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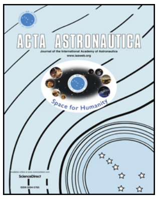

# Project Lyra: Sending a spacecraft to 1I/'Oumuamua (former A/2017 U1), the interstellar asteroid

Andreas M. Hein[a,*], Nikolaos Perakis[a], T. Marshall Eubanks[a,b], Adam Hibberd[a], Adam Crowl[a], Kieran Hayward[a], Robert G. Kennedy III[a], Richard Osborne[a]

[a] *Initiative for Interstellar Studies, Bone Mill, New Street, Charfield, GL12 8ES, United Kingdom*
[b] *Space Initiatives Inc., United States*

## 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 an other star system. 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 a mission to 1I/'Oumuamua and potential similar objects. Reaching 1I/'Oumuamua via a spacecraft launched in a reasonable timeframe of 5-10 years (launch in 2022-2027) requires an Earth departure hyperbolic excess velocity between 33 and 76 km/s for mission durations between 30 and 5 years, respectively. Different mission durations and their velocity requirements are explored with respect to the launch date, assuming direct impulsive transfer to the intercept trajectory. In addition, missions using a powered Jupiter gravity assist combined with a solar Oberth manoeuvre are explored, using solid rocket engines and Parker Solar Probe heat shield technology. For such a mission, a Falcon Heavy-class launcher would be able to launch a spacecraft of dozens of kilograms towards 1I/'Oumuamua, if launched in 2021. An additional Saturn gravity assist would allow for the launch of a New Horizons-class spacecraft. Further technology options are outlined, ranging from electric propulsion, and more advanced options such as laser electric propulsion, solar and laser sails. To maximize science return, decelerating the spacecraft at 'Oumuamua is highly desirable, compared to the minimal science return from a flyby. Electric and magnetic sails could be used for this purpose. It is concluded that although reaching the object is challenging, there seem to be feasible 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]. It is likely that this object has its origin outside the solar system [2–9], with a velocity at infinity of 26.33 km/s, an eccentricity of 1.20, and an incoming radiant (direction of motion) near the solar apex in the constellation Lyra [10]. Its orbital features have been analyzed by Refs. [10,24,25]. Due to the non-observation of a tail in the proximity of the Sun, the object seems to be an asteroid [11]. However, it has been hypothesized that either a cometary tail was present for a brief moment but was not observed [12], as 1I/'Oumuamua was discovered post perihelion, or that an organically rich surface, resulting in an insulating mantle prevented a cometary tail from forming [13]. Such a mantle could be the result of long-term cosmic ray exposure, although Jackson et al. argue against this possibility [14]. The comet hypothesis has been supported by the observation of non-gravitational acceleration, which can be explained by cometary outgassing [15]. However, the question is still far from resolved [16]. Spectroscopic results [12,13,17–21] indicate that the object is reddish, with a distribution similar to Trans-Neptunian objects [18,19,21]. The rapidly changing albedo has also lead to the assumption that the object is rotating and is highly elongated [19,22,23] with estimated dimensions of 230 m × 35 m × 35 m [21]. The axis ratio of $\geq 6.\, 3^{+1.3}_{-1.1}: 1$ seems larger than for any solar system body [21]. Hypotheses for its origin range from a star of the Local Association [4] to a more distant origin in the galactic thin disk, with the ejection dating back several billion years [7,20].

Estimates for the abundance of interstellar objects with a similar size are wide-ranging. Feng and Jones [4] estimate an abundance of interstellar objects larger than 100 m as $6.0 \times 10^{-3} AU^{-3}$. The steady state population of interstellar objects with a size of the order of 100 m inside the orbit of Neptune has been estimated as on the order of $10^4$ by Jewitt et al. [21]. 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. In addition, detailed in-situ studies of interstellar materials at interstellar distances are likely decades away. For example, Breakthrough Starshot, which is developing a laser-propelled interstellar probe along with a beaming infrastructure

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[*] Corresponding author.
*E-mail address:* andreas.hein@i4is.org (A.M. Hein).

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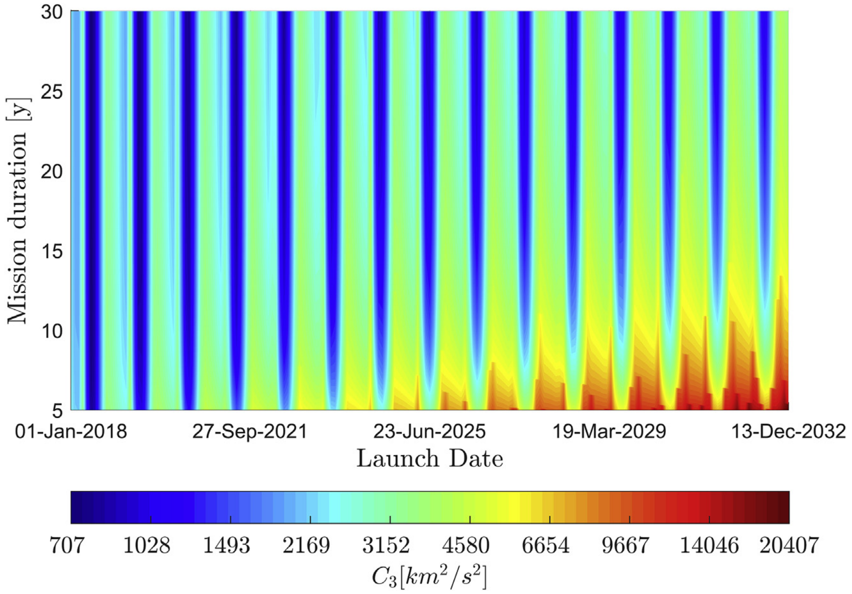

**Fig. 1.** Characteristic energy $C_3$ with respect to mission duration and launch date.

currently aims at a launch date in the 2040s [26]. Hence, an interesting question is if there is a way to exploit this unique opportunity to study interstellar material 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 2017 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 flyby or rendezvous. As 1I/‘Oumuamua is already leaving our solar system, any spacecraft launched in the future would need to chase it. The challenge is formidable. With a heliocentric hyperbolic excess velocity of 26.33 km/s, 1I/‘Oumuamua is considerably faster than Voyager 1, the fastest object leaving the solar system humanity has ever built, which has a hyperbolic excess velocity of 16.6 km/s. Therefore, just the challenge of reaching the object would push the current technological envelope of space exploration. Hence, sending a spacecraft to 1I/‘Oumuamua is interesting from both, a scientific and technological point of view. This paper presents some preliminary results for the feasibility of a mission to 1I/‘Oumuamua and similar objects. We first present an analysis of trajectories without flybys, then trajectories with flybys, and finally concepts and technologies for a potential mission to 1I/‘Oumuamua.

