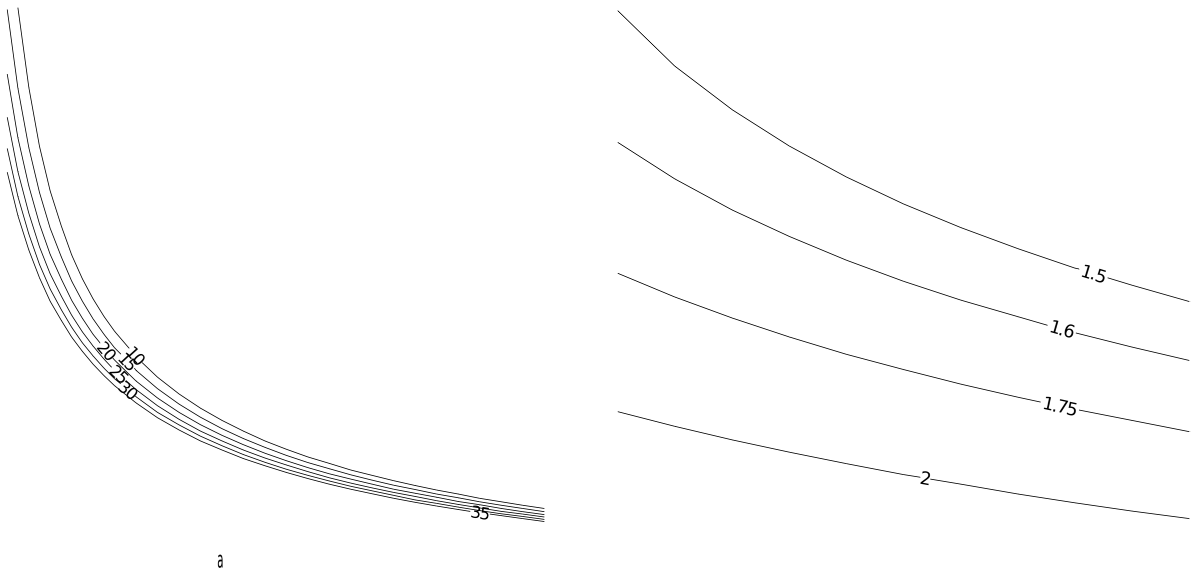

Fig. 1. Left: Optimal flight time to $100\ AU$ as a function of the electric sail acceleration at $1\ AU$ for different values of maximum cone angle a_{max}. Right: Case of small a_{max}, with roles of a_{max} and acceleration interchanged in the plot.

Figure 1 shows the flight time to $100\ AU$ as a function of the basic acceleration $a_{\bullet}$ for different maximum cone angles a_{max}. The trajectory starts from $1\ AU$ and goes directly outward, without planetary and/or photonic gravity assists. For $a_{\bullet} > 3\ mm/s^2$ the cone angle has a minor effect. For $a_{\bullet} < 3\ mm/s^2$ its effect is quite modest.

For some scientific experiments, especially for accurate trajectory monitoring aimed to test the Pioneer anomaly, a continuous propulsion along the whole trajectory may represent a problem. Figure 2 shows a version of Fig. 1 where the electric sail is completely switched off (or jettisoned) at Uranus heliocentric distance $19.12\ AU$. Accordingly, for 80% of its journey until $100\ AU$ the spacecraft is coasting freely. The flight times grow rather significantly for small values of $a_{\bullet}$, but the differences with respect to the continuously propelling case of Fig. 1 become negligible when $a_{\bullet} > 4\ mm/s^2$.

We now consider the escape problem, i.e. the question of how long it takes to reach an open trajectory that will permanently exit the Solar System and where this point is reached.

