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Rapid Reconnaissance and Characterization of Potentially Hazardous Asteroids and Comets with Solar Sailcraft

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Abstract

Rapid reconnaissance and characterization of asteroids and comets is one of the stated priorities for planetary defense in the 2023 decadal survey on planetary science and astrobiology [1]. Traditional asteroid reconnaissance spacecraft like OSIRIS-REx, Lucy, or Psyche have years long development cycle to launch, extensive post-launch trajectory arrival times, and cost hundreds of millions of dollars. With short warning times of a few years or less, that does not leave much time to develop a spacecraft, fly the mission, and collect necessary characterization data to inform mitigation activities and disaster planning accordingly. We propose the use of an articulated vane solar sail spacecraft or sailcraft to accomplish an asteroid or comet reconnaissance mission as a flyby or rendezvous that would be faster to respond and cheaper to develop and operate compared to traditional spacecraft missions.

Sailcraft provide propellant-free propulsion that can reach high velocity and short arrival times to inclined orbits that chemical or low thrust propulsion spacecraft cannot achieve in some cases. This new type of fractionated solar sail has been under development for the past decade has improved attitude control and less structural mass than large sheet sailcraft designs. The flexibility of the mission design space is significant given the low overall sailcraft mass, allowing a constellation to be built and launched into station-kept orbits at several distances from the Sun for optimized rapid deployment toward a newly discovered asteroid or comet. The sailcraft would perform routine scientific tasks at their respective heliocentric stations and configure into a rapid reconnaissance mission at the discovery of a new object.

In this paper we investigate several planetary defense rapid reconnaissance mission scenarios using simulated Earth impact asteroid and comet trajectories with short warning times [2] to determine how effective a sailcraft mission architecture is for timely flybys or rendezvous. We also discuss current sailcraft development, cost, and realistic added mission objectives to maximize the science return.

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Keywords: Planetary Defense, Solar Sail, Intercept, Rendezvous, Reconnaissance

Outline:

Introduction:

One of the goals in the 2018 National Near-Earth Object Preparedness Strategy and Action Plan is the development of technologies and designs for rapid-response NEO reconnaissance missions [1]. A capability to rapidly launch a spacecraft to rendezvous with or fly by a NEO and perform reconnaissance is the only clear way to provide detailed and accurate information for an effective deflection or disruption mission. The report also identifies the necessity of assessing technologies and concepts for rapid-response NEO reconnaissance missions, evaluating the capabilities of current and projected domestic and international launch vehicle infrastructure to support planetary defense missions, and creating plans for the development, testing, and implementation of NEO reconnaissance mission systems.

To address these goals and promote establishment of operational rapid NEO reconnaissance capabilities, a series of three workshops held in 2023 were chartered to understand NEO reconnaissance requirements, identify technology gaps that would limit NEO reconnaissance performance, and develop future mission concepts to demonstrate, exercise, improve, and maintain NEO reconnaissance capabilities [2]. Key features of an incoming asteroid or comet that determine the associated scenario-dependent NEO characterization/reconnaissance requirements were identified in the first workshop. The most important information highlighted in this workshop was the need for rapid return of information on the object's orbit and possible impact location, mass, size and composition, and rotation rate [3].

The second workshop identified technology gaps and potential concepts for NEO flyby reconnaissance performance [3]. Among the topics discussed were instrumentation and measurement capabilities, navigation and CONOPS, spacecraft design and development, and integration, build, testing, and launch. An emerging tech gap identified in the workshop was how will a flyby recon mission be accomplished repeatedly and consistently while ensuring rapidity and cost effectiveness. The third workshop pointed out technology gaps and potential concepts for NEO rendezvous reconnaissance performance. It identified studies to investigate mission design requirements, concurrent characterization and mitigation, and flight system and trajectory design [3].

The Origins, Worlds, and Life 2023 2032 Planetary Science and Astrobiology Decadal Survey [4] recommended that a rapid-response, flyby reconnaissance mission targeting a near-Earth object (NEO) population of ~50- to 100-m-diameter objects, which pose the highest probability of a destructive Earth impact, be given the highest priority. "Such a mission should assess the capabilities and limitations of flyby characterization methods to better prepare for a short-warning-time NEO threat".

A candidate object is Asteroid 2024 YR4, which reached Level 3 on the Torino Scale in early 2025. The object is estimated to be about 40 to 90 meters wide [5], and on 18 February 2025 it reached a 3.1% chance of impacting Earth on Dec. 22, 2032 [6]. Later observations reduced the chance of Earth impact in 2032 to negligible. 2024 YR4 is moving farther away on its outbound path around the Sun and should remain observable through early April 2025, after which it will be too far and too faint to be detected from the ground [5]. The asteroid will continue its orbit around the Sun and will safely return to Earth's neighborhood in 2028. Although the additional measurements have practically ruled out an impact in 2032, 2024 YR4's orbital characteristics have provided an opportunity to answer the Decadal Survey's rapid recon recommendation [4] and address some of the NEO Warp workshop's findings [1].

The estimated impact probability evolution of 2024 YR4 kicked off an international response to the impact threat by the UN affiliated International Asteroid Warning Network (IAWN) and the Space Mission Planning Advisory Group (SMPAG) [7]. IAWN and SMPAG agreed in 2017 on criteria and thresholds for impact response actions, including issue of a warning of predicted impacts exceeding a probability of 1% for all objects characterized to be greater than 10 meters in size [8]. Asteroid 2024 YR4 met these criteria. IAWN would have recommended terrestrial preparedness planning had 2024 YR4's impact been predicted to be within 20 years, probability of impact was greater than 10%, and the object was estimated to be greater than 20 meters in size. Asteroid 2024 YR4 does not meet all these criteria (specifically, the 10% impact probability threshold was not met – the probability peaked at 3.1% and dropped to a negligible level).

This study investigates mission scenario options that provide a swift response to inspect a potentially hazardous asteroid (PHA) using modern solar sailcraft capability. There are several mission trades to consider from the perspective of launched versus strategically deployed sailcraft or PHA flyby versus rendezvous or the timeliness of the sailcraft to reach a PHA based its orbital geometry.

Sailcraft that are launched from Earth directly or as a rideshare toward the target asteroid/comet will receive a velocity boost that will place the sailcraft in heliocentric space depending on the launch energy or C3. At that point, the solar sail will deploy to leverage the photon acceleration to arrive at the target and either flyby or rendezvous with the target to start reconnaissance and characterization.

A rendezvous mission will be much more taxing to achieve, having to match both position and velocity at a given date rather than just the position for a flyby. There is also consideration for sailcraft that are pre-deployed in circular heliocentric orbits closer to the Sun than Earth to take advantage of the increased solar radiation pressure. The photon momentum exchange is greater as the sailcraft gets closer to the Sun and pushing it to achieve higher velocities and using the sail to shape the trajectories to arrive at the target faster than chemical or electric propulsion missions depending on orbit geometries. These pre-deployed missions between Mercury, Venus, and Earth orbits could perform other science collection activities while waiting to be recommissioned to a PHA of interest in a timely and cost-effective manner.

This study highlights simulated and real PHA cases, such as PDC25, PDC23, Comet cPDC 2019, Apophis, and 2024-YR4, where it is advantageous to employ a sailcraft reconnaissance mission with three or less years of warning time with several alternatives to demonstrate the flexibility in mission design space.

Solar Sailcraft:

Solar sailcraft offers several advantages for rapid reconnaissance missions to asteroids and comets within the inner solar system that could impact or threaten Earth. The solar sail provides propellent-less acceleration allowing continuous shaping of the trajectory in route to the target. One of the key design parameters is the area-to-mass ratio of the sailcraft, meaning a large sail area and a low spacecraft mass will improve the acceleration performance of the vehicle.

