Project Lyra: Sending a Spacecraft to 1I/'Oumuamua (former A/2017 U1), the Interstellar Asteroid

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Abstract

The first definitely interstellar object 1I/'Oumuamua (previously A/2017 U1) observed in our solar system provides the opportunity to directly study material from other star systems. Can such objects be intercepted? The challenge of reaching the object within a reasonable timeframe is formidable due to its high heliocentric hyperbolic excess velocity of about 26 km/s; much faster than any vehicle yet launched. This paper presents a high-level analysis of potential near-term options for such a mission. Launching a spacecraft in a reasonable timeframe of 5-10 years requires a hyperbolic solar system excess velocity between 33 to 76 km/s for mission durations between 30 to 5 years. Different mission durations and their velocity requirements are explored with respect to the launch date, assuming direct impulsive transfer to the intercept trajectory. Several technology options are outlined, ranging from a close solar Oberth Maneuver using chemical propulsion, and the more advanced options of solar and laser sails. To maximize science return decelerating the spacecraft at 'Oumuamua is highly desirable, due to the minimal science return from a hyper-velocity encounter. It is concluded that although reaching the object is challenging, there seem to be viable options based on current and near-term technology.

1. Introduction

On October 19th 2017, the University of Hawaii's Pan-STARRS 1 telescope on Haleakala discovered a fast-moving object near the Earth, initially named A/2017 U1, but now designated as 1I/'Oumuamua [1]. This object was found to be not bound to the solar system, with a velocity at infinity of ~26 km/s and an incoming radiant (direction of motion) near the solar apex in the constellation Lyra [2]. Due to the non-observation of a tail in the proximity of the Sun, the object does not seem to be a comet but an asteroid. More recent observations from the Palomar Observatory indicate that the object is reddish, similar to Kuiper belt objects [3]. This is a sign of space weathering. Its orbital features have been analyzed by [2,4].

At present, the frequency of similar objects entering the solar system is poorly constrained. As 1I/'Oumuamua is the nearest macroscopic sample of interstellar material, likely with an isotopic signature distinct from any other object in our solar system, the scientific returns from sampling the object are hard to understate. Detailed study of interstellar materials at interstellar distances are likely decades away, even if Breakthrough Initiatives' Project Starshot, for example, is vigorously pursued. Hence, an interesting question is if there is a way to exploit this unique opportunity by sending a spacecraft to 1I/'Oumuamua to make observations at close range.

The Initiative for Interstellar Studies, i4is, has announced Project Lyra on the 30th of October to answer this question. The goal of the project is to assess the feasibility of a mission to 1I/'Oumuamua using current and near-term technology and to propose mission concepts for achieving a fly-by or rendezvous. The challenge is formidable: According to current estimates, 1I/‘Oumuamua has a heliocentric hyperbolic excess velocity of 26 km/s. This considerably faster than any object humanity has ever launched into space. Voyager 1, the fastest object humanity has ever built, has a hyperbolic excess velocity of 16.6 km/s. As 1I/‘Oumuamua is already leaving our solar system, any spacecraft launched in the future would need to chase it. However, besides the scientific interest of getting data back from the object, the challenge to reach the object could stretch the current technological envelope of space exploration. Hence, Project Lyra is not only interesting from a scientific point of view but also in terms of the technological challenge it presents. Figure 1 shows the logo for Project Lyra.

Figure 1: Logo for the i4is initiative Project Lyra

This paper presents some preliminary results for a mission concept to 1I/‘Oumuamua.