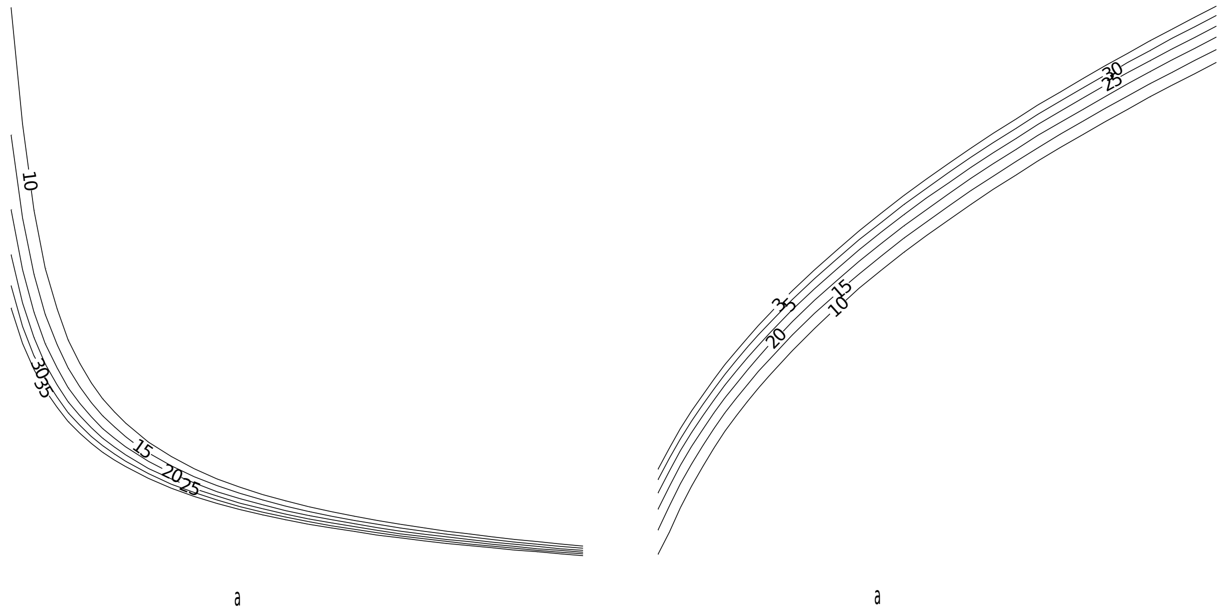

Fig. 2. Left: Same as left panel of Fig. 1, but with electric sail turned off (or jettisoned) at Uranus distance $19.12\ \mathrm{AU}$. Right: Final hyperbolic excess velocity.

Figure 3 shows the time necessary to reaching escape conditions for different basic accelerations $a_{\bullet}$ and different maximum cone angles a_{max}. The dependence of the time on the basic acceleration level is very steep: for $a_{\bullet} > 2\ \mathrm{mm/s^2}$ an escape trajectory is reached in less than approximately 2 years depending on the cone angle, but when $a_{\bullet} = 1\ \mathrm{mm/s^2}$ it may take up to 10 years.

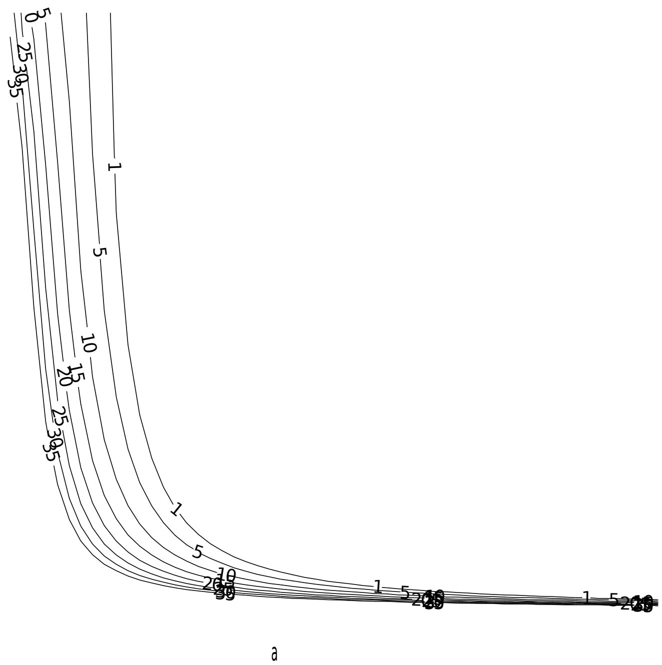

Fig. 3. Time to reach an escape trajectory from the Solar System as a function of electric sail basis acceleration $a_{\bullet}$ and for discrete values of the maximum cone angle a_{max}.

Figure 4 shows the solution of the hyperbolic escape problem using a concrete electric sail thrust model where the (copper) wire thickness is fixed at $20\ mm$ and the payload fraction h (that is the ratio payload mass/total launch mass) is varied continuously [2,3]. Rough (but hopefully reasonable) values for the electric sail engineering parameters such as the electron gun mass have been derived from existing flight-tested hardware.

