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ELECTRIC SAIL OPTION FOR COMETARY RENDEZVOUS

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Abstract: This paper discusses a preliminary study of the transfer trajectory toward the comet 67P/Churyumov-Gerasimenko for a spacecraft whose primary propulsion system is an Electric Solar Wind Sail. The use of a propellantless propulsion system with a continuous thrust is theoretically able to simplify the transfer trajectory by avoiding the need of intermediate flyby maneuvers. The problem is addressed in a parametric way, by looking for the potential optimal launch windows as a function of the thruster performance. The study is completed by a mass breakdown analysis, for some mission scenarios, based on the actual payload mass of the spacecraft Rosetta.

Keywords: Electric Solar Wind Sail, comet rendezvous, mission towards 67P/Churyumov-Gerasimenko

1. INTRODUCTION

The recent soft-landing of the robotic lander Philae [1] on the nucleus of the comet 67P/Churyumov-Gerasimenko (67P), is the realization of an ambitious and advanced space mission in which a cometary rendezvous, first in the history of the spaceflight, was completed on August 2014 by the European space probe Rosetta. Through in-situ measurements [2], Rosetta and its lander Philae could give interesting answers to some important questions raised by the international scientific community since many decades, such as to investigate both the origin of comets and the relationship between cometary and interstellar material. These results could be of crucial importance to obtain additional information about the origin of the Solar System and, more important, of life on Earth [3].

In terms of propellant consumption, a direct transfer towards comets using a chemical propulsion system is usually a very demanding option due to the high orbital eccentricity of these celestial bodies, which is often combined with a considerable orbital inclination with respect to the Ecliptic plane (for example, the eccentricity of the comet 67P is 0.641 and its orbital inclination is 7 deg). A typical solution to save propellant mass is to plan a mission including one or more intermediate flyby maneuvers. This approach, however, introduces a substantial complication in the transfer trajectory and causes a significant increase of the flight time due to the constraints related to the planetary ephemerides. For example, in its ten years long journey to the comet 67P, Rosetta exploited three gravity assists with Earth (on 2005, 2007, and 2009), and one with Mars (on 2007).

An interesting option for saving time and propellant mass, and for avoiding the need of complex flyby maneuvers, is offered by the use of a continuous-thrust, propellantless, propulsion system such as a photonic solar sail or the more recent Electric Solar Wind Sail (E-sail). Even though the strength of the E-sail effect (Coulomb drag effect on charged tether or wire) has not yet been measured in space, laboratory measurements by Siguier et al. [4] around a charged wire in a flowing plasma resembling LEO conditions indicate [5] that the size of the forming electron sheath is in good agreement with earlier theoretical predictions [6]. On a technical side, a 1 km long sample of E-sail tether has been already produced [7], a lightweight Remote Unit compatible with a solar distance of 0.9-4 au is at TRL 4-5 [8] and a 100 m long E-sail tether will fly onboard Aalto-1 CubeSat, which is scheduled to be launched into a LEO orbit in the autumn of 2015 [9].

The aim of this paper is to analyze an E-sail based mission scenario towards comet 67P by taking into account some important characteristics of the Rosetta spacecraft. In particular, the same payload mass of Rosetta's mission has been considered to facilitate a direct performance comparison, but the same results are also applicable, at least qualitatively, to other Jupiter's families of comets. The transfer problem is addressed in a parametric way by looking at the minimum flight time to fulfill the comet rendezvous as a function of the spacecraft characteristic acceleration a_c. The latter is defined as the maximum propulsive acceleration when the Sun-spacecraft distance is one astronomical unit. For a fixed value of a_c, the minimum flight time is initially obtained assuming an ephemeris-free model, that is, by neglecting the relative position of the celestial bodies along their own orbits. Not only this model provides the minimum transfer time (compared to the problem in which the actual planetary ephemerides are taken into account), but it also allows the optimum starting position along the Earth's heliocentric orbit to be found, as well as the optimum arrival position along the comet's heliocentric orbit.

Using the results obtained in the ephemeris-free model, the minimum-time rendezvous problem is then addressed by taking into account the ephemerides constraint for a time interval that includes the launch dates corresponding to the optimal relative positions of the celestial bodies. Some representative values of a_c are used to compare the simulation results (including a preliminary mass breakdown analysis) with the real flight times of the Rosetta mission.