The traditional approach to sailcraft construction has been the planar sail or large sheet designs that have made to space flight. The drawback with these designs is the single degree of freedom to accomplish multiple tasks, such as maintaining trajectory control, power generation, communication links, and sensor pointing. Conversely, an articulating vane sail design has multiple degrees of freedom available to resolve these pointing and control constraints while allowing easier scalability of vehicle by comparison, but this comes at a higher level of structural complexity.

The SOLSTICE vehicle depicted in Figure 1, is a vectored sailcraft that is fully 3-axis stabilized using reaction wheels for attitude control. Separating the attitude control from the power generation, propulsion, and communications is achieved using multifunctional articulated sails [9]. This sailcraft, developed by LGarde and NXTRAC, also has practical benefits of being low cost to develop in ~$12M per vehicle. Low launch costs can be achieved as the vehicles are being compact, and, with low mass to launch, multiple vehicles can reside on a rideshare or be the primary satellite on a small rocket [10,11]. This SOLSTICE vehicle provides exceptional capability and scalability to be developed, deployed, and put into operation for reconnaissance missions to potential PHA targets for further characterization.

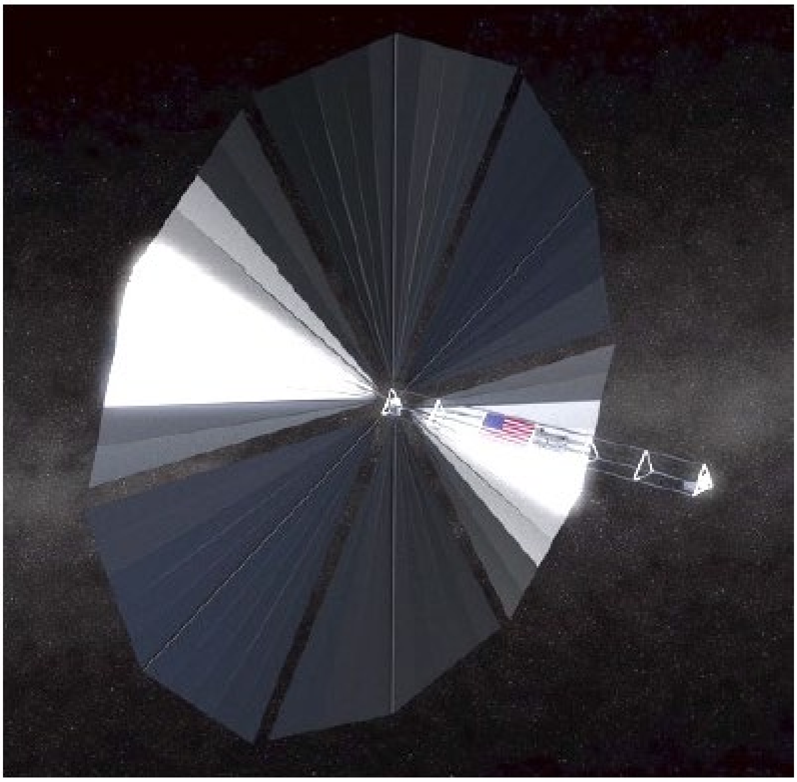

Figure 1: Depicts the SOLSTICE-1 vectored sailcraft, developed by LGarde and NXTRAC that provides a scalable, controllable, and cost-efficient model for a PHA reconnaissance mission. This prototype vehicle and components are being developed and tested under a NOAA contract with flight demonstration opportunities as the next stage [10].

Technical Discussion of Flybys and Rendezvous of PHAs:

Solar Sail Acceleration Equation

A solar sail generates acceleration by using the light from the Sun. Some of the sunlight is absorbed, pushing the sailcraft directly away from the Sun, while some of the sunlight is reflected. The direction of the force imparted on the sailcraft by this reflected light can be controlled by turning the face of the sail. Turning the face of the sail also affects the area that is facing the Sun, which controls the magnitude of the force.

The equation to determine the acceleration imparted on the sail by the Sun is defined as

$$\boldsymbol{a}_{sail} = \Phi\eta \left(\frac{R}{s}\right)^2 \left(\frac{A}{m}\right) \cos\theta \left[C_A \hat{\boldsymbol{s}} + 2C_M \cos\theta \hat{\boldsymbol{n}}\right]$$

where Φ is the solar flux as measured at R = 1 AU, A is the net sail area oriented at angle θ, the vehicle mass m, and the reflectivity C_M and absorptivity C_A of the sail [9]. The control is the normal direction of the sail, $\hat{\boldsymbol{n}}$, and $\hat{\boldsymbol{s}}$ represents the direction outward from the Sun.

The equation shows that the acceleration provided by the sail is dependent on the area to mass ratio. This ratio is a property of the spacecraft hardware design, and it is a common measure of a sail design's efficiency. Sailcraft have flown that have an area to mass ratio of 6m^2/kg, but recent innovative designs have achieved 20m^2/kg and are projected to reach as high as 50m^2/kg [9]. This study will parametrize area to mass ratio to look at a range of possible values.

The acceleration is also proportional to the inverse square of the distance from the Sun. This means that the sail will provide more acceleration as it gets closer to the Sun. This will impact the trajectory design, since the sailcraft will have a higher control authority near the Sun.

Methodology

The purpose of this study was to examine options for sailcraft to reach asteroids via fly-by or rendezvous to gather precise data. To accomplish this, a parameter sweep was conducted over different impactful variables: launch conditions, asteroid reach conditions (rendezvous/fly-by), the sailcraft's area-to-mass ratio, and launch time. For each combination of variables, the sailcraft trajectory was optimized using ASSET, a trajectory optimization program that allowed the sail to continuously change its orientation to minimize time-of-flight [12]. By changing the sail's orientation, the force vector changes, similar to a continuous thruster changing its direction. There are also some constraints on the trajectory – the sailcraft may not get closer than 0.2 AU to the Sun, and the sail can only change its direction by a maximum of 50 degrees per day. ASSET uses the equation of motion, constraints, and variables to output the optimal sailcraft trajectory and control history [12].

The chosen values of the parameters to be considered were based on realistic projections and possible scenarios. The values for area-to-mass ratio of the solar sail were 20, 30, 40, and 50 m^2/kg [9], and the time of launch was as varied between 3 and 0.5 years before the asteroid impacting/flying-by Earth in one-month intervals. For each asteroid, both rendezvous and fly-by options were considered.

For the launch conditions, three Earth-based options were examined: leaving Earth with a C3 of 154, 50, or 0 km^2/s^2. C3 is a measure of how much energy the spacecraft has when escaping the sphere of influence of a planet. A C3 of 154 km^2/s^2 was achieved for the Parker Solar Probe, so this was treated as the maximum energy that can be realistically expected for a launch vehicle to provide to the spacecraft [13]. A C3 of 50 km^2/s^2 can be achieved by a larger set of launch vehicles, so this was used as a case representative of a more typical launch. A C3 of 0 km^2/s^2 corresponds to the sailcraft just barely leaving the Earth's sphere of influence, which would be the case if the sailcraft was a secondary payload and only separated from the upper stage after it completed a heliocentric disposal burn.

There were also three non-Earth based launch options starting from circular orbits smaller than that of Earth. This corresponds to a conceptual constellation of sailcraft near the orbits of Mercury or Venus discussed earlier. In this case, sailcraft would have been deployed beforehand to conduct science in the inner solar system but would be ready to be deployed to a given asteroid as soon as the command is given. This will be represented as circular orbits of varying radii, all in the ecliptic plane. The orbits will have AU radii of 0.72, 0.50, and 0.39, corresponding respectively to the orbital radius of Venus, half of the Earth's orbital radius, and the orbital radius of Mercury. The benefit of this proactive set of reconnaissance sailcraft will be explored by comparison to the Earth-launch cases.