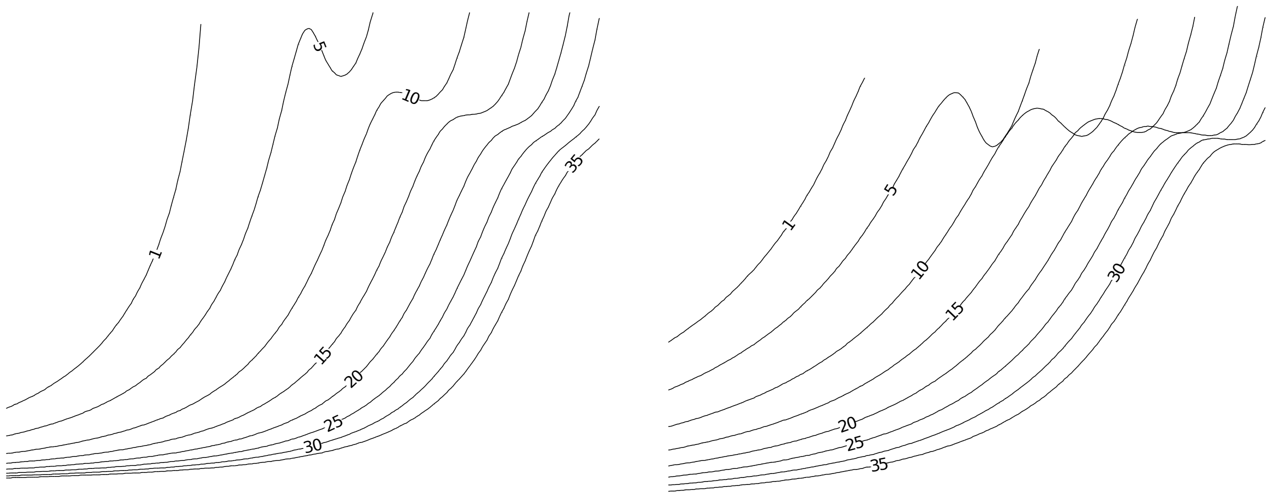

Fig. 4. Left: Time to reach the escape trajectory from the Solar System using a complete thrust model as a function of the payload fraction h for $20\ mm$ wire diameter and for discrete values of the maximum cone angle a_{max}. Right: Sun-spacecraft distance (in Astronomical Unit) where escape condition is reached.

Finally, in Figure 5 we consider the problem of making a flyby of one of the outer giant planets, Uranus or Neptune. For example, even for a reasonably modest basic acceleration $a_{\bullet} = 2\ mm/s^2$, the minimum flight times to Uranus and Neptune are less than 4 and 6 years, respectively. The relative shortness of these flight times along with the fact that there is a new launch window every year (since no gravity assists are used) could make these trajectories particularly attractive. Similar flyby trajectories could be easily constructed for other outer Solar System targets such as Kuiper belt objects.

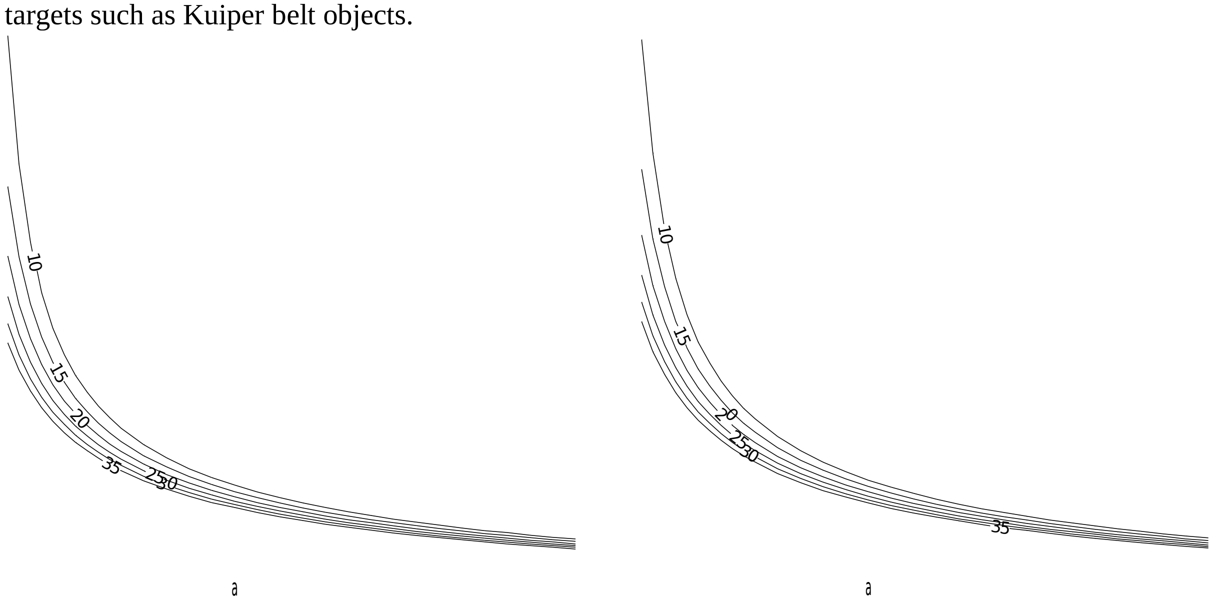

Fig. 5. Optimal time to reach Uranus (left) and Neptune (right) flyby, as a function of electric sail acceleration at $1\ AU$ and for a few values of the maximum cone angle a_{max}.

3. CONCLUSIONS

Even reasonably modest types of electric sail seem to be capable of providing interesting performance. This result comes without the need to wait for rare launch windows (like when using chemical or ion propulsion with planetary gravity assists) and also without a necessity to make a near-Sun flyby. A near-Sun flyby would increase also the electric sail's final speed; to what extent, it remains to be studied. The electric sail thrust decays with radial distance as $1/r^{7/6}$, which is slower than for the solar sail $1/r^2$. This gives an electric sail benefit for outgoing missions relative to solar sails. The fact that the thrust does decay, however, also means that if needed the propulsion can be switched off (e.g., electric sail tethers jettisoned) at some point, which is probably of importance to studies of the Pioneer anomaly.

4. ACKNOWLEDGMENTS

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5. REFERENCES

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