2. SIMULATION RESULTS WITH AN EPHEMERIS-FREE MODEL

The optimal orbit-to-orbit heliocentric transfer is first analyzed as a function of the spacecraft characteristic acceleration in the range $a_c \in [0.15, 1]\,\mathrm{mm/s^2}$. It is assumed that the spacecraft is subjected to the E-sail thrust and to the gravitational effect of the Sun only, thus neglecting any perturbation from other celestial bodies. During the coasting phases, the motion is therefore Keplerian, whereas the spacecraft is initially assumed to track an Earth's heliocentric orbit.

In the numerical simulations, the orbital elements of Earth+Moon barycenter and comet 67P are taken from the JPL's ephemerides database, corresponding to the date of 10 August 2014, whose Modified Julian Date (MJD) is 56879. Figure 1 shows the minimum flight times, corresponding to the ephemeris-free model, as a function of the spacecraft characteristic acceleration. Note that a flight time of about ten years, comparable to that actually required by Rosetta to complete its rendezvous mission with the comet 67P, is obtained using $a_c \simeq 0.18\,\mathrm{mm/s^2}$, i.e. a moderate value of the spacecraft characteristic acceleration.

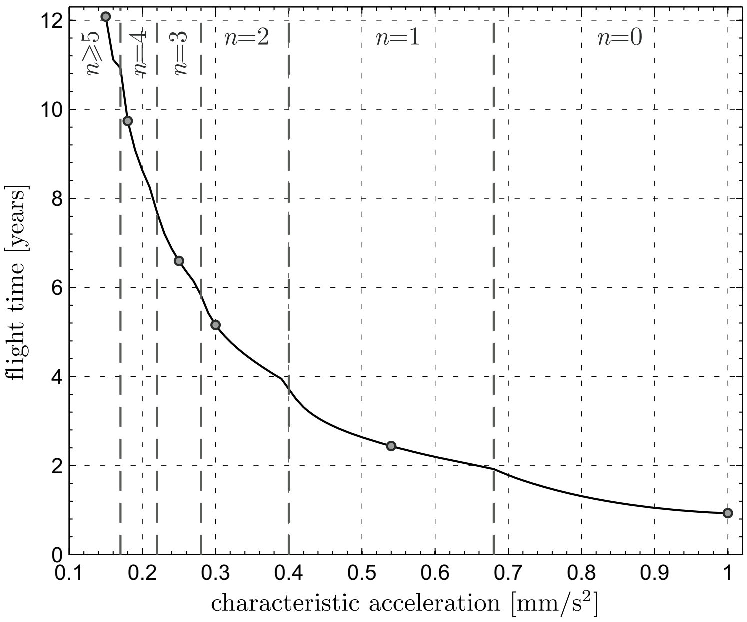

Fig. 1: Minimum flight time as a function of the spacecraft characteristic acceleration in an ephemeris-free model. The circles correspond to the trajectories illustrated in Fig. 3.

The usefulness of an ephemeris-free model, when compared to a ephemeris-constrained model, is not only confined to the reduced computational time it requires. In fact, an ephemeris-free model gives interesting information about the characteristics of the transfer orbit as, for example, the number n of spacecraft's full revolutions around the Sun during the transfer. In this sense, Fig. 1 shows that a reduction of the spacecraft characteristic acceleration implies a substantial increase of the number n, especially when the value of a_c falls below $0.3\,\mathrm{mm/s^2}$. For this reason, it is useful to ideally classify the transfer orbit within three possible families as a function of the value of parameter n.

The first type of transfer, which will be referred to as "rapid" transfer, is characterized by the fact that the comet 67P is reached before completing a (single) full revolution around the Sun ($n = 0$). This type of transfer is obtained with $a_c > 0.68\,\mathrm{mm/s^2}$, and it requires a flight time less than two years (or even less than one year if $a_c \geq 0.94\,\mathrm{mm/s^2}$). An example of rapid transfer trajectory with a flight time of about 340 days is drawn in Fig. 2, which shows the ecliptic projection of the optimal trajectory when $a_c = 1\,\mathrm{mm/s^2}$. Note that all of the transfers studied in this paper are fully three-dimensional even if, for the sake of visualization, the figures show the ecliptic projection of the orbits.

On the other hand, a transfer that requires a number of revolutions $n \geq 3$ is referred to as "slow" transfer. Taking into account Fig. 1, such a transfer is obtained when $a_c < 0.28\,\mathrm{mm/s^2}$. In this case the flight time is greater than six years and its length quickly increases as a_c is decreased. The slow transfers are characterized by involved spacecraft trajectories in which the propulsion system is switched off or on many times, so that a number of coasting arcs take place.