The asteroids that were investigated for this study included three simulated asteroids and two real asteroids. The simulated asteroids include PDC 2025, PDC 20-23, and cPDC 2019, corresponding respectively to the simulations done for the Planetary Defense Conferences in 2025, 2023, and the comet example from the 2019 conference. The real asteroids considered were Apophis and YR4, which will make near-Earth passes in 2029 and 2032, respectively. Both asteroids made headlines when preliminary observations indicated that the chances of impact were near 3%, and both are large enough to cause severe damage should they impact [5,14]. The table below shows information about the orbits of these asteroids and the comet, which were taken from JPL's Horizons System [15]. A sailcraft trajectory will be optimized to minimize time-of-flight for each of these five targets, and each combination of parameters.

Asteroid	**Potential Impact Date**	**Inclinatio n (deg)**	**Perihelion (AU)**	**Aphelion (AU)**	**Period (days)**
PDC 2025	4/24/2041	10.7	1.0	2.29	774
PDC 2023	10/22/2036	10.17	0.90	1.08	359
cPDC 2019	2/28/2021	128	0.92	444	1,214,265
Apophis	4/13/2029	3.3	0.75	1.10	324
2024 YR4	12/22/2032	3.46	0.84	4.2	1,467

Asteroid PDC 2023 In-Depth Analysis

A large amount of data was generated for each asteroid included in this study. In the interest of brevity, only the results using PDC 2023 will be presented in depth The trends identified apply to the results from all other asteroids in some form, and for the other asteroids, only portions of the results will be shown.

The asteroid from PDC 2023 has an orbit shape very similar to that of Earth and is inclined by 10 degrees relative to the ecliptic. The results will show how the asteroid's orbit affects the time it takes for a sailcraft to arrive, and the influence of the parameters, such as launch conditions and area to mass ratio.

Fly-by Case

First, the amount of time required for the sailcraft to fly-by the asteroid was explored. The results are in Figure 2 for sails with an area-to-mass ratio of 50m^2/kg, where the x-axis shows "launch time before impact," or the time-to-impact at the departure point of the sailcraft, and the y-axis shows "arrival time before impact," or the time-to-impact at the point that the sailcraft reaches the asteroid. Note that the term "launch" will be used for departures from inner orbits as well as conventional launches from Earth. The dotted line represents the points where the launch and arrival times would be equal. The distance from this line is the sail's time-of-flight from launch to arrival. To use this plot, choose a point on the x-axis to launch the sail and note that the values of the y-axis at each of the points represents the time between sail arrival and the asteroid impacting Earth. This could be important for utilizing the data coming from the sail.

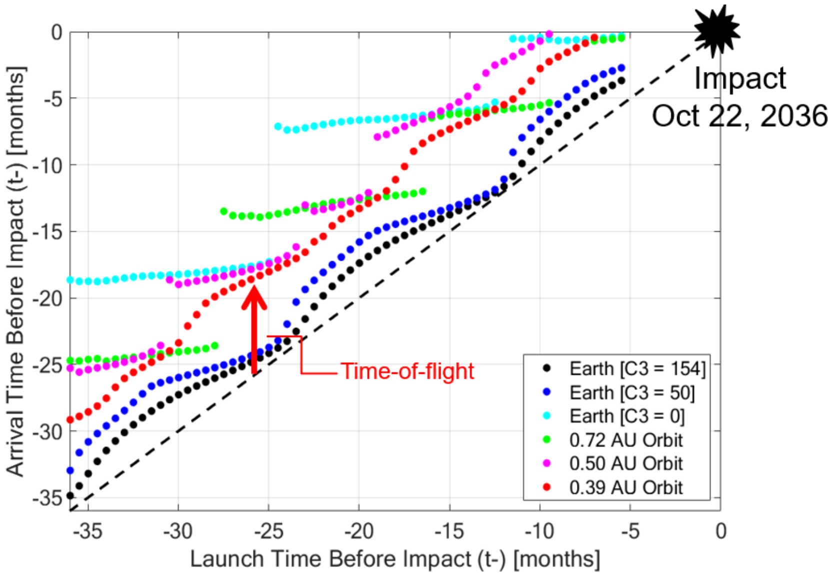

Figure 2: Launch time vs arrival time for solar sailcraft trajectories that fly-by asteroid PDC 2023. Each dot represents a solar sailcraft trajectory that was optimized for minimum time-of-flight, and the launch condition was parametrized for both Earth-based launches of different C3 and circular ecliptic constellations of different radii in the inner solar system.

Each point on the plot represents an optimized trajectory. This is shown in Figure 3 for two examples using different launch conditions: a circular orbit at 0.5 AU and an Earth-based launch with a C3 of 50 km^2/s^2. The spacecraft, plotted in black, departs from its starting point and controls the direction of the sail, denoted by small black arrows, to fly-by the asteroid, plotted in red. The trajectories can look very different from each other depending on launch condition: the dedicated launch results tend to look ballistic, and the inner orbit results tend to have non-trivial flight profiles. Sometimes the sail lowers its perihelion to get closer to the Sun and have more control authority, and then at some point it adjusts its sail direction to move itself outward towards the asteroid in a very elliptical trajectory and flies by at an angle.

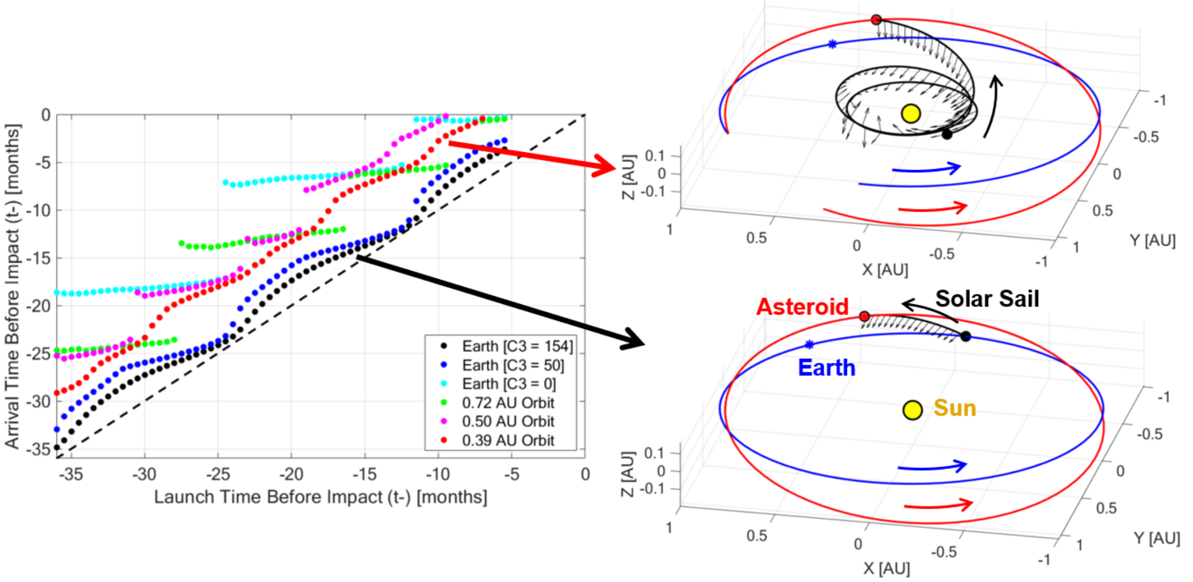

Figure 3: Two sample trajectories that fly-by asteroid PDC 2023 are called out. The top trajectory shows the sail starting from a 0.39 AU radius constellation 10 months before impact, and the bottom plot shows the sail being launched from Earth with a very powerful rocket.