## 2. Trajectory analysis

In the following section, we provide a first-order trajectory analysis assuming one or more impulsive transfers in the vicinity of the Earth and a direct trajectory to 1I/‘Oumuamua. Furthermore, we present results for more complex trajectories with a Jupiter gravity assist and a solar Oberth manoeuvre.

### 2.1. Analysis of trajectories without gravity assists

Given the hyperbolic excess velocity and its inclination with respect to the solar system ecliptic, the first question to answer is, what is the required velocity increment ($\Delta v$, a key parameter for designing the propulsion system) to reach the object? The $\Delta v$ for a mission without gravity assist is calculated by determining the transfer hyperbola from Earth orbit with respect to the position of 1I/‘Oumuamua at a certain point in time. Using the *vis-viva* equation (1), which is a result of the law of conservation of mechanical energy, the orbital velocity $v$ of a body on a hyperbolic trajectory can be computed.

$$v = \sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right)} \tag{1}$$

where $\mu$ is the standard gravitational parameter, $r$ is the radial distance of the object from the central body, and $a$ the semi-major axis. With a few arithmetic manipulations, the relationship (2) between the orbital velocity $v$, the escape velocity $v_{esc}$ from the Sun, and the hyperbolic excess velocity $v_\infty$ can be obtained.

$$v = \sqrt{v_\infty^2 + \frac{2\mu}{r}} \tag{2}$$

$v_\infty$ can be understood as the velocity at infinity with respect to the Sun. Note that the Earth's orbital velocity can be exploited for reducing the required $\Delta v$. Nevertheless the high inclination of 1I/‘Oumuamua relative to the ecliptic requires significant additional $\Delta v$.

$$\Delta v = v - v_{earth}\cos i \cos \eta = \sqrt{v_\infty^2 + \frac{2\mu}{r}} - v_{earth}\cos i \cos \eta \tag{3}$$

where $i$ is the inclination of the trajectory with respect to the ecliptic and $\eta$ the angle between the velocity vector of the trajectory and the velocity vector of the Earth.

Obviously, a slower spacecraft will reach the object later than a faster spacecraft, leading to a trade-off between mission duration (from launch to encounter) and required $\Delta v$. Furthermore, the earlier the spacecraft is launched the shorter the mission duration, as the object is closer. However, a launch date within the next 5 years is likely to be unrealistic, given the time it currently takes to design and develop a new spacecraft. Even 10 years could be challenging, in case new technologies need to be developed. A third trade-off is between launch date and $\Delta v$, expressed in terms of characteristic energy $C_3$. The characteristic energy is the square of the Earth departure hyperbolic excess velocity $v_{\infty,1}$. These trade-offs are captured in Fig. 1. The figure plots the characteristic energy $C_3$ 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 flyby is taken into consideration, only a direct trajectory towards the object. It can be seen that a minimum $C_3$ exists, which is about 703 $km^2/s^2$ (26.5 km/s). However, this minimum value rapidly increases when the launch date is moved into the future. At the same time, a longer mission duration leads to a decrease of the required $C_3$ but also implies an encounter with the object at a larger distance from the Sun. We assume that the earliest realistic launch date for a probe would be between 5 and 10 years in the future (2022-2027). The required $v_{\infty,1}$ is between 33 and 76 km/s, for mission durations between 30 and 5 years, respectively. For example, assuming a launch date for a probe 10 years in the future (2027), $v_{\infty,1}$ is at 37.4 km/s (1400 $km^2/s^2$) with a mission duration of about 15 years. These values show that such a mission is extremely challenging with conventional propulsion systems in the absence of flyby manoeuvres.

Apart from the hyperbolic excess velocity at launch, the excess velocity relative to the object at encounter ($v_{\infty,2}$) has to be taken into account, since it defines the type of mission that is achievable, for example, a flyby or orbital insertion. $v_{\infty,2}$ can be calculated via equation (4), where $v_{\infty,2}$ is the difference between the heliocentric hyperbolic excess of the spacecraft $v_{\infty,SC}$ and the heliocentric hyperbolic excess of 1I/'Oumuamua $v_{\infty,1I}$.

$$v_{\infty,2} = v_{\infty,SC} - v_{\infty,1I} \tag{4}$$

A high $v_{\infty,2}$ reduces the time available for measurements close to the interstellar object during the flyby. By contrast, a low value for $v_{\infty,2}$ could even enable orbital insertion around the object with an impulsive or low thrust manoeuvre to decelerate the probe. The excess velocity at arrival is plotted in Fig. 2 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 favourable position for a launch towards the object. It can be seen that a $v_{\infty,2}$ below 1 km/s implies a launch in 2018 and a flight duration of over 15 years. Such a value for $v_{\infty,2}$ does not prohibit an orbital insertion around 1I/'Oumuamua. However, this minimum value rapidly increases for later launch dates. The earliest realistic launch date for a probe would be between 5 and 10 years in the future (2022-2027). The resulting values for $v_{\infty,2}$ between 5 and 50 km/s exceed the current chemical and electric propulsion system capabilities in deep space, and hence, a flyby of 1I/'Oumuamua seems to be the only feasible option.