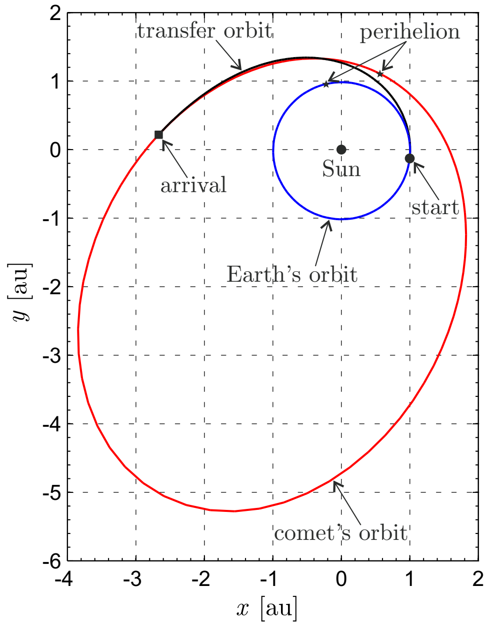

Fig. 2: Optimal transfer orbit when $a_c = 1$ mm/s^2 in an ephemeris-free model (ecliptic projection).

Finally the intermediate case, in which $n = \{1,2\}$, is referred to as "moderate" transfer. In this case the flight times are between two and six years, and the spacecraft characteristic accelerations are roughly in the range $a_c \in [0.28, 0.68]\,\mathrm{mm/s^2}$. The analysis of those trajectories is much simpler than in the case of slow transfers, partly because the number of coasting phases is small (i.e. not exceeding two or three). To summarize, the shape of the spacecraft trajectory (and, in particular, the value of n) is strongly dependent on the value of a_c, as is clearly shown in Fig. 3.

It is interesting to note that, according to Fig. 3, the optimal transfer in the ephemeris-free model is characterized by a final true anomaly (on the comet's heliocentric orbit at rendezvous) which is nearly independent of the value of a_c. Such a true anomaly value is about $\nu_f \simeq 140\,\mathrm{deg}$ which, taking into account the comet's orbital data, implies that the Sun's distance at rendezvous is roughly $r_f \simeq 4\,\mathrm{au}$. This is an useful result, because one important constraints of Rosetta mission is related to the rendezvous distance [10], which must take place at a Sun's distance less than 4.4 au. Another mission constraint [10] states that the spacecraft shall support full science operation at a distance not less than 3.25 au from the Sun. From this viewpoint an orbital rendezvous (see the black squares in Fig. 3) that takes place when the comet is going away from its perihelion, is advantageous. The flight times that are summarized in Fig. 1 should be considered as a first approximation only of the actual results that can be found by taking into account the real position of the celestial bodies (i.e. the Earth at departure and the comet at rendezvous) along their own orbits. In this sense, these results represent the starting point for a more accurate analysis with ephemeris-constrained data, which is the subject of the next section.

3. Simulation results with an ephemeris-constrained model

When the actual positions of the two celestial bodies along their own orbits are taken into account, the optimal launch date and the corresponding optimal trajectory can be calculated with the following approach. For a given value of spacecraft characteristic acceleration, the ephemeris-free model provides the minimum time