The "step" nature of Figure 2 occurs because the phasing of the asteroid, and where it is relative to a plane-crossing, has an impact on what trajectories are possible. A sailcraft can avoid a plane change, which is expensive in terms of acceleration, by flying by the asteroid at the plane-crossing of the orbits. This is shown in the lefthand case below. This is only possible if the sailcraft can reach the point that the asteroid crosses the ecliptic plane in time, which is not always the case. If this first fly-by opportunity cannot be reached, the sailcraft must fly-by at the next plane crossing opportunity. It is also possible for the sail to change its plane, but this requires the sail to point in certain directions for prolonged periods of time, which extends the time-of-flight.

Changing the orbital plane can extend the fly-by opportunity near the plane-crossing, which creates a collection of solutions near each plane crossing, shown by the near-horizontal lines of cyan, green, and magenta in Figure 2. Notice that these

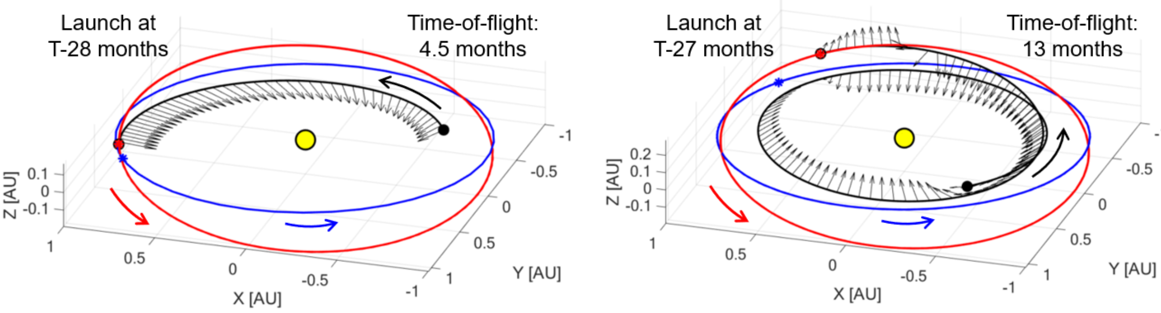

Figure 4: Two fly-by sail trajectories that launch one month apart show very different behavior because the window of opportunity near a plane-crossing is available for the lefthand plot, but not the righthand plot.

occur at approximately six-month intervals on the y-axis, corresponding with the asteroid crossing the ecliptic plane every six months. The righthand example below shows the trajectory and control history of a sailcraft going from a circular orbit of 0.72 AU in the ecliptic, launching at 27 months before impact. It changes its orbital plane significantly to fly by the asteroid and the control history shows that the sail was pointing significantly out-of-plane to produce those results.

The results above were for an area to mass ratio of 50 m^2/kg, which is the high end of projections from cutting-edge solar sail technology experts [9]. This study also examined area to mass ratios of 20, 30, and 40 m^2/kg. The full set of results for a fly-by of PDC 2023 are shown in the plots below, separated by Earth and non-Earth departures for clarity. The results from larger area-to-mass ratios are represented by larger dots.

The area-to-mass ratio has very little effect for launches from Earth, plotted on the left. This is because the fly-by can be achieved with just the launch, so the sail's effectiveness does not make a difference. In the Earth launch case with zero C3, the windows of opportunity are more influential than the area-to-mass ratio, so that ratio does not have too large of an affect. The righthand plot shows the results for different area-to-mass ratios when the trajectory starts from an inner orbit.

The results are clustered around six-hour intervals on the y-axis, which corresponds with the asteroid's plane crossings. The trajectories of smaller area to mass ratio sails take more time than that of higher area to mass ratios, and in some cases this difference dictates whether an opportunity window can be accessed. The 20 m^2/kg sails cannot always access the same fly-by opportunities that the 50 m^2/kg trajectories can access. The top left portion of the righthand plot is occupied by smaller dots, corresponding to smaller area to mass ratio results, that were less performant than the corresponding larger sails, so they were precluded from the earlier fly-by windows and "relegated" to a later window.

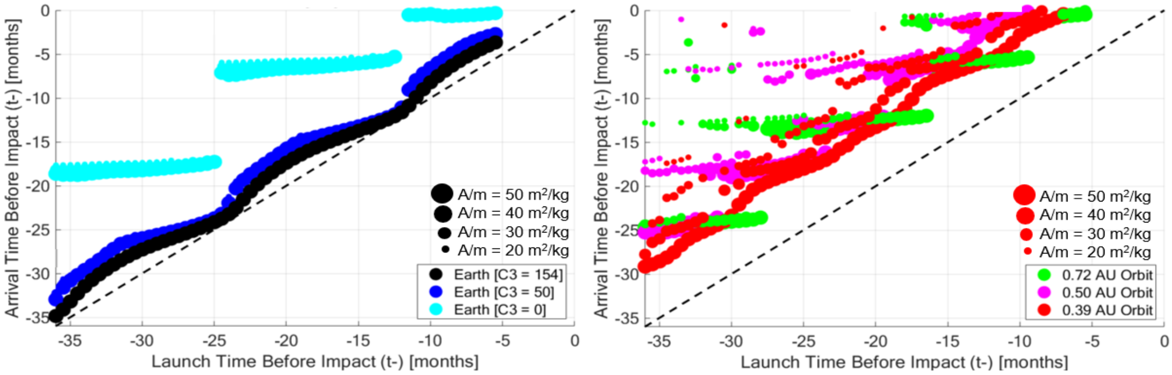

Figure 5: The fly-by results for sailcrafts reaching asteroid PDC 2023 are plotted for different area to mass ratios of the sail, with the righthand plot showing results from an inner orbit and the lefthand plot showing results with launches from Earth.

The takeaway from Figure 5 is that the area to mass ratio of a solar sail can be very influential in amount of time it would take to fly-by an asteroid, but it is not a uniform effect and must be evaluated on a case-by-case basis. In general, the area to mass ratio is more impactful for trajectories that rely on performance of the sail, but the asteroid geometry can also magnify or curtail this performance difference.

Rendezvous Case

While the above results considered the case where the spacecraft would fly-by the asteroid to collect data, it is also possible to rendezvous with the asteroid to get data with higher consistency and fidelity. It is worth investigating the results to analyze the tradeoff between data fidelity and arrival time before asteroid-Earth impact. The difference between rendezvous and fly-by from a trajectory design standpoint is that a rendezvous requires the spacecraft to match the asteroid's velocity, which is a consideration that greatly constrains the optimization problem. The following section will investigate the rendezvous results for asteroid PDC 2023. The launch/arrival times are plotted in Figure 6 for a sail with an area to mass ratio of 50 m^2/kg.