Fig. 3 shows the approximate distance at which the spacecraft passes the object. For a realistic launch date of 2022-2027, the spacecraft flies past the object at a distance from the Sun between 50 and 200 AU. At such a distance, observing the object and transmitting the data back becomes an issue and nuclear energy sources such as radioisotope thermoelectric generators (RTGs) are required.

Fig. 4 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 blue circle) at the bottom right of the figure. The trajectories of the comet and the spacecraft are almost straight lines.

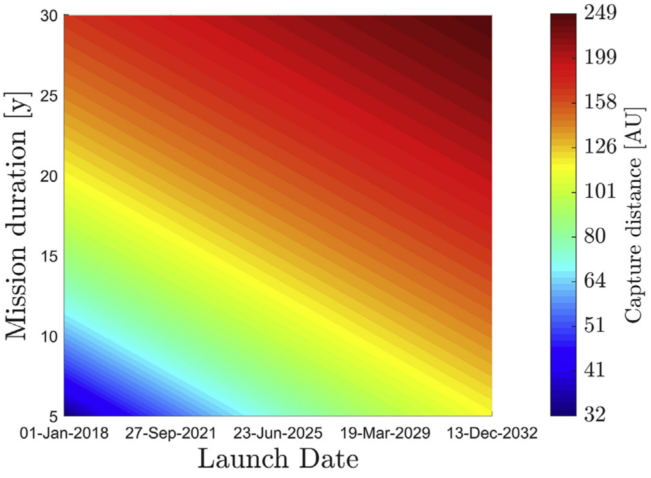

**Fig. 3.** Launch date versus mission duration. Colour code indicates the capture distance, i.e. the distance from the Sun at which the spacecraft passes the object. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

An alternative proposal is to be ready for the next interstellar object to enter our solar system by developing the means to quickly launch a spacecraft towards such an object upon detection, as proposed by Seligman and Laughlin [49]. In the following, we assume an object with the same orbital parameters as 1I/'Oumuamua.

Two scenarios are analyzed: First, a mission with a short duration of only a year, leading to an encounter only 5.8 AU from the Sun. The required hyperbolic excess velocity $v_{\infty,1}$ is approximately 20 km/s. Finally, due to the angle of the encounter, a high velocity relative to the object would be expected, amounting to 13.6 km/s, shown in Fig. 5.

Second, a mission on the same launch date but with a duration of 20 years is shown in Fig. 6. At encounter, the relative velocity of the spacecraft with respect to the object is relatively low (about 600 m/s for this specific case), which would be an opportunity for a deceleration manoeuvre. Hence, early detection and quick launch reduce the difficulty of reaching an interstellar object with similar orbital parameters to 1I/'Oumuamua, although it remains challenging from a propulsion perspective.

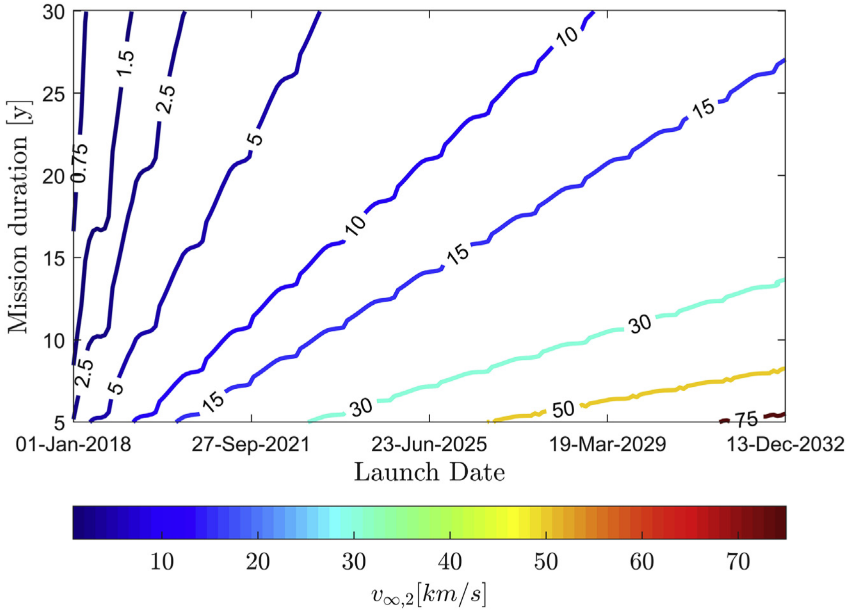

**Fig. 2.** Encounter velocities with respect to mission duration and launch date.

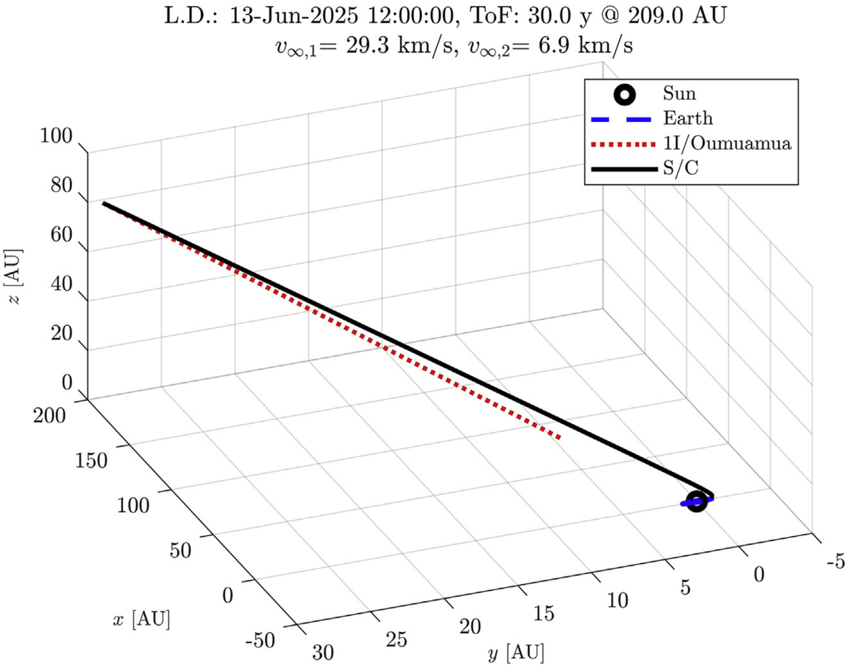

**Fig. 4.** Sample spacecraft trajectory for a launch in 2025 and an encounter with 1I/‘Oumuamua in 2055.

To summarize, the difficulty of reaching 1I/‘Oumuamua is a function of when to launch, the Earth departure 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 5-10 years (2022-2027), the Earth departure 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).