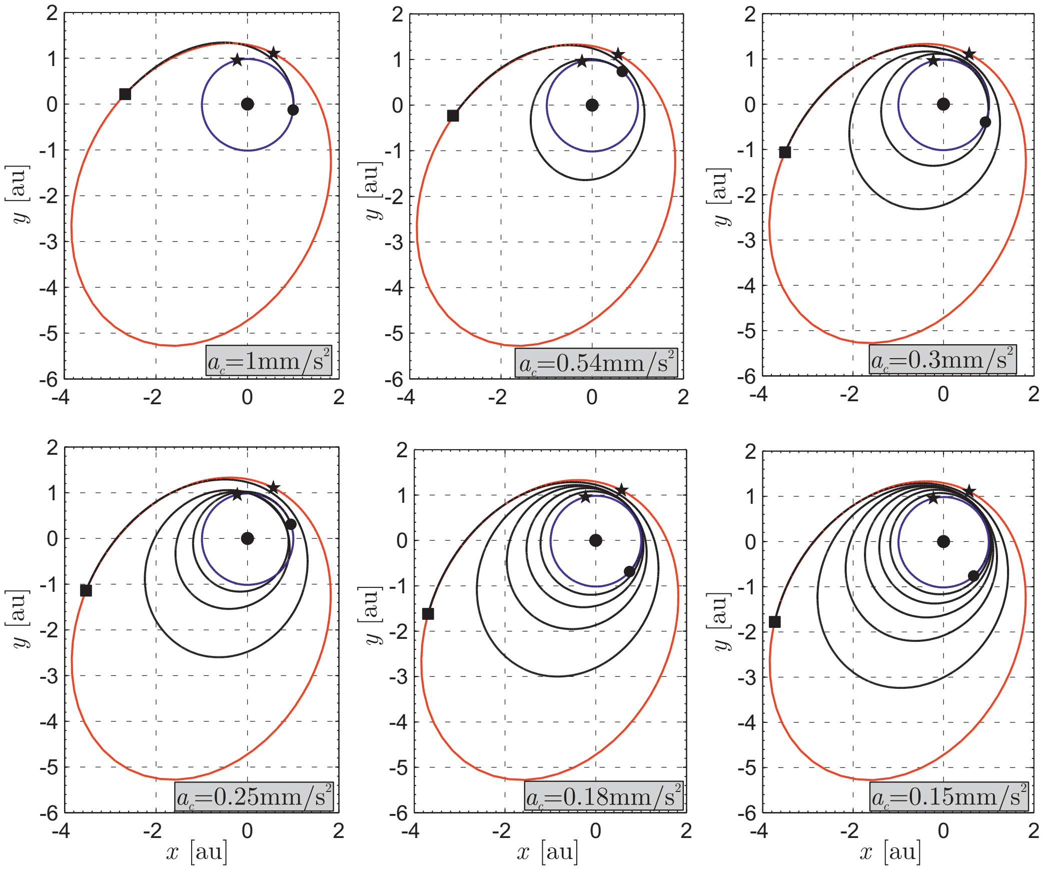

Fig. 3: Optimal transfer orbits in an ephemeris-free model for some values of a_c (ecliptic projection).

interval (Δt) and the spacecraft true anomaly along the Earth's heliocentric orbit at departure (ν_i) and along the comet's orbit at rendezvous (ν_f). Using the orbital data corresponding to the position of the two celestial bodies on 10 August 2014, and solving a classical Kepler problem, it is possible to find the best departure date at which the actual position of the two celestial bodies is closest to the spatial configuration of the ephemeris-free model. For a near-term mission, the best departure date has been calculated within a time range of ten years, from the 1st January 2015 to the 1st January 2025. When the best departure date is known, the constrained minimum flight time is found starting from the actual Earth's position at the departure date, and enforcing the final spacecraft position to coincide with the actual position of the comet at the rendezvous date. This method may be applied to all values of the spacecraft characteristic acceleration within the range used in the preliminary analysis with the ephemeris-free model. Three different mission scenarios will now be discussed.

3.1. Slow transfer

In this first case study, the spacecraft characteristic acceleration is assumed to be $0.2\,\mathrm{mm/s^2}$. The minimum flight time in an ephemeris-free model is 3149 days (about 8.63 years) and, during the transfer, the spacecraft completes four revolutions around the Sun. In particular, the topology of the transfer trajectory is close to that illustrated in Fig. 3 with $a_c = 0.18\,\mathrm{mm/s^2}$. When the constraint due to ephemerides is taken into account, the best departure date is 14 October 2020. In that case the flight time is 3164 days (only 0.5% greater than the minimum, ephemeris-free, value), and the rendezvous takes place at a Sun's distance of 3.44 au, when the true anomaly is about 130 deg. This transfer scenario is illustrated in Fig. 4.

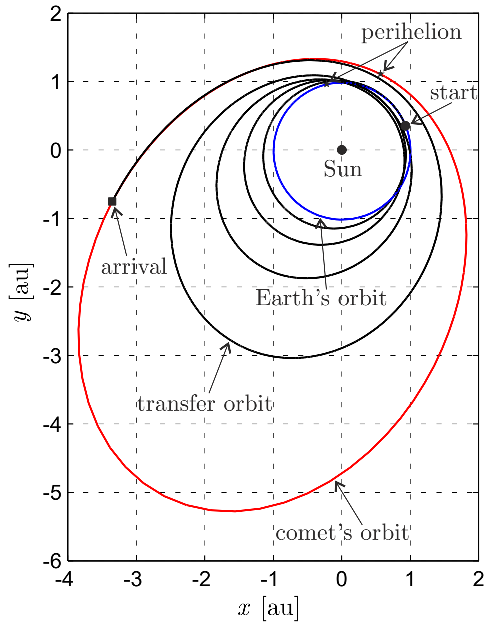

Fig. 4: Optimal transfer trajectory when $a_c = 0.2$ mm/s^2, departure date 14 October 2020 (ecliptic projection).