2. Trajectory Analysis

Given the hyperbolic excess velocity and its inclination with respect to the solar system ecliptic, the first question to answer is the required velocity increment (DeltaV) to reach the object, a key parameter for designing the propulsion system. Obviously, a slower spacecraft will reach the object later than a faster spacecraft, leading to a trade-off between trip duration and required DeltaV. Furthermore, the earlier the spacecraft is launched, the shorter the trip duration as the object’s distance increases with time. However, a launch date within the next 5 years is likely to be unrealistic, and even 10 years could be challenging, in case new technologies need to be developed. Hence, a third basic trade-off is between launch date and trip time / characteristic energy C_3. The characteristic energy is the square of the hyperbolic excess velocity, which can be understood as is the velocity at infinity with respect to the Sun. These trade-offs are captured in Figure 2. The figure plots the characteristic energy for the launch with respect to mission duration and launch date. An impulsive propulsion system with a sufficiently short thrust duration is assumed. No planetary or solar fly-by is assumed, only a direct launch towards the object. It can be seen that a minimum C_3 exists, which is about 26.5 km/s (703km^2/s^2). However, this minimum value rapidly increases when the launch date is moved into the future. At the same time, a larger mission duration leads to a decrease of the required C_3 but also implies an encounter with the asteroid at a larger distance from the Sun. A realistic launch date for a probe would be at least 10 years in the future (2027). At that point, the hyperbolic excess velocity is already at 37.4km/s (1400km^2/s^2) with a mission duration of about 15 years, which makes such an orbital insertion extremely challenging with conventional launches in the absence of a planetary fly-by.

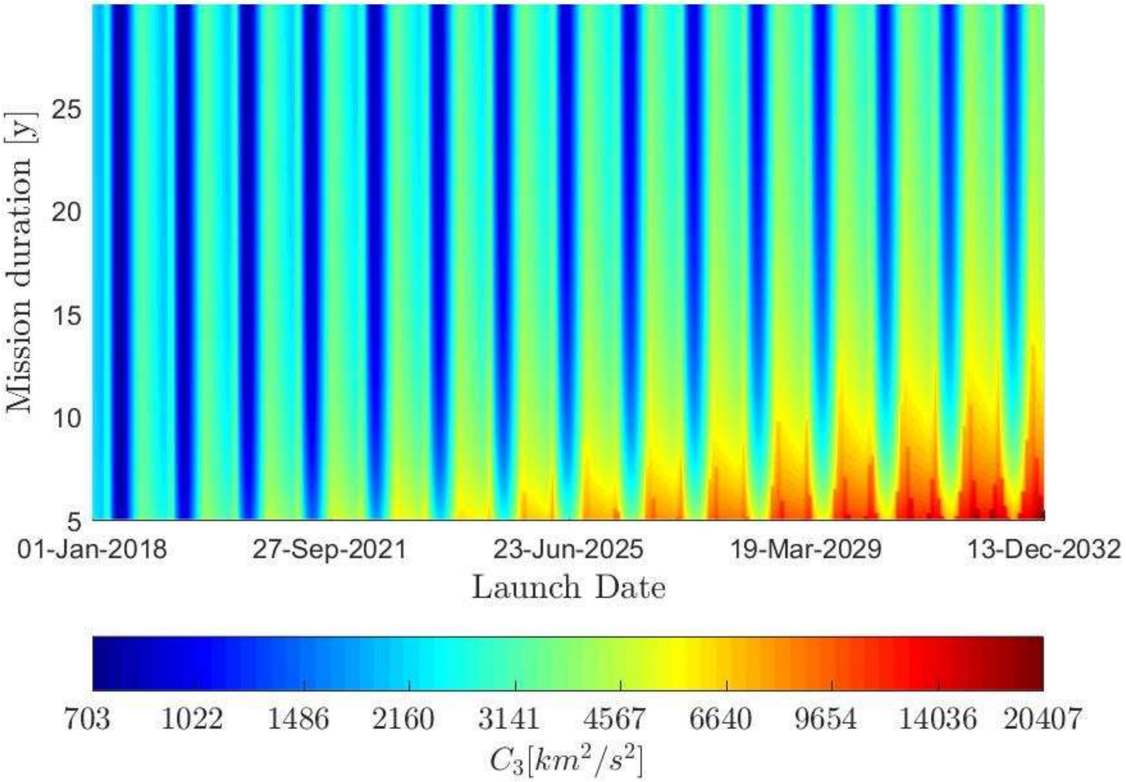

Figure 2: Characteristic energy C3 with respect to mission duration and launch date.