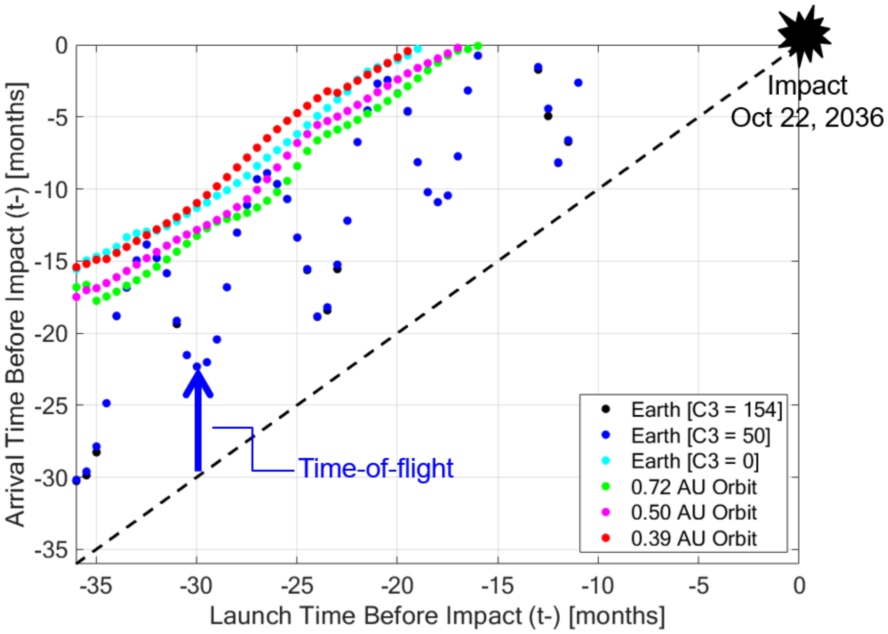

Figure 6: Launch time vs arrival time for solar sail trajectories that rendezvous with asteroid PDC 2023. Each dot represents a solar sail trajectory that was optimized for minimal time-of-flight, and the launch condition was parametrized for both Earth-based launches of different C3 and circular ecliptic constellations of different radii in the inner solar system

What is notable about these results is that at most potential launch times, an Earth launch with C3 of 50 km^2/s^2 results in shorter time-of-flights (and thus more time to process the data before the asteroid impacts Earth) than any inner solar system orbit. Yet there is a "wave" form to the results, the reason for which will be discussed in detail below, which creates certain windows in which a departure from an orbit at 0.72 AU is more optimal. For example, if the asteroid were discovered at t-minus 33 months and there was a well-located sailcraft from a pre-existing constellation at 0.72 AU, it could arrive at the asteroid with 17 months before impact, compared to 14 months for a dedicated launch.

Also note that dedicated launches cannot be commissioned instantly – it takes time to procure the rocket, load the vehicle on the pad, etc. The dedicated launches – the blue and black dots – are often plotted directly on top of each other, signifying that they result in the same trajectory; for a rendezvous with an object with an Earth-like orbit, only a certain amount of C3 is needed. Another takeaway is that the cyan dots, representing a "minimal launch" condition that barely escapes the sail from Earth's sphere of influence, consistently underperforms that of the green and magenta dots, representing sails in pre-existing constellation at 0.72 and 0.5 AU, respectively. This plot can be used to determine the best way to rendezvous with this asteroid using a solar sailcraft.

The “wave” nature of the dedicated launch results occurs because of the phasing at the time of launch compared with the plane crossings of the asteroid and the Earth. If the Earth is at or near one of the plane crossings at launch, the excess velocity provided by the C3 can be used to directly launch the sail into the plane of the asteroid. This is the case in the lefthand side of Figure 7. If Earth is not near the plane crossings at the time of launch, the excess velocity provided by the C3 cannot be used to launch into the asteroid’s plane, and the sail itself must spend time to perform the plane change. This is the case in the righthand side of the plot below. Since the simulated asteroid in question will collide with Earth and has a period similar to that of Earth, the impact point is a plane crossing and the plane crossings occur roughly every six months, which matches the “wave” period in the figure above. Other asteroids may not have a period like that of Earth but will still have this “wave” pattern that is due to phasing. For highly elliptical orbits, the phasing at launch may impact whether the rendezvous opportunity is at perihelion or aphelion, which would produce a similar wave pattern.

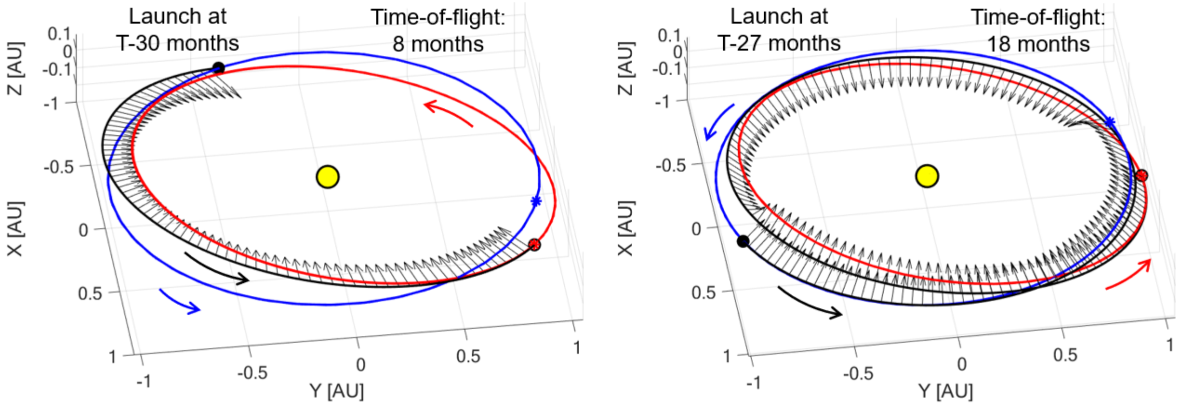

Figure 7: Two rendezvous sail trajectories that launch three months apart show very different behavior because in the lefthand plot, the Earth is near the orbital plane-crossing and the launch can put the sail in the same orbit as the asteroid, but the righthand plot does not have that capability and must use the sail to do a plane change.

The results above were for an area to mass ratio of 50 m^2/kg, but this study also examined area to mass ratios of 20, 30, and 40 m^2/kg. The full set of results are shown in Figure 8, separated by Earth and non-Earth departures for clarity. The results from larger area to mass ratios are represented by larger dots. The area to mass ratio

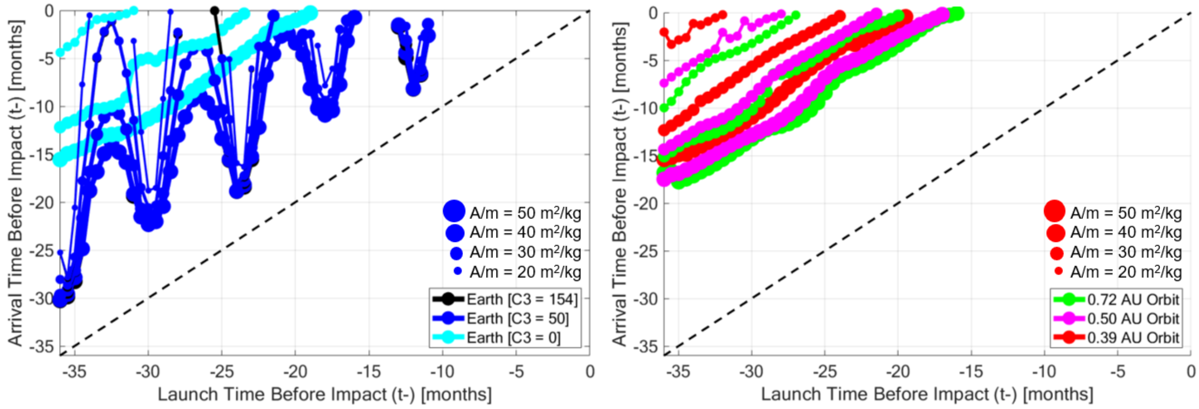

Figure 8: The rendezvous results for sails reaching asteroid PDC 2023 are plotted for different area to mass ratios of the sail, with the righthand plot showing results from an inner orbit and the lefthand plot showing results with launches from Earth.

has a greater importance for rendezvous cases than fly-by cases, because the spacecraft needs the sail to match the velocity of the asteroid as it approaches.