The use of a propulsion system with a continuous thrust allows a certain flexibility to be obtained in the departure date. In this respect, a possible shift of the departure date, compared to the nominal value of 14 October 2020, implies an increase of the total flight time. Nevertheless, such an increase is rather small, in percentage terms, even if the departure date is either advanced or delayed by some weeks. This is confirmed by the results of Fig. 5, which shows the sensitivity of the flight time as a function of the departure date, using a time interval of three months around the nominal date of 14 October 2020. For example, by delaying the departure date of one and half month (thus starting on the 1st December 2020), the minimum flight time would be 3225 days, which means a transfer time increase less than 2% with respect to the optimal value of 3164 days. Figure 5 also shows the distance from the Sun at rendezvous r_f as a function of the departure date. Note that the value of r_f is always less than the maximum distance (4.4 au) enforced by the mission requirements for Rosetta [10]. In this case the final Sun's distance displays a more pronounced variation with the departure date. For example, a departure date on 1st December 2020 corresponds to a Sun's distance of 4.04 au, with an increase of about 17% with respect to the value that can be obtained when the nominal departure date is selected.

3.2. Moderate transfer

In this case the value of the spacecraft characteristic acceleration is set equal to 0.4 mm/s^2. The ephemeris-free model states that the minimum flight time is 1357 days, i.e. about 3.71 years. Accordingly, the ephemeris-constrained model suggests an optimal departure date on 15 July 2019. In that scenario the comet 67P can be reached within a flight time of about 1359 days, nearly coinciding with that of the ephemeris-free model. The optimal trajectory completes one revolution around the Sun, as is shown in Fig. 6.

In terms of performance sensitivity to the departure date, Fig. 7 shows that a delay of few weeks in the departure date corresponds to a flight time increase of about one hundred days. An earlier launch, instead, does

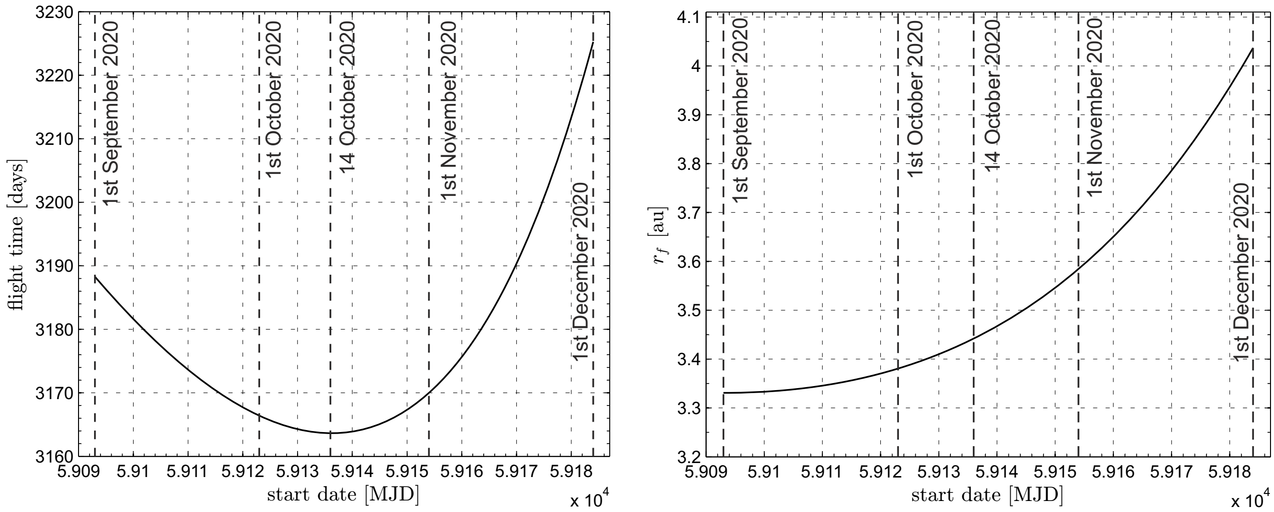

Fig. 5: Minimum flight time and Sun-spacecraft distance at rendezvous when $a_c = 0.2$ mm/s^2.