Apart from the hyperbolic excess velocity at launch, the excess velocity relative to the asteroid at encounter ($v_{\infty,2}$) has to be taken into account since it defines the type of mission that is achievable. A high excess velocity with respect to the asteroid reduces the flight duration but also reduces the time available for the measurements close to the interstellar object. On the other hand, a low value for $v_{\infty,2}$ could even enable orbital insertion around the asteroid with an impulsive or low thrust maneuver to decelerate the probe. The excess velocity at arrival is plotted in Figure 3 as a function of the launch date and the flight duration. The deformations of the velocity curves is due to the Earth's orbit around the Sun, which results in a more or less favorable position for a launch towards the object. It can be seen that a minimum excess velocity of about 26.75km/s implies a launch in 2018 and a flight duration of over 20 years. Such value for excess velocity does not prohibit an orbital insertion around 'Oumuamua. However, this minimum value rapidly increases for later launch dates. A realistic launch date for a probe would be between 5 to 10 years in the future (2023 to 2027). At that point, the required hyperbolic excess velocity for the mission is between 33 to 76 km/s, for mission durations between 30 to 5 years. These values highly exceed the current chemical and electric propulsion system capabilities for deceleration and orbital insertion, and hence a fly-by would be more reasonable.

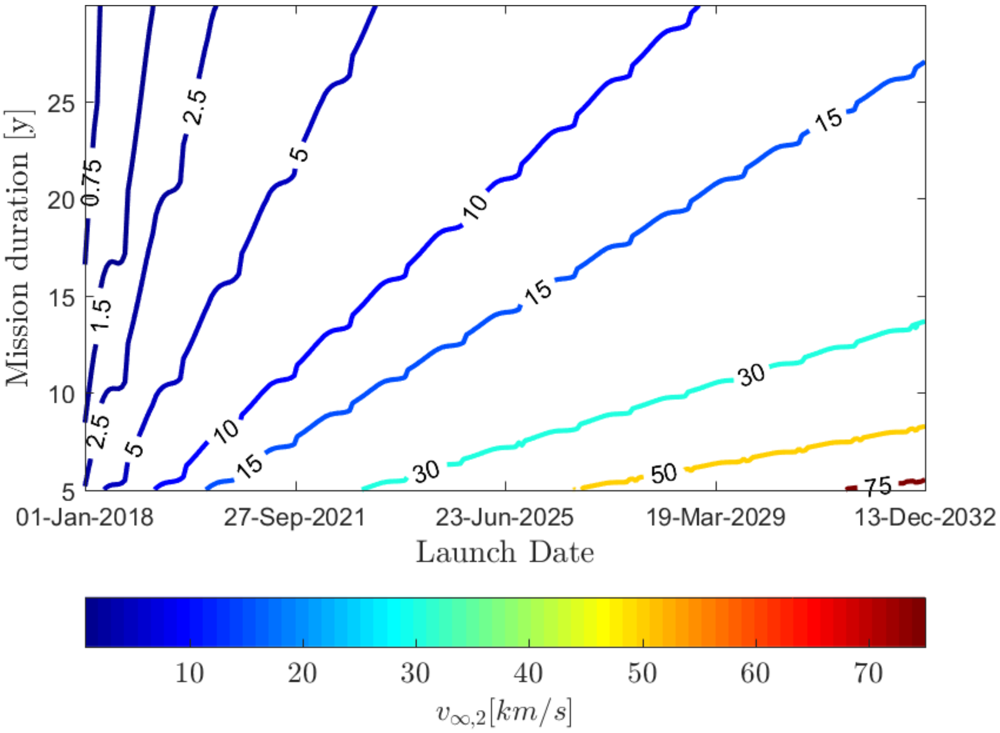

Figure 3: Hyperbolic excess velocities with respect to mission duration and launch date

Figure 4 shows the approximate distance at which the spacecraft passes the object. For a realistic launch date of 2027 or later, the spacecraft flies past the object at a distance between 100 and 200 AU, which is similar to the distance to the Voyager probes today. At such a distance, obviously power and communication becomes an issue and nuclear power sources such as RTGs are required.