The above plots show that the area to mass has a large effect on the rendezvous trajectories. For the Earth-based launches with a C3 above 50, this effect depends on the phasing at the point of launch. The area to mass ratio has the least effect when the excess velocity provided by the launch vehicle can be used to get in-plane with the asteroid, at which point the sail only needs to adjust phasing to rendezvous, as discussed above. The area to mass ratio has the largest effect when the phasing is least optimal, because at this point the performance of the trajectory is more dependent on how effective the sail is at generating acceleration. For the inner constellation orbits, the smaller area to mass ratio has a nearly uniform effect on the results. These trajectories rely on the sail to go from their starting orbit to rendezvous with the asteroid, so it was expected that less efficient sails would lead uniformly to less performant trajectories. Similar analysis conducted on other asteroids shows that these results are consistent.

Asteroid PDC 2025

The asteroid from PDC 2025 is more challenging for a spacecraft to reach than the asteroid from PDC 2023 because it has an inclination of about 11 degrees with a very high aphelion. It has an orbital period of 25.5 months, which makes the epoch 25.5 months before Earth impact a critical point: the asteroid would be at the exact point in space that it will impact the Earth, and the Earth is slightly behind phase because it is slightly more than 2 years from the impact point. It can be expected that this will affect the performance of time-optimal solar sailcraft trajectories. Figure 9 shows the fly-by times for a sailcraft with an area to mass ratio of 50 m^2/kg. There is no rendezvous possible with a sailcraft for this asteroid.

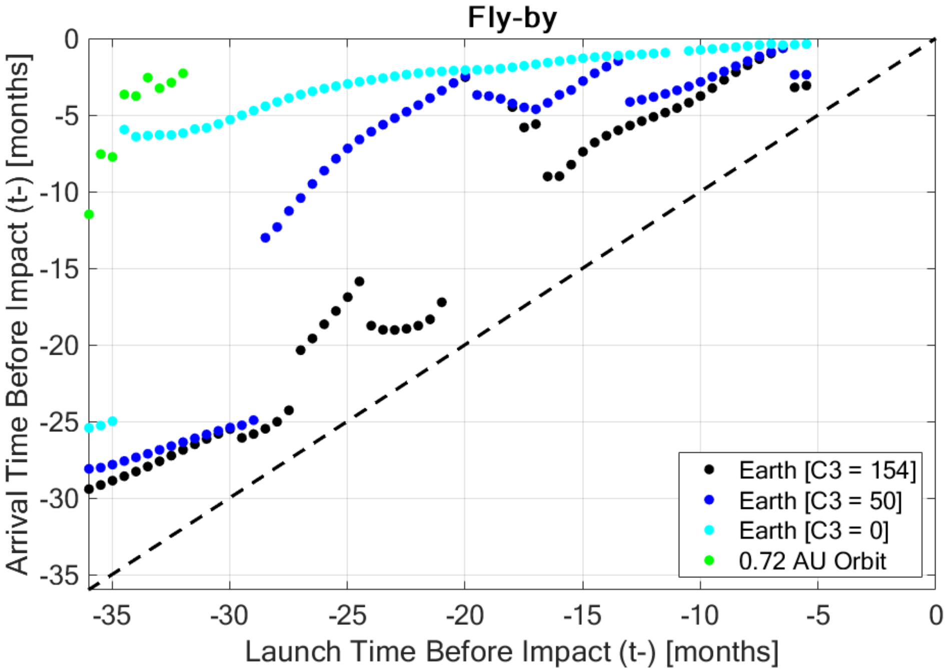

Figure 9: Launch time vs arrival time for solar sail trajectories that fly-by asteroid PDC 2025. Each dot represents a solar sail trajectory that was optimized for minimal time-of-flight, and the launch condition was parametrized for both Earth-based launches of different C3 and circular ecliptic constellations of different radii in the inner solar system. Note that for this case, no fly-by trajectories were possible for a constellation of 0.50 AU or 0.39 AU

Figure 9 shows that, aside from a handful of successful trajectories from an orbit of 0.72 AU that depart over 30 months from impact time, the only feasible departure point is Earth. The asteroid has a perihelion of 1 AU and an aphelion of 2.29 AU, so it is always relatively far from the Sun, where a solar sail is ill-suited because of the diminishing power of the Sun. This is also simply farther from the inner orbits, with a relatively high inclination that makes it even more difficult to reach.

From the Earth, the dedicated launches have windows of opportunity where it is more optimal to launch, separated by distinct regimes. At times near 25.5 months before impact, when the asteroid is exactly one orbital period before impact and crossing the ecliptic plane, a strong enough launch can reach the asteroid quickly.

Launches before this epoch can direct the spacecraft to fly-by the asteroid near the point it crosses the ecliptic to avoid an expensive plane change. This is like the reasoning for the "step" nature of asteroid PDC 2023.

Overall, the asteroid of PDC 2025 is difficult to reach via any trajectory, including that of a solar sailcraft. Figure 10 shows a sample trajectory – an Earth launch ten months before impact that reaches the asteroid three months before impact. It is evident that the trajectory not only required a plane change, but also an aphelion raise, which is mostly accomplished by the 50 km^2/s^2 launch.

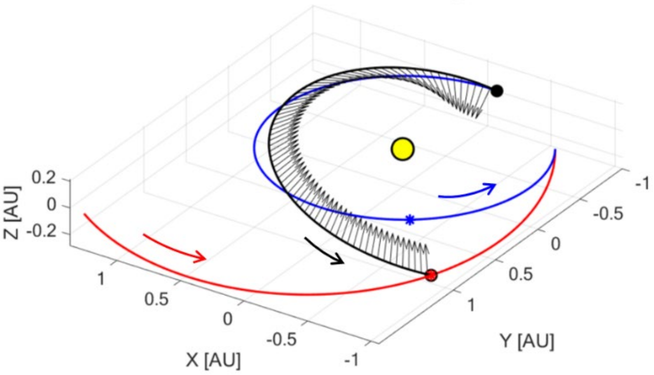

Figure 10: Solar sail trajectory that launched from Earth ten months before impact and did a fly-by with the asteroid three months before impact, for a time-of-flight of seven months. The launch provided the sail with 50 km^2/s^2 of C3.

Apophis

Discovered in 2004, Apophis is a near Earth asteroid that will pass Earth in 2029 at a distance closer than geostationary orbit [15]. While this asteroid will not collide with Earth, it is a notable example of a close call that warrants further investigation and data collection. It has a relatively small inclination relative to the ecliptic, with an orbit shape similar to that of Earth but more eccentric, with a perihelion of 0.75 AU. This makes it a prime candidate for visitation by a solar sailcraft that is already placed in some inner orbit. Figure 11 shows the fly-by results for a sail with an area to mass ratio of 50 m^2/kg.

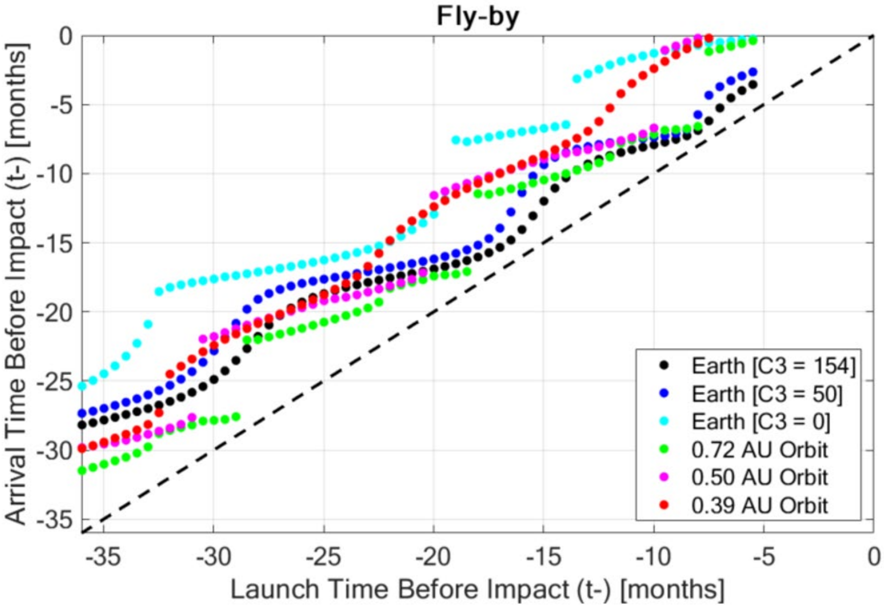

Figure 11: Launch time vs arrival time for solar sail trajectories that fly-by Apophis. Each dot represents a solar sail trajectory that was optimized for minimal time-of-flight, and the launch condition was parametrized for both Earth-based launches of different C3 and circular ecliptic constellations of different radii in the inner solar system.