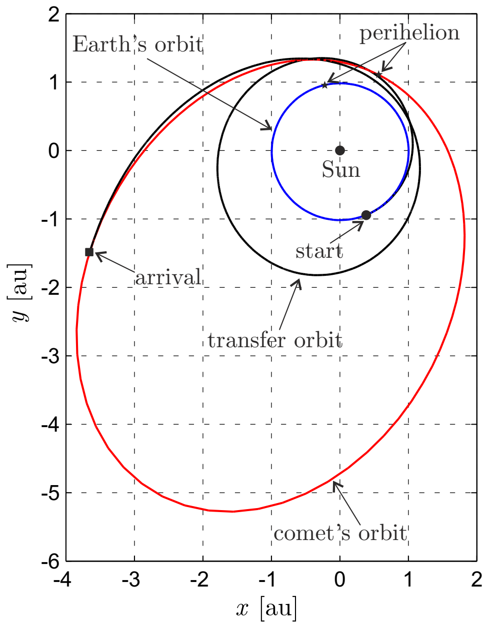

Fig. 6: Optimal transfer trajectory when $a_c = 0.4$ mm/s^2, departure date 15 July 2019 (ecliptic projection).

not affect substantially the total flight time, because a departure on 1st June 2019 implies, for example, that the comet 67P is reached in less than 1400 days. Moreover, the Sun-spacecraft distance at rendezvous is between 3.9 au and 4.6 au. In particular, the distance corresponding to the best departure date is $r_f \simeq 3.95$ au, a value compatible with the mission requirements of Rosetta. The constraint on the final distance tends to reduce the admissible launch window. Indeed, Fig. 7 shows that a departure beyond 15 August 2019 implies a final distance from the Sun exceeding the limit of 4.4 au.

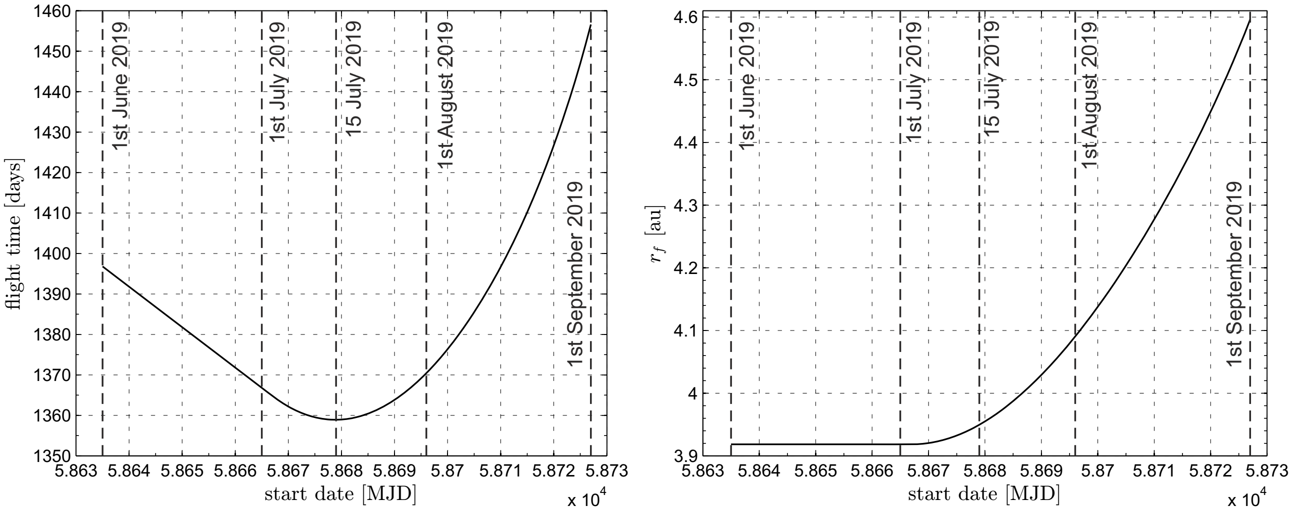

Fig. 7: Minimum flight time and Sun-spacecraft distance at rendezvous when $a_c = 0.4$ mm/s^2.

3.3. Rapid transfer

For the rapid transfer case, the example value of the spacecraft characteristic acceleration is $a_c = 1\,\mathrm{mm/s^2}$. Adopting the same nomenclature used for a photonic solar sails [11], $a_c = 1\,\mathrm{mm/s^2}$ is referred to as "canonical" value, as it is the reference value used to quantify the mission performance in a given mission scenario. Since the ephemeris-free model provides a minimum flight time of 340 days, and a true anomaly at departure (arrival) of about 250 deg (112 deg), the previously described procedure states that the best departure date is on 3 September 2021. Starting from that date, the flight time with ephemerides constraint is 393 days, which corresponds to an increase of about 15% compared to the ephemeris-free model. A high value of a_c implies that the flight times are moderate (about one year) and the introduction of a constraint on the ephemerides has a strong (percentage) effect on the total flight time. The transfer trajectory is drawn in Fig. 8, which is similar to that obtained for an ephemeris-free model and illustrated in Fig. 2.