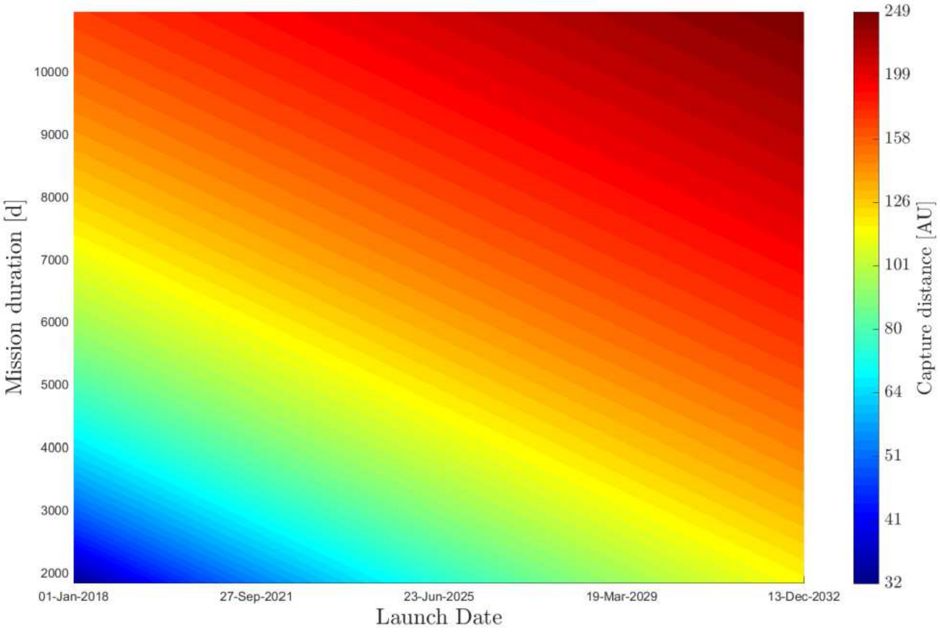

Figure 4: Launch date versus mission duration. Color code indicates the distance at which the spacecraft passes the object

Figure 5 shows a sample trajectory with a launch date in 2025. The orbit of Earth can be seen as a tiny ellipse around the Sun (indicated as a black circle) at the bottom right of the figure. The trajectories of the comet and the spacecraft are almost straight lines.

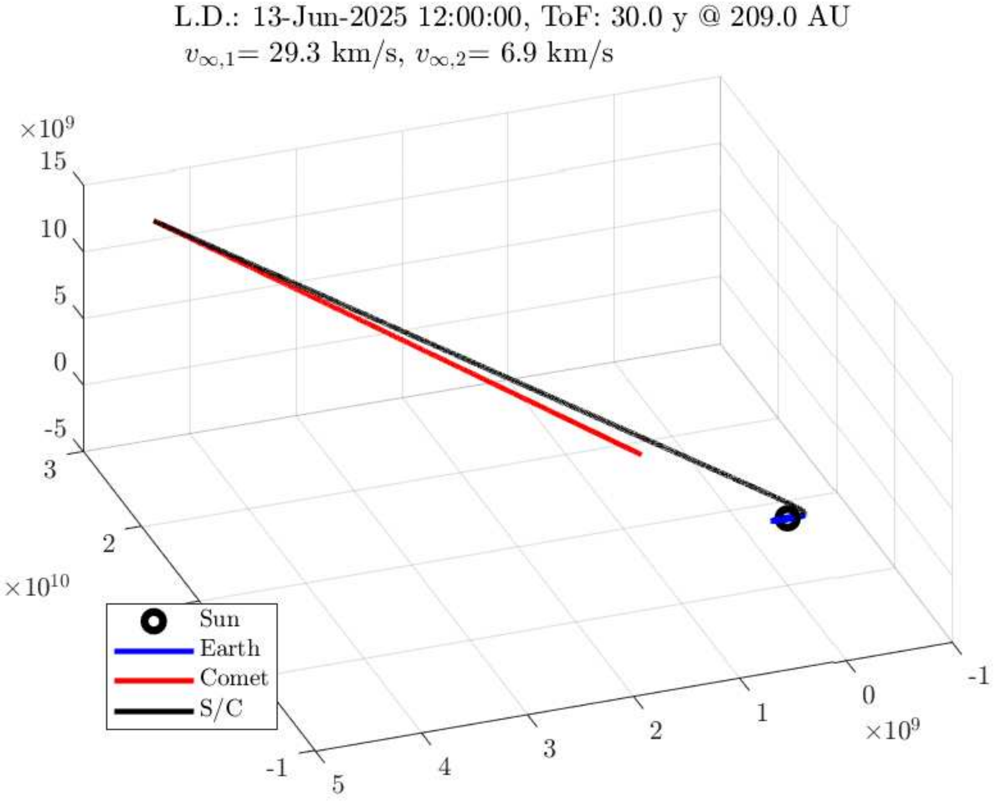

Figure 5: Sample spacecraft trajectory for a launch in 2025 and an encounter with 1I/‘Oumuamua in 2055

Another proposal is to not necessarily chase 1I/‘Oumuamua but to prepare for the next interstellar object to enter our solar system by developing the means to quickly launch a spacecraft towards such an object.