### 2.2. Analysis of trajectories with flybys

In order to achieve the required hyperbolic excess (at least 30 km/s) for a rendezvous with 1I/‘Oumuamua using chemical propulsion systems, a Jupiter gravity assist is combined with a close, powered slingshot at the Sun (down to 3 solar radii). The powered solar flyby is also known under “Oberth Manoeuvre” [27,28]. The architecture is based on the Keck Institute for Space Studies (KISS) [29] and the Jet Propulsion Laboratory (JPL) [30] interstellar precursor mission studies. In the following, a few results for this mission architecture are presented. Details about the required technologies are provided in section 3.

For calculating the trajectory, the Optimum Interplanetary Trajectory Software (OITS) developed by Adam Hibberd was used. A patched conic approximation is applied, i.e. within the sphere of influence of a celestial body, only its respective gravitational attraction is taken into consideration and the gravitational attraction of other bodies are neglected. The trajectory connecting each pair of celestial bodies is

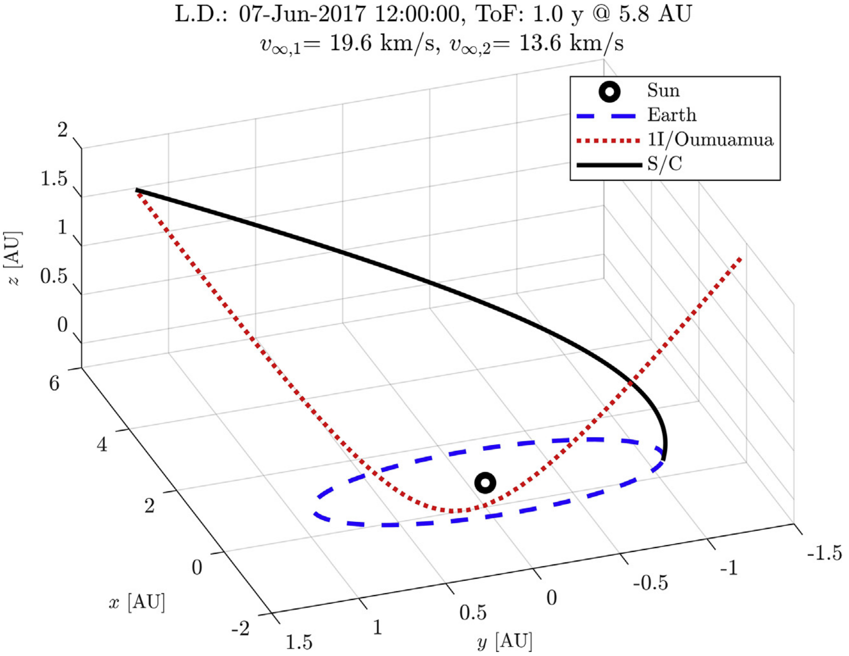

**Fig. 5.** Trajectory for a launch in 2017 and an encounter in 2018.

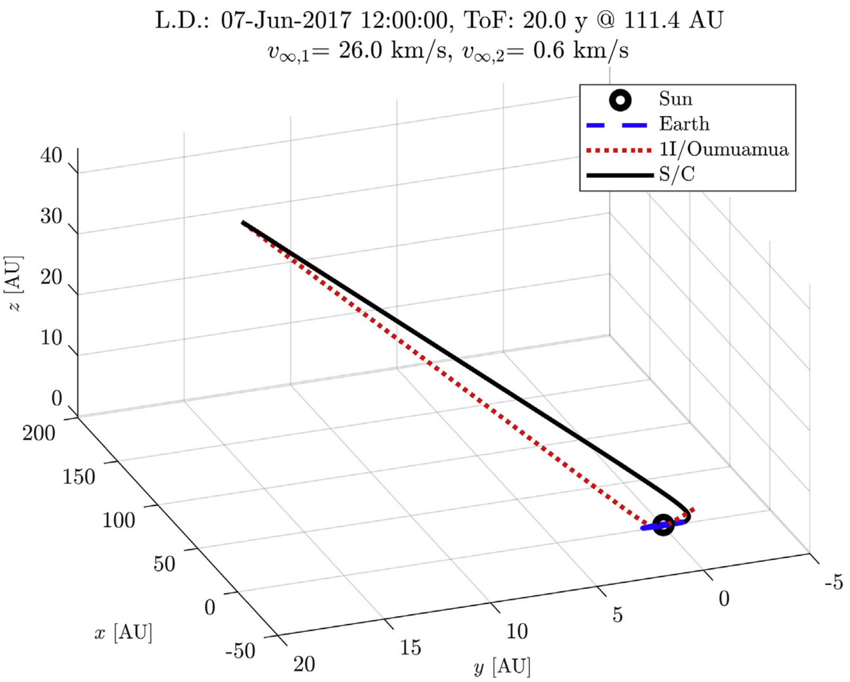

**Fig. 6.** Trajectory for a launch in 2017 and an encounter in 2037.

determined by solving the Lambert problem using the Universal Variable Formulation [31]. This non-linear global optimization problem with inequality constraints is solved using the NOMAD solver [48].