The parametric analysis of the sensitivity to the departure date is shown in Fig. 9, which comprises the data involving a time range of two months around the nominal departure date. The figure shows the existence of a marked sensitivity to the departure date (in particular for a delayed launch), which implies a flight time increase of more than one hundred days. In all of the analyzed cases the Sun's distance at rendezvous is always less than the maximum value of 4.4 au, as is shown in Fig. 9. Moreover, the rendezvous always takes place when the comet is moving away from the Sun, that is, when the true anomaly is less than 180 deg. In the optimal case the final distance is $r_f \simeq 2.85$ au and the corresponding true anomaly is $\nu_f \simeq 116$ deg.

4. Spacecraft main characteristics

Having found the transfer performance in terms of optimal flight times and the best departure dates as a function of the value of a_c, it is now interesting to analyze the main characteristics of the E-sail based spacecraft. To this end, a preliminary spacecraft mass breakdown analysis was performed using a parametric and semi-analytical model, originally discussed in Ref. [12], whose main input performance parameter is given by the spacecraft characteristic acceleration. In particular, the auxiliary tethers are assumed to be made of 7.6 μm thin kapton, whereas the nominal tether voltage is set equal to 25 kV. For comparative purposes, the same payload

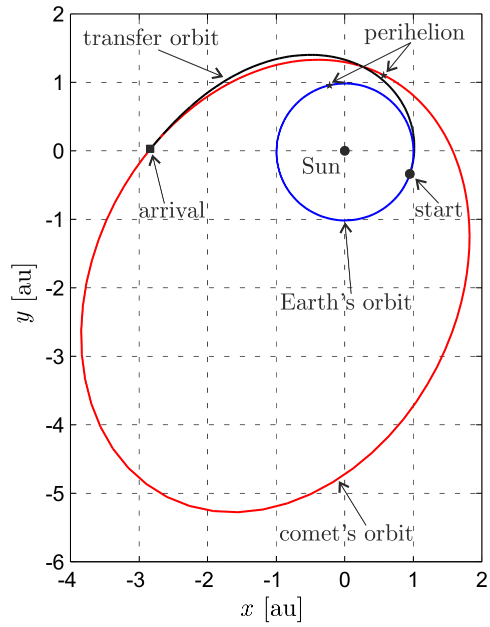

Fig. 8: Optimal transfer trajectory when $a_c = 1$ mm/s^2, departure date 3 September 2021 (ecliptic projection).