Two scenarios are analysed: First a mission with short duration of only a year, leading to an encounter only 5.8 AU from the sun. However the required hyperbolic excess velocity the current launcher capabilities at approximately 20 km/s. Finally, due to the angle of the encounter, a high velocity relative to the asteroid would be expected, amounting to 13.6 km/s, shown in Figure 6.

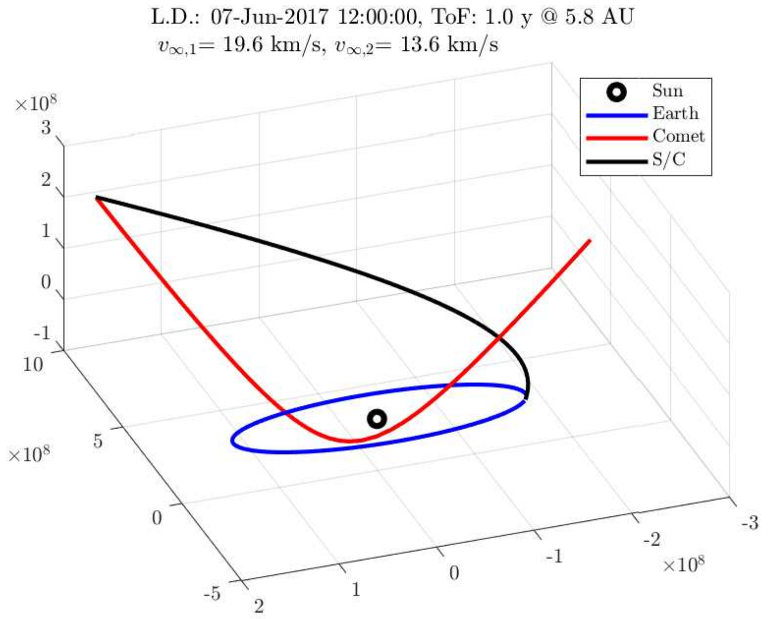

Figure 6: Trajectory for a launch in 2017 and an encounter in 2018

A mission on the same launch date but with a duration of 20 years is shown in Figure 7. At encounter, the relative velocity of the spacecraft with respect to the object is relatively low (about 600m/s for this specific case), which would be an opportunity for a deceleration maneuver.