The time-of-flight does not exceed 15 months in the above plot, meaning the asteroid is relatively well positioned to fly-by from any launch condition. This is because of the small inclination and Earth-like orbit. One notable takeaway from the above plot is that a sailcraft that begins in a 0.72 AU orbit, represented by green dots, consistently out-performs all other launch options for launches more than 18 months before the asteroid's close flyby of Earth.

There are certain launch times where multiple possible inner orbit launch conditions outperform the Earth-launch with a very high C3. This shows that there could be faster data collection if there were a preset constellation of sailcraft in inner orbit, and that is amplified considering that a sailcraft in this constellation could be tasked to fly-by the asteroid instantly, whereas a launch from a heavy lift vehicle could take months to schedule and execute.

If the launch can only barely escape Earth's sphere of influence, a case represented by the cyan dots above, that consistently leads to longer flight times than any inner orbits. For this asteroid, and other asteroids with similar characteristics, a sail constellation would save months of time for collecting data via a fly-by.

Rendezvous is the preferred method for more high-fidelity data collection. The results for rendezvous trajectories to Apophis with a 50 m^2/kg solar sail are shown in Figure 12. the same "wave" nature of rendezvous trajectories was discussed earlier. The results from a 0.72 AU orbit and the Earth dedicated launches intertwine, meaning that the best launch condition is dependent on launch time.

The conclusion from the fly-by case mostly applies for the rendezvous case: for launch times earlier than 20 months before potential impact, a sail starting at an orbit of 0.72 AU has the best results, with limited exceptions. This is because sails starting from this inner orbit have the benefit of more power from the Sun, while also being phased in the most opportune place under the assumption that there is a sufficient constellation where the most opportune spacecraft can be tasked. The Earth launches, on the other hand, are dependent on the Earth's phasing relative to the asteroid, which can be very poor.

Figure 12 shows an example rendezvous trajectory for the case where the sail begins its trajectory 23 months before near-impact and arrives 15 months before near-impact, which is roughly three months before any result from other launch conditions.

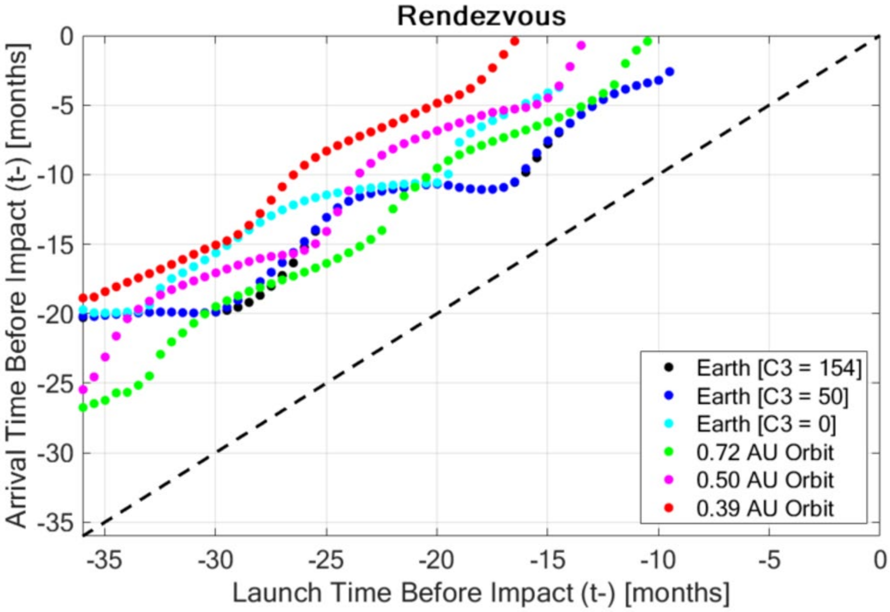

Figure 12: Launch time vs arrival time for solar sail trajectories that fly-by Apophis. Each dot represents a solar sail trajectory that was optimized for minimum time-of-flight, and the launch condition was parametrized for both Earth-based launches of different C3 and circular ecliptic constellations of different radii in the inner solar system.

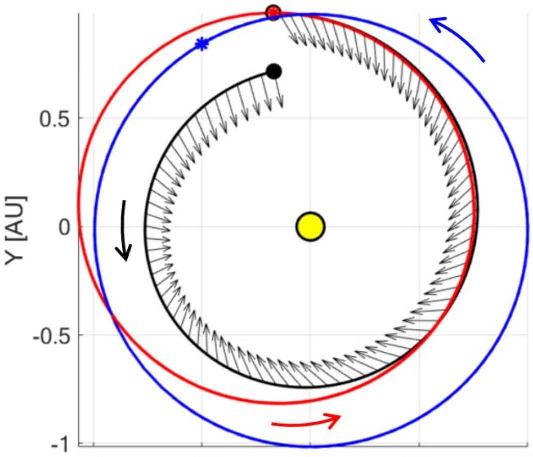

Figure 13: Solar sail trajectory that launched from Earth 23 months before impact and did a rendezvous with the asteroid 15 months before impact, for a time-of-flight of eight months. The sail began in a circular ecliptic orbit with a radius of 0.72 AU.

Comet cPDC2019

The comet from PDC 2019 presents a huge challenge for any spacecraft that would try to reach it before it impacted Earth. Its orbit is nearly parabolic, with an inclination of 128 degrees relative to the ecliptic, which makes it both highly inclined and retrograde to Earth's orbit. This rules out rendezvous as a practical possibility, and only leaves fly-by as an option to get close-range data. Figure 14 shows the results for possible sailcraft trajectories to fly-by this hypothetical asteroid.

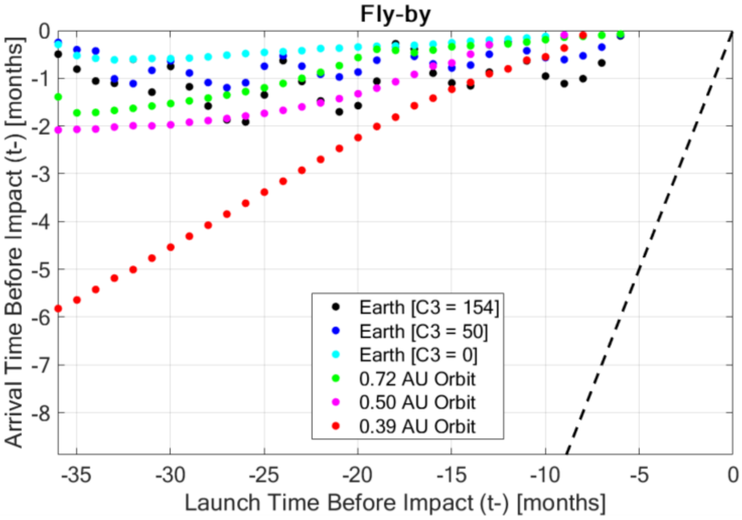

Figure 14: Launch time vs arrival time for solar sail trajectories that fly-by comet cPDC 2019. Each dot represents a solar sail trajectory that was optimized for minimum time-of-flight, and the launch condition was parametrized for both Earth-based launches of different C3 and circular ecliptic constellations of different radii in the inner solar system.