The resulting minimal Δ*v* for an eight-year flight duration is shown in Fig. 7. The Δ*v* varies between 18 km/s for a launch date in April to May 2021 up to a value of 54 km/s for a launch in October 2021. The fluctuation in Δ*v* is mainly due to the Earth's alignment with Jupiter, which fluctuates on a yearly cycle. A second fluctuation is due to the alignment of Jupiter with 1I/'Oumuamua, which fluctuates on a Jupiter-yearly cycle, equivalent to about 12 Earth years, resulting in a minimal Δ*v* in 2021 and 2033. The dashed curve shows the minimum Δ*v* for a trajectory without the Jupiter gravity assist and the solar Oberth manoeuvre. It can be seen that the Δ*v* is always higher, although the difference is only about 5 km/s for a launch in July to September.

Fig. 8 shows a visualization of the trajectory with the first leg from Earth to Jupiter, the second leg from Jupiter to the Sun, and the subsequent encounter trajectory with 1I/'Oumuamua with an encounter at 69 AU. The heliocentric hyperbolic excess velocity is 55.7 km/s.

The minimum Δ*v* budget for the year 2021 is decomposed in Table 1. The $C_3$ after Earth escape is 99.7 km$^2$/s$^2$.

The duration of the individual trajectory legs is shown in Table 2. The Earth-Jupiter outbound leg has a duration of about 18 months, about 10.5 months for getting from Jupiter to the Sun, and 69 months from the Sun to 1I/'Oumuamua.

A further possibility for reducing the total Δ*v* requirement is to add a Saturn gravity assist after the Oberth manoeuvre. The Saturn gravity assist provides an additional deflection of the trajectory towards 1I/'Oumuamua, thereby relaxing the requirement for the Jupiter powered gravity assist and the Oberth manoeuvre. An example for this mission configuration is shown in Fig. 9 with a launch date in 2020.

As summarized in Table 5, the velocity requirement for this mission is listed, whereas Table 6 shows the start and end date of each individual trajectory leg. Due to the additional gravity assist, the flight duration is increased and the probe arrives at the target in 2049, at a distance of 183 AU from the Sun. Compared to the mission scenario utilizing no Saturn gravity assist, the larger distance from the Sun implies lower light intensity during payload operations, which would significantly restrict any optical measurements.

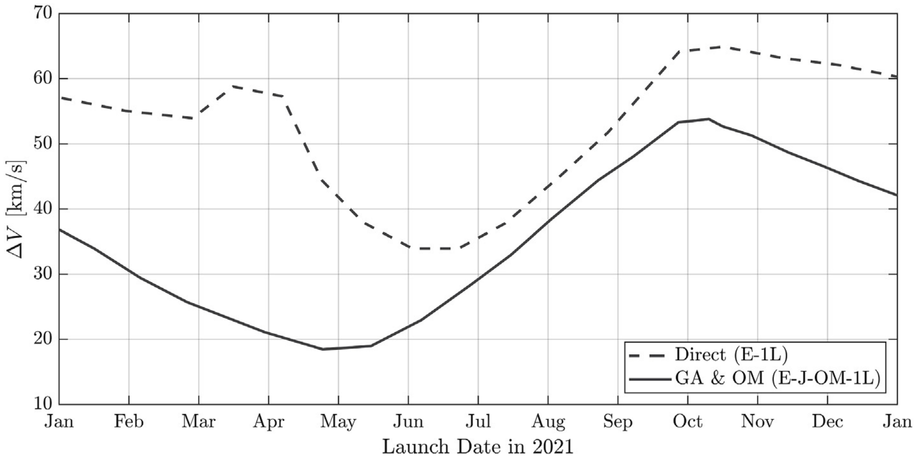

**Fig. 7.** Minimum Δ*v* for combined Jupiter gravity assist (GA) and solar Oberth manoeuvre (OM) and a launch date in 2021.

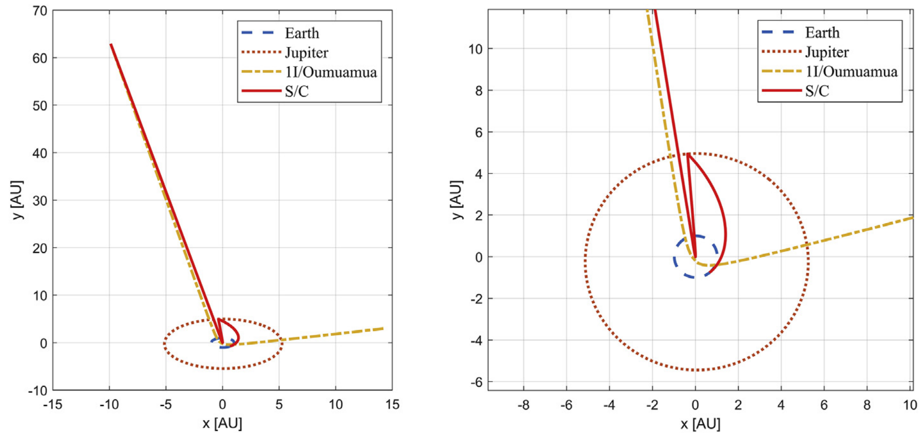

**Fig. 8.** Trajectory with Jupiter gravity assist and solar Oberth manoeuvre.

**Table 1**
$\Delta v$ budget for minimum $\Delta v$ trajectory for a launch in 2021.

| Manoeuvre | $\Delta v$ [m/s] |
|---|---|
| Earth departure | 9985 |
| Jupiter gravity assist | 4166 |
| Solar Oberth manoeuvre | 4181 |
| **Total $\Delta v$** | **18,332** |

**Table 2**
Start and end dates of the trajectory legs for a mission using Jupiter gravity assist and Oberth manoeuvre.

| Trajectory leg | Start date | End date |
|---|---|---|
| Earth to Jupiter | 2021 April 30 | 2022 October 6 |
| Jupiter to Sun | 2022 October 6 | 2023 July 14 |
| Sun to 1I/‘Oumuamua | 2023 July 14 | 2029 April 23 |