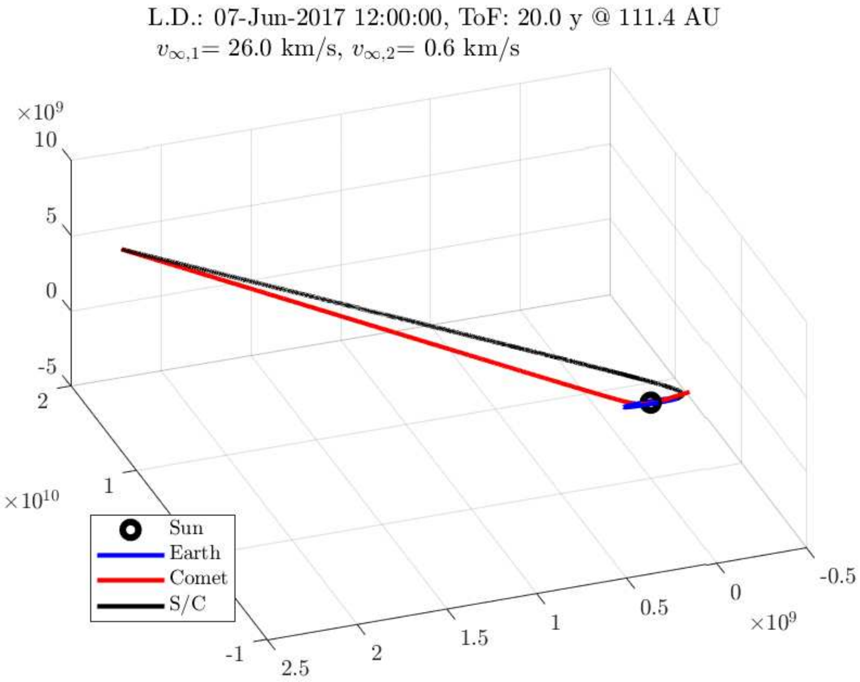

Figure 7: Trajectory for a launch in 2017 and an encounter in 2037

To summarize, the difficulty of reaching 1I/‘Oumuamua is a function of when to launch, the hyperbolic excess velocity, and the mission duration. Future mission designers would need to find appropriate trade-offs between these parameters. For a realistic launch date in 5 to 10 years, the hyperbolic excess velocity is of the order of 33 to up to 76 km/s with an encounter at a distance far beyond Pluto (50-200AU).

3. Concepts and Technologies

As shown previously, chasing 1I/‘Oumuamua with a realistic launch date (next 5-10 years), is a formidable challenge for current space systems.

Nominally a single launch architecture, via the Space Launch System (SLS) for example, would simplify mission design. However other launch providers project promising capabilities in the next few years. One potential mission architecture is to make use of SpaceX’s Big Falcon Rocket (BFR) and their in-space refueling technique with a launch date in 2025. To achieve the required hyperbolic excess (at least 30 km/s) a Jupiter flyby combined with a close solar flyby (down to 3 solar radii), nicknamed “solar fryby” is envisioned. This maneuver is also known under “Oberth Maneuver” [5]. The architecture is based on the Keck Institute for Space Studies (KISS) [6] and the Jet Propulsion Laboratory (JPL) [7] interstellar precursor mission studies. Using the BFR however eliminates the need for multi-planet flybys to build up momentum for a Jupiter trajectory. Instead via direct launch from a Highly Eccentric Earth Orbit (HEEO) the probe, plus various kick-stages, is given a C3 of 100 km²/s² into an 18 month trajectory to Jupiter for a gravity assist into the solar fryby. A multi-layer thermal shield protects the spacecraft, which is boosted by a high-thrust solid rocket stage at perihelion. The KISS Interstellar Medium study computed that a hyperbolic excess velocity of 70 km/s was possible via this technique, a value which achieves an intercept at about 85 AU in 2039 for a 2025 launch. More modest figures can still fulfill the mission, such as 40 km/s with an intercept at 155 AU in 2051. With the high approach speed a hyper-velocity impactor to produce a gas 'puff' to sample with a mass spectrometer could be the serious option to get in-situ data.

The above architecture emphasizes urgency, rather than advanced techniques. Using more advanced technologies, for example solar sails, laser sails, and laser electric propulsion could open up further possibilities to flyby or rendezvous with 1I/‘Oumuamua. In the following, first order analyses for solar and laser sail missions are given.

For the solar sail mission, a launch from Earth orbit is assumed, given a time to launch of 3 to 4 years. The velocity requirement is ~55 km/s, suggesting a lightness number for the mission of 0.15, and a characteristic acceleration of 0.009 m/s2. This requires a sail loading of 1 g/m², advanced materials with light payloads might achieve 0.1 g/m². Given this, for different spacecraft masses assuming a sail loading of σ = 1 g/m² sail design leads to the values shown in Table 1 for a circular and square-shaped sail.

Table 1: Solar sail parameters with respect to spacecraft mass

Spacecraft mass [kg]	Sail area [m²]	Circular radius [m]	Square size [m]
0.001	1	0.56	1
0.01	10	1.78	3
0.1	100	5.64	10
1	1000	17.84	32
10	10,000	56.42	100
100	100,000	178.41	316

The most appropriate and practical design would assume a launch in 4 years and a 1 kg spacecraft mass and lower.

Laser-pushed sail-based missions, based on Breakthrough Initiatives' Project Starshot technology [8–10], would use a 2.74 MW laser beam, with a total velocity increment of 55 km/s, launched in 3.5 years (2021), accelerating at 1g for 3,000s, the probe size would be about 1 gram. It would reach 1I/'Oumuamua in about 7 years. With a 27.4 MW laser then a 10 gram probe could be used. Higher spacecraft masses could be achieved by using different mission architectures, lower acceleration rates, and longer mission durations. However, with such a laser beaming infrastructure in place, hundreds or even thousands of probes could be sent, as illustrated in Figure 8. Such a swarm-based or distributed architecture would allow for gathering data over a larger search volume without the limitations of a single monolithic spacecraft.