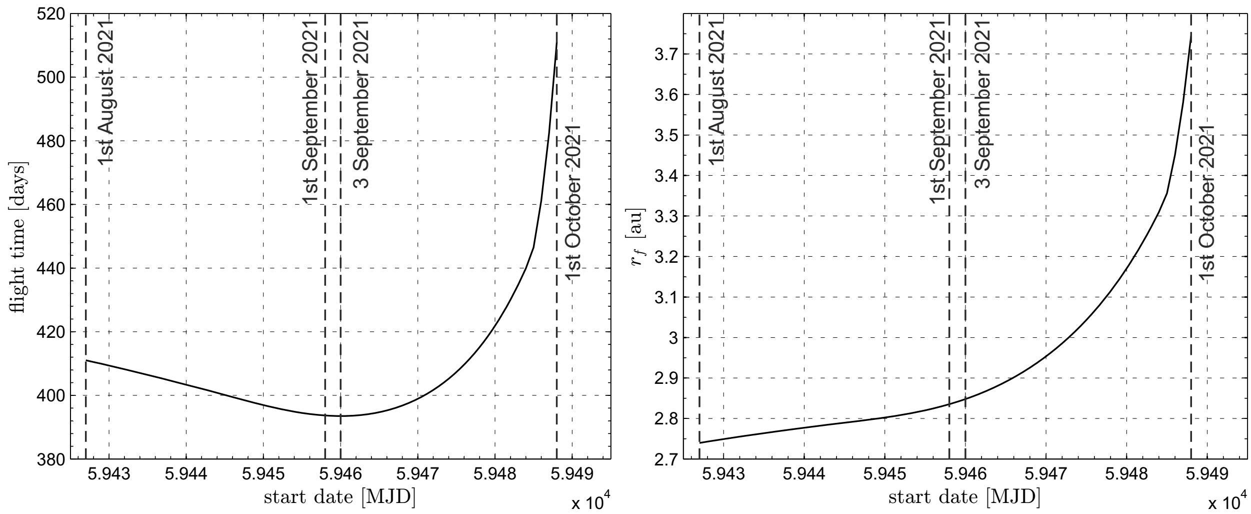

Fig. 9: Minimum flight time and Sun-spacecraft distance at rendezvous when $a_c = 1$ mm/s^2.

mass used in the Rosetta spacecraft is assumed, that is, a total payload mass of 265 kg, comprising 165 kg of science payload and 100 kg of lander [13].

Taking into account the results from the previous section, the representative values of spacecraft characteristic acceleration are chosen to be $a_c = \{0.2, 0.4, 1\}\,\text{mm/s}^2$, which correspond to the cases of slow, moderate and rapid transfers. The results are summarized in Table 1 for mission scenarios with and without the lander.

For each pair of payload mass and spacecraft characteristic acceleration, Table 1 shows the required total E-sail tether length L_{tot}, the total mass of the spacecraft including a 20 % of uncertainty margin, the number of tethers N, the length of each tether L_{tether}, and the optimal ephemeris-free flight time. Table 1 shows that, even in the challenging case in which the lander is included and the spacecraft characteristic acceleration is $1\,\text{mm/s}^2$,

Tab. 1: Spacecraft main parameters for some representative mission scenarios.

payload mass [kg]	$a_c\,[\mathrm{mm/s^2}]$	flight time [years]	$L_{\mathrm{tot}}\,[\mathrm{km}]$	$m\,[\mathrm{kg}]$	N	$L_{\mathrm{tether}}\,[\mathrm{km}]$
	0.2	8.6	242	701	24	10.1
265	0.4	3.7	506	733	36	14.1
	1.0	0.9	1412	819	60	23.5
	0.2	8.6	154	446	20	7.7
165	0.4	3.7	325	470	28	11.6
	1.0	0.9	919	533	48	19.1
	0.2	8.6	33	96	8	4.1
30	0.4	3.7	73	105	12	6.1
	1.0	0.9	225	130	24	9.4

a solution exists with a reasonable value of in-flight total mass of about 820 kg. Also, a spacecraft without a lander and a mission with a moderate value of flight time (for example, 3.7 years), requires a total mass of 470 kg and about 28 tethers of 11 km length each. Finally, Tab. 1 summarizes the main spacecraft characteristics for a hypothetical mission with a (small) payload mass of 30 kg. Note that a scientific payload mass value on the order of 10 kg – 20 kg is consistent with other studies for a rendezvous mission with a near-Earth asteroid using a solar sail-based spacecraft [14]. In that case, a rapid transfer would require a total in-flight mass of 130 kg and 24 tethers of 9.4 km length each.

5. Conclusions

The capability of providing a continuous propulsive acceleration, for a prolonged time interval and without the need of any propellant, makes an E-sail an interesting option for missions toward minor celestial bodies such as the comets. An analysis of a mission scenario involving a rendezvous mission to the comet 67P/Churyumov-Gerasimenko has shown that an E-sail based spacecraft with medium-low performance is able to reach this celestial body with transfer times comparable to that of the European Rosetta mission. Moreover, significantly shorter flight times can be obtained with an E-sail of medium-high performance. In particular, assuming a scientific payload mass of 30 kg and a spacecraft characteristic acceleration of about $0.4\,\mathrm{mm/s^2}$, the optimal ephemeris-free flight time is 3.7 years and the propulsion system requires 12 tethers of 6.1 km length each. In that case, the total in-flight mass is 105 kg including a 20 % margin. This preliminary mission analysis proofs that, as soon as the E-sail will be successfully developed to a flight readiness level, it will become a very useful tool in performing rendezvous missions to comets (such as comets of Jupiter's family), including (but not limited to) missions similar to that currently performed by Rosetta.

An interesting extension of this work involves the possibility of widening the space mission, including an Earth return phase. As a matter of fact, since no propellant is required by the spacecraft, the only condition for the return phase fulfillment is that the vehicle has to wait until a suitable reentry window opens. Such a mission extension would theoretically guarantee not only an in situ analysis of the comet, but also the possibility of transferring to Earth some samples taken from the comet's surface.

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