**Table 3**
Propulsion characteristics and mass budget for Jupiter gravity assist plus Oberth manoeuvre, SLS launcher.

| | Jupiter gravity assist | Solar Oberth |
|---|---|---|
| $\Delta v$ [m/s] | 4166 | 4181 |
| $I_{sp}$[s] | 292 | 292 |
| Mass ratio | 4.3 | 4.3 |
| Initial mass | 6000 | 987 |
| Final mass [kg] | 1401 | 229 |
| Propellant mass [kg] | 4599 | 758 |
| Solid rocket engine dry mass [kg] (9%) | 414 | 68 |
| Solid rocket engine wet mass [kg] | 5013 | 826 |
| Final mass after Oberth manoeuvre and engine ejection [kg] | | 161 |
| Heat shield mass [kg] | | 39 |
| **Spacecraft mass [kg]** | | **122** |

A Jupiter gravity assist would require alignment of Jupiter with 1I/‘Oumuamua, imposing constraints on potential launch dates. A combined Jupiter and Saturn gravity assist would impose even more constraints. Hence, one question is whether we could achieve a solar Oberth manoeuvre without a gravity assist. A sample manoeuvre would involve a $C_3$ of $64\,\mathrm{km}^2/\mathrm{s}^2$ for leaving Earth and would catapult the spacecraft into an elliptic, heliocentric orbit with an aphelion of 4.1 AU. In order to perform an Oberth manoeuvre, a $\Delta v$ of 7.35 km/s is required at aphelion.

In the following section, potential near- and mid-term technologies that could be used for a mission to 1I/‘Oumuamua are presented.

**Table 4**
Propulsion characteristics and mass budget for Jupiter gravity assist plus Oberth manoeuvre, Falcon Heavy.

| | Jupiter gravity assist | Solar Oberth |
|---|---|---|
| $\Delta v$ [m/s] | 4166 | 4181 |
| $I_{sp}$ [s] | 292 | 292 |
| Mass ratio | 4.3 | 4.3 |
| Initial mass | 1800 | 296 |
| Final mass [kg] | 420 | 69 |
| Propellant mass [kg] | 1380 | 227 |
| Solid rocket engine dry mass [kg] (9%) | 124 | 20 |
| Solid rocket engine wet mass [kg] | 1504 | 248 |
| Final mass after Oberth maneuver and engine ejection [kg] | | 48 |
| Heat shield mass [kg] | | 12 |
| **Spacecraft mass [kg]** | | **36** |

## 3. Concepts and technologies

As shown previously, chasing 1I/‘Oumuamua with a near-term launch date (next 5-10 years), is a formidable challenge for current space systems. However, we will demonstrate that currently planned launch systems and existing technologies can be used for such a mission.

### *3.1. Technologies for solar Oberth Manoeuvre*

Three launch systems that will be available in the next 5-10 years that could be used for a mission to 1I/‘Oumuamua are NASA's Space Launch System (SLS), the SpaceX Falcon Heavy, and the SpaceX Big Falcon Rocket (BFR). Nominally a single launch architecture, for example, using the SLS 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. Using the BFR eliminates the need for multi-planet gravity assists to build up momentum for a Jupiter trajectory. Instead, the probe and its kick-stages would be launched from a highly eccentric Earth orbit (HEO) and is given a $C_3$ of $100\,\mathrm{km}^2/\mathrm{s}^2$ into an 18 month trajectory to Jupiter for a gravity assist into the solar Oberth manoeuvre. A heat shield protects the spacecraft, which is boosted by a high-thrust solid rocket engine at perihelion. The KISS Interstellar Medium study computed that a heliocentric hyperbolic excess velocity of 70 km/s was possible via this technique [29]. As the calculations in section 2.2 have shown, this is more than enough for reaching 1I/‘Oumuamua within 8-14 years. More modest figures can still fulfil the mission, such as 40 km/s with an intercept at 155 AU in 2051. With the

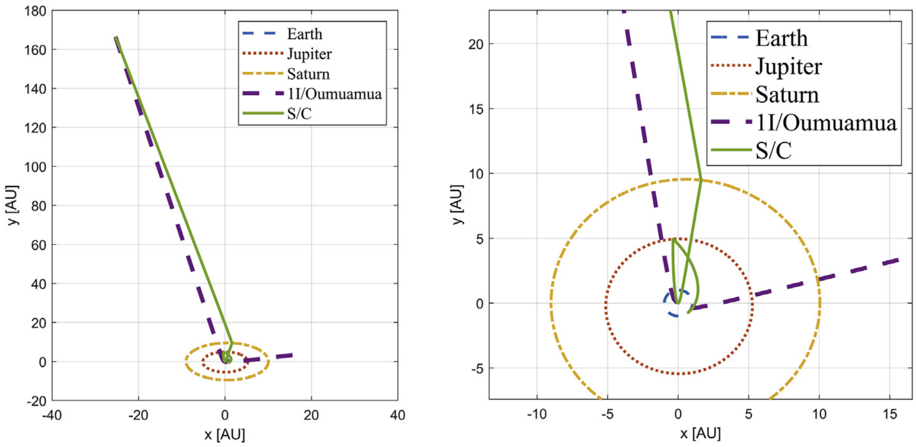

**Fig. 9.** Trajectory with Jupiter gravity assist, solar Oberth manoeuvre and Saturn gravity assist.

**Table 5**
$\Delta v$ budget for minimum $\Delta v$ trajectory in 2020 using Jupiter gravity assist, Oberth manoeuvre and Saturn gravity assist.

| Manoeuvre | $\Delta v$ [m/s] |
|---|---|
| Earth departure | 9991 |
| Jupiter gravity assist | 1965 |
| Solar Oberth manoeuvre | 1650 |
| Saturn gravity assist | 0 |
| **Total $\Delta v$** | **13,606** |

**Table 6**
Start and end dates of the trajectory legs for a mission using Jupiter gravity assist, Oberth manoeuvre and Saturn gravity assist.