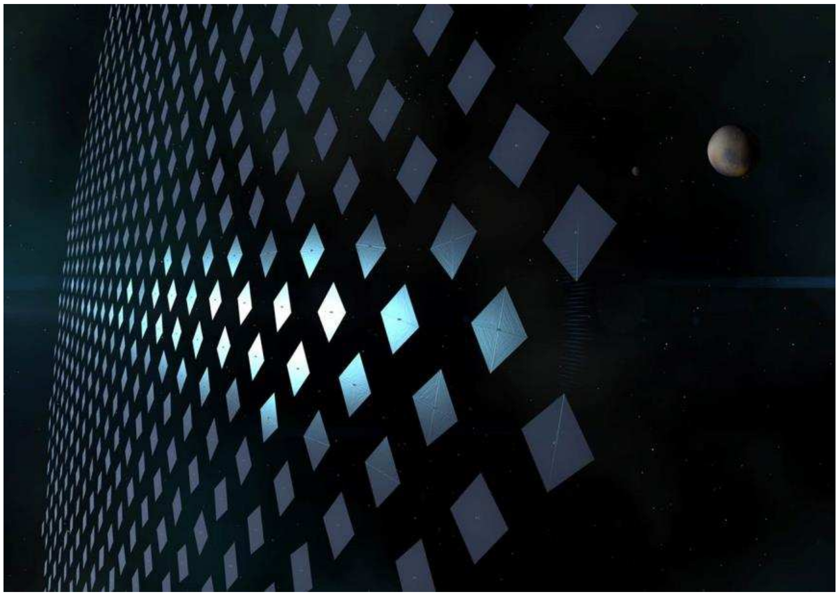

Figure 8: Laser sail swarm (Image credit: Adrian Mann)

Another concept proposed by Streeman and Peck [11] is to send ChipSats into the magnetosphere of Jupiter, then using the Lorentz force to accelerating them to very high velocities of about 3,000 km/s [12,11,13]. However, controlling the direction of these probes might not be trivial.

An important implication is that once an operational Project Starshot beaming infrastructure has been established, even at a small scale, missions to interstellar objects flying through the solar system could be launched within short notice and could justify their development. The main benefit of such an architecture would be the short response time to extraordinary opportunities. The investment would be justified by the option value of such an infrastructure.

Regarding deceleration at the object, obviously existing propulsion systems could be used, e.g. electric propulsion, though limited by the low specific power of RTGs as a power source. With an intercept distance beyond the Heliosphere, into the pristine Interstellar Medium (ISM) more advanced technologies such as magnetic sails [14,15], electric sails [16], and the more recent magnetoshell braking system [17] are worth investigating. The Technological Readiness of these more advanced technologies is currently low, dependent on breakthroughs in superconducting materials manufacture, but they would multiply the scientific return by orders of magnitude.

The small size of the object and its low albedo will make it difficult to observe it once it has entered deep space again. This means the navigation problem of getting a sufficiently accurate fix on 1I/‘Oumuamua to get close enough to the object to send back useful data is considerable. Due to the positional uncertainty of such a difficult-to-track object, a distributed, swarm-based mission design that is able to span a large area, should be investigated.

4. Conclusions

The discovery of the first interstellar object entering our solar system is an exciting event and could be the chance of a lifetime or several lifetimes. In order to assess the feasibility of reaching this object, i4is has recently initiated Project Lyra. In this article, we identified key challenges of reaching 1I/‘Oumuamua and ballpark figures for the mission duration and hyperbolic excess velocity with respect to the launch date. In any case, a mission to the object will stretch the boundary of what is technologically possible today. A mission using conventional chemical propulsion system would be feasible using a Jupiter flyby to gravity-assist into a close encounter with the Sun. Given the right materials, solar sail technology or laser sails could be used.

An important result of our analysis is that the value of a laser beaming infrastructure from the Breakthrough Initiatives’ Project Starshot would be the flexibility to react quickly to future unexpected events, such as sending a swarm of probes to the next object like 1I/‘Oumuamua. With such an infrastructure in place today, intercept missions could have reached 1I/‘Oumuamua within a year.

Future work within Project Lyra will focus on analyzing the different mission concepts and technology options in more detail and to downselect 2-3 promising concepts for further development.

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