The figure shows a clear advantage for a solar sail that begins closer to the Sun. This advantage is because the solar radiation pressure is greater at closer range to the Sun due to the tightly packed photons that exchange that momentum, and the solar sailcraft can use this power boost to change its orbital inclination and increase its aphelion revolution by revolution, as shown in Figure 15.

Orbits farther from the Sun must first spiral inwards towards the Sun to get this increased control authority. Note that, in this example and all the simulations in this paper, the closest allowed distance to the Sun was 0.2 AU, which is why the trajectory below keeps that distance to the Sun; it would go closer to the Sun to get more power, and generate slightly better results, if that constraint were not implemented. The Earth-based launch results stay near the one-month arrival time because they can only reach the asteroid as it is nearly impacting the Earth, and phasing can influence that result.

This comet would present an extremely large threat to Earth, and solar sailcraft could be used to gather data with more than two months warning time to get more

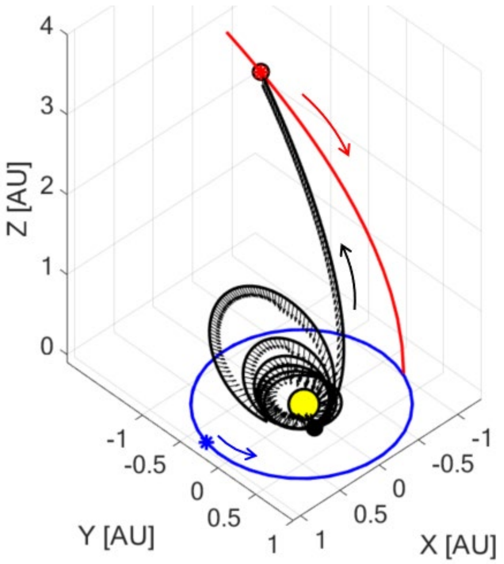

Figure 15: Solar sail trajectory that launched from Earth 36 months before impact and did a fly-by with the asteroid six months before impact, for a time-of-flight of 30 months. The sail began in an ecliptic orbit with a radius of 0.39 AU.

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precise information with reasonable time spans to facilitate emergency procedures on Earth.

2024 YR4

The final asteroid of interest is asteroid 2024 YR4, which will have a close pass with Earth in 2032. To explore options of sailcraft gathering data at this potentially hazardous asteroid, the sailcraft trajectories were run for both fly-by and rendezvous opportunities. 2024 YR4 has an extremely large aphelion that precludes rendezvous opportunities for cases that launch within three years of impact, so only fly-by trajectories will be examined. Figure 16 shows these results.

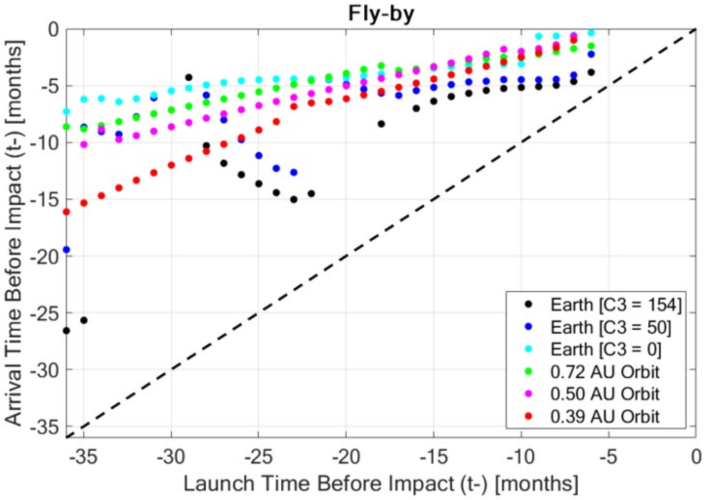

Figure 16: Launch time vs arrival time for solar sail trajectories that fly-by asteroid 2024 YR4. Each dot represents a solar sail trajectory that was optimized for minimum time-of-flight, and the launch condition was parametrized for both Earth-based launches of different C3 and circular ecliptic constellations of different radii in the inner solar system.

Similar to the results from other asteroids that have a large aphelion, the time-of-flight from the inner orbit constellations are faster from orbits of smaller radii. The results from the 0.39 AU orbit were better than that of 0.50 AU, which are better than that of the 0.72 AU. The launches from Earth are very dependent on phase, as the point of launch is most optimal when the Earth's velocity can be utilized best to benefit the sail trajectory. The example trajectory in Figure 17 launches from Earth 25 months before potential impact and reaches the asteroid 13.5 months before impact.

When the Earth is on the opposite side of its orbit, the launch cannot provide a delta-v that is as effective. This is the case for launches from 27 to 35 months before potential impact and launches 17 to 21 months before potential impact. In these windows, it would be better for the sail to start in an orbit the size of Mercury's. This showcases that for this very publicized asteroid, there are clear benefits of a solar sail constellation that could be assembled before an asteroid is even detected.

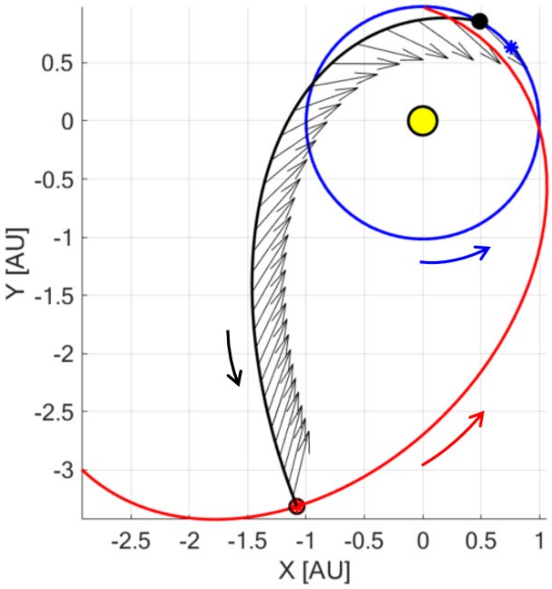

Figure 17: Solar sail trajectory that launched from Earth 25 months before impact and did a fly-by with the asteroid 13.5 months before impact, for a time-of-flight of 11.5 months. The launch provided the sail with 154 km^2/s^2 *of C3.*

Conclusions:

This study shows that solar sailcraft present an option for a rapid response to observe and characterize potentially hazardous asteroids and comets that might threaten our planet. Use of solar sailcraft to accomplish these reconnaissance missions presents a highly flexible trade space of options while offering low development costs to implement.

For all target bodies considered in this study, there are flyby and/or rendezvous mission options available in three years or less. These trajectories are dependent on the orbital geometry of the incoming target, whether these sailcraft are strategically deployed into inward heliocentric orbits or directly launched at the target.

These deployed systems could also collect science data on other astronomical, heliophysics, or planetary phenomenon while waiting to be commissioned for a reconnaissance mission, and the propellent-less propulsion of the solar sail in route to the target object aids in achieving difficult flybys and rendezvous by matching both positions and velocities.

In some cases, like PDC25, the sailcraft may not be the most effective vehicle to accomplish the reconnaissance. A traditional chemical or electric propulsion spacecraft could perform the task. In other cases, like the comet cPDC2019, the sailcraft is the best option due to the delta-v and plane change demands necessary to arrive as early as possible given the short warning time.

The benefits of developing and deploying these sailcraft ahead of time cuts out years of build-to-launch time in the event of a short warning event, creates lower production costs over time as more are built, and enables incorporation of new, more capable technology and payloads. This production could scale to other cislunar and interplanetary missions to enable low-cost science missions across the solar system.

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