| Trajectory leg | Start date | End date |
|---|---|---|
| Earth to Jupiter | 2021 April 30 | 2022 October 5 |
| Jupiter to Sun | 2022 October 5 | 2024 August 14 |
| Sun to Saturn | 2023 November 20 | 2025 January 26 |
| Saturn to 1I/'Oumuamua | 2025 January 26 | 2049 September 7 |

**Table 7**
Propulsion characteristics and mass budget for Jupiter gravity assist plus Oberth manoeuvre, SLS launcher.

| | Jupiter gravity assist | Solar Oberth |
|---|---|---|
| $\Delta v$ [m/s] | 1965 | 1650 |
| $I_{sp}$ [s] | 292 | 292 |
| Mass ratio | 2.0 | 1.8 |
| Initial mass | 6000 | 2753 |
| Final mass [kg] | 3021 | 1548 |
| Propellant mass [kg] | 2979 | 1205 |
| Solid rocket engine dry mass [kg] (9%) | 268 | 108 |
| Solid rocket engine wet mass [kg] | 3247 | 1314 |
| Final mass after Oberth manoeuvre and engine ejection [kg] | | 1439 |
| Heat shield mass [kg] | | 110 |
| **Spacecraft mass [kg]** | | **1329** |

**Table 8**
Propulsion characteristics and mass budget for Jupiter gravity assist plus Oberth manoeuvre, Falcon Heavy.

| | Jupiter gravity assist | Solar Oberth |
|---|---|---|
| $\Delta v$ [m/s] | 1965 | 1650 |
| $I_{sp}$ [s] | 292 | 292 |
| Mass ratio | 2.0 | 1.8 |
| Initial mass | 1800 | 826 |
| Final mass [kg] | 906 | 464 |
| Propellant mass [kg] | 864 | 362 |
| Solid rocket engine dry mass [kg] (9%) | 80 | 33 |
| Solid rocket engine wet mass [kg] | 974 | 394 |
| Final mass after Oberth manoeuvre and engine ejection [kg] | | 432 |
| Heat shield mass [kg] | | 33 |
| **Spacecraft mass [kg]** | | **399** |

**Table 9**
SLS Block 1B EUS-based spacecraft mass budget for Jupiter gravity assist plus Oberth manoeuvre.

| Space system element | Mass [kg] |
|---|---|
| Jupiter powered gravity assist solid rocket engine (9% dry mass) | 5013 |
| Solar Oberth manoeuvre solid rocket engine (9% dry mass) | 826 |
| Spacecraft wet mass | 122 |
| Heat shield | 39 |
| **Total mass** | **6000** |

high approach speed a hyper-velocity impactor could produce a gas cloud, which is then sampled with a mass spectrometer. Due to their higher maturity compared to the BFR, in the following, we focus on the SLS and Falcon Heavy as potential launch systems for a spacecraft to 1I/'Oumuamua.

Similar to the KISS study [29], we assume a solid rocket engine for the Oberth manoeuvre burn. However, contrary to the KISS study, an additional solid rocket engine is used during the powered Jupiter gravity assist. We assume a scaled up version of the Star solid rocket engine with an $I_{sp}$ of 292 s for both solid rocket engines. In addition, due to the time constraints on mission duration, no deep space manoeuvre for reducing the $C_3$ is performed, which is estimated by the KISS study to take almost two years.

According to Creech [36], using a SLS Block 1B with an Exploration Upper Stage (EUS) can achieve a $C_3$ of 100 $\text{km}^2/\text{s}^2$ with a 6 metric ton payload. We estimate the shield mass, using values from the Solar Parker probe, and multiply the combined wet mass of the solid rocket engine and the final mass after solid engine ejection by 4.4%. Using these estimates and calculating the masses for the solid rocket engines, the heat shield and the spacecraft wet mass yields the values in Table 9. Table 3 for a Jupiter gravity assist plus Oberth manoeuvre. With an additional Saturn gravity assist, roughly 11 times higher spacecraft masses can be achieved, due to the much lower $\Delta v$, as shown in Table 7.

As an alternative, the Falcon Heavy is considered. The payload mass for a $C_3$ of 100 $\text{km}^2/\text{s}^2$ is roughly 1800 kg. Working backwards yields the values in Table 4 and Table 10 with a wet mass of the final

**Table 10**
Falcon Heavy-based spacecraft mass budget for Jupiter gravity assist plus Oberth manoeuvre.

| Space system element | Mass [kg] |
|---|---|
| Jupiter powered gravity assist solid rocket engine | 1504 |
| Solar Oberth manoeuvre solid rocket engine | 248 |
| Spacecraft wet mass | 36 |
| Heat shield | 12 |
| **Total mass** | **1800** |

spacecraft of about 36 kg.

With an additional Saturn gravity assist, a Falcon Heavy could send a New Horizons-class spacecraft to 1I/'Oumuamua, as shown in Table 8.

The above architecture emphasizes urgency, rather than advanced techniques. An alternative to applying the 7.35 km/s at aphelion by a powered gravity assist is by an electric propulsion system, such as the NASA NEXT ion engine [32,33]. Assuming a pre-Oberth mass of 5745 kg, and allowing 500 kg for ion drives, Xenon tanks, etc. results in 1224 kg of Xenon. A 10% margin results in 1350 kg, for a total mass of 7595 kg. The SLS Block 1B will be able to achieve $C_3 = 64\ \text{km}^2/\text{s}^2$. A $\Delta v$ of 7.35 km/s over 2 years requires an acceleration of $1.1 \times 10^{-4}\ \text{m/s}^2$, which results in a thrust of the order of 0.8 N. With the published NEXT efficiency, a total electric power of 24 kW would be needed, ideally at 4 AU. If power would be supplied by solar arrays, it results in surface area of about $1000\ \text{m}^2$ for panels with 25% efficiency. Although the Juno spacecraft uses solar arrays at about the same distance as power supply, the power generated is about two orders of magnitude lower. A less mature technology for supplying power to a spacecraft at 4 AU distance would be a laser electric propulsion system, such as proposed by Landis et al. [34] where power is beamed over planetary distances and converted into electricity via solar arrays. Taking a sample specific mass for the power conversion system of 0.25 kg/kW from Brophy [35], it would result in a mass of 96 kg. The beam power of the corresponding laser infrastructure would be on the order of 1 MW.

Using more advanced technologies, for example, laser electric propulsion, solar sails, and laser sails 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.

### 3.2. Technologies for solar and laser sails

For the solar sail mission, a launch from Earth orbit is assumed, given a launch in 2020-2021. We assume a representative velocity requirement of ~55 km/s, suggest a lightness number λ (ratio of the maximum acceleration of the spacecraft divided by the Sun's local gravity) for the mission of 0.15, and a characteristic acceleration of $0.009\ \text{m/s}^2$. This requires a sail loading of $1\ \text{g/m}^2$; advanced materials with light payloads might achieve $0.1\ \text{g/m}^2$. Given this, assuming a sail loading of $\sigma = 1\ \text{g/m}^2$ leads to the spacecraft masses shown in Table 11 for a circular and square sail.

Extrapolating from existing solar sailcraft such as LightSail-1, a launch in 3-4 years (2020-2021) of a kg-class spacecraft seems to be feasible.

**Table 11**
Solar sail parameters with respect to spacecraft mass for $\sigma = 1\ \text{g/m}^2$.

| Spacecraft mass [kg] | Sail area [$\text{m}^2$] | Circular diameter [m] | Square size [m] |
|---|---|---|---|
| 0.001 | 1 | 1.1 | 1 |
| 0.01 | 10 | 3.6 | 3.2 |
| 0.1 | 100 | 11 | 10 |
| 1 | 1000 | 36 | 32 |
| 10 | 10,000 | 113 | 100 |
| 100 | 100,000 | 357 | 316 |

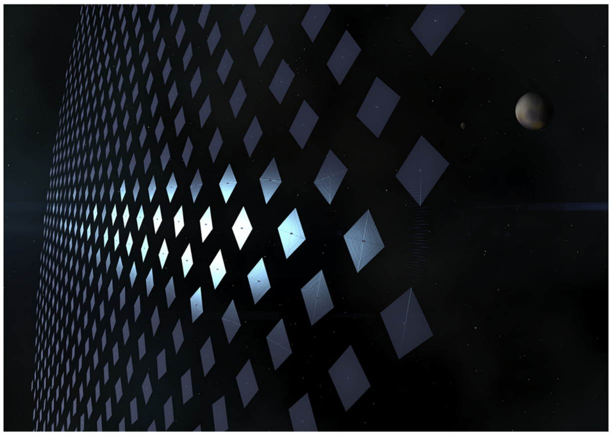

**Fig. 10.** Laser sail swarm (Image credit: Adrian Mann).

Laser-pushed sail-based missions, based on Breakthrough Starshot technology [37–39], would employ a 2.7 MW laser beam for a 1 g probe. With a total velocity increment of 55 km/s, launched in 3.5 years (2021), accelerating at 1 g for 3,000 s, it would reach 1I/'Oumuamua in about 7 years (see Fig. 1). A 27.4 MW laser would allow for a 10 g probe to be launched. 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, though they would neither be launched nor arrive all at once as depicted in the artist's concept in Fig. 10. 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.

An important implication is that once an operational Breakthrough 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 [40]. 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.

### 3.3. Lorentz force acceleration

Another concept proposed by Streetman and Peck [41] is to send ChipSats into the magnetosphere of Jupiter, then using the Lorentz force to accelerate them to very high velocities of about 3000 km/s [41–43]. However, controlling the direction of these probes might not be trivial.

### 3.4. Technologies for deceleration

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 laser electric propulsion [35], magnetic sails [44,45], electric sails [46], and the more recent magnetoshell braking system [47] 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.

### 3.5. Navigation

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 collect and send back useful data is considerable. There are therefore two alternatives for increasing the likelihood of getting sufficiently accurate remote sensing data back. Either a spacecraft with a sufficiently large aperture is sent sufficiently close to the object or a sufficiently large number of spacecraft is sent to the object with at least one spacecraft approaching close enough.

Let $m$ be the apparent optical magnitude and $H$ the absolute optical magnitude (for 1I, 22.5-25 depending on the optical phase. Intercept is at a distance $R$ from the Sun, and the spacecraft is a distance $d$ away from 1I/‘Oumuamua).

Then

$$m = H + 2.5\log\left(\frac{d^2R^2}{1AU^4}\right) = H + 5\log\left(\frac{dR}{1AU^2}\right) \tag{5}$$

With a sufficiently large telescope aperture, the largest detectable $m$ happens to be $\sim H$, which gives immediately for detection

$$d \sim \frac{1}{R} \tag{6}$$

If $R$ is 100 AU, $d$ is of the order of 1/100 AU, or 1.5 million km. If $R$ is 150 AU, $d$ is $\sim$1 million km.

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 a unique opportunity for in-situ observations. This article identifies key challenges of reaching 1I/‘Oumuamua and ballpark figures for the mission duration and hyperbolic excess velocity with respect to the launch date. Furthermore, a more detailed mission analysis is performed for a combined powered Jupiter gravity assist and solar Oberth manoeuvre. It is demonstrated that based on currently existing technologies such as from the Parker Solar Probe, launchers such as the Falcon Heavy and Space Launch System could send spacecraft with masses ranging from dozens to hundreds of kilograms to 1I/‘Oumuamua if launched in 2021. A further increase in spacecraft mass can be achieved with an additional Saturn gravity assist post solar Oberth manoeuvre. The potential of more advanced technologies such as laser electric propulsion, solar and laser sails would also allow for chasing 1I/‘Oumuamua, although their development will likely push launch dates farther into the future and might be more attractive for reaching future ‘Oumuamua-like objects. The value of a laser beaming infrastructure from Breakthrough Starshot could be the flexibility to react quickly to future unexpected events, such as sending a swarm of probes to the next object. 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.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actaastro.2018.12.042.

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