As a contributor to Project Lyra, the investigation of spacecraft missions to the first interstellar object to be discovered in our Solar System, designated 'Oumuamua, I was responsible for the development of a powerful software tool called ‘Optimum Interplanetary Trajectory Software’ (OITS). It is through exploiting OITS to investigate 'Oumuamua as a target that I introduced myself to the Project Lyra team, who had already conducted some investigations of their own on the subject by this time.

For an overview of the results of this research, spanning several peer-reviewed papers and preprints it turns out there are several different routes a chemical-rocket-propelled spacecraft could exploit to catch-up with 'Oumuamua. The emphasis is on chemical propulsion due to its high 'Technical Readiness Level' (TRL) and, conveniently, it is a high thrust option rendering the results of OITS both valid and pertinent.

The following are the feasible trajectory options for Project Lyra with chemical propulsion:

1) A Solar ‘Slingshot’ or Solar Oberth Manoeuvre (SOM)
2) A Jupiter Oberth Manoeuvre (JOM)
3) A Passive Jupiter Gravitational Assist (PJGA)
4) A Double Jupiter Gravitational Assist (DJGA)

Note that a direct route is not listed above as it requires too high a mission ΔV, an important finding highlighted in the first Project Lyra paper. But it doesn’t end there, it turns out there are plenty of further problems in the realisation of a mission to ‘Oumuamua.

The main issue is simply one of uncertainty as to where ‘Oumuamua will be in ~30 years or so time, which would be around the time the putative Lyra craft would catch the target. There are two contributing factors to this positional uncertainty, both associated with the calculation of ‘Oumuamua’s trajectory as it encountered the inner solar system. The first is the short time span over which ‘Oumuamua ephemerides were measured, to wit, the overall observation cadence started from 14th October 2017 (prediscovery by the Catalina Sky Survey), continued through to the 19th October initial detection by Pan-STARRS 1, and finally ended at the last date the Hubble Space Telescope observed ‘Oumuamua before it became too dim on 2nd January 2018.

The second factor was the presence of a non-gravitational acceleration clearly and unambiguously identified by performing a fit to ‘Oumuamua’s trajectory as it receded from the Sun. There is a lot of debate and even controversy over the cause of this anomalous acceleration which we shan’t delve into here, though no one disputes its presence and although the error bar on this is more than would be desired, nevertheless the magnitude of this acceleration compared to its standard deviation, makes it a significant discovery.

Adam Hibberd

[1] More details of this pioneering work in Paul Gilster’s Centauri Dreams Project Lyra: Sending a Spacecraft to 1I/Oumuamua (formerly A/2017 U1), the Interstellar Asteroid (www.centauri-dreams.org/2017/11/10/project-lyra-sending-a-spacecraft-to-1ioumuamua-formerly-a2017-u1-the-interstellar-asteroid/) and our first academic paper on arXiv with the same title (arxiv.org/abs/1711.03155).
When we consider both influences on uncertainty, we find that in 30 years hence, the lateral position error of ‘Oumuamua is on the order of one or two Moon distances. This would appear to render a mission (which would naturally have to return useful data on ‘Oumuamua back to Earth) an impossibility, especially when one considers the encounter distance from the Sun would be ~200 au, and thus ‘Oumuamua would be exceedingly dim. But let’s now look at the LORRI telescope.

If we examine the performance of the Long-Range Reconnaissance Imager (LORRI) telescope on board New Horizons (the NASA mission destined for Pluto in 2015), it managed to detect Pluto at a maximum distance of d ~170 million km. Clearly with sufficient exposure time, New Horizons could image Pluto at this huge distance. Project Lyra has conducted a detailed analysis of this and has discovered with a significantly longer exposure time (~11 hours), the LORRI should also be able to observe ‘Oumuamua at the low brightness levels previously mentioned (even lower than Pluto).

Investigations reveal that for the nominal Project Lyra mission with a Solar Oberth at 6 SR (Solar Radii) and journey time of 22 years, first detection would occur 43 hours in advance of closest approach. ie ~5 million km before reaching ‘Oumuamua. (As a sanity check, assuming an inverse square drop-off with Sun-distance, this scales up nicely, ie to easily within an order of magnitude of the previously quoted 170 million km for New Horizons.) Note also that the LORRI telescope has a resolution of 5 microradians, and at a distance of 5 million km, this translates to a pixel size of 25 km, which is ~100 times ‘Oumuamua’s diameter. (Do read on as this apparent obstacle will be resolved further down.)

At any rate, putting aside this difficulty and assuming an Earth-Moon distance uncertainty in ‘Oumuamua’s lateral displacement of ~500,000 km, with detection 43 hours out, we would need therefore a ΔV from the approaching spacecraft of 3.2 km/s. It turns out that this would be practically speaking beyond a chemical rocket, especially after a journey time of 22 years or so in deep space. But there is a possible alternative solution to a New Horizons LORRI telescope onboard the Lyra craft.

Alongside i4is’s colleagues at Space Initiatives Inc, i4is is currently working on a NIAC, which stands for ‘NASA Innovative and Advanced Concepts’. This work is currently in Phase 1, and is to do with optical communications of a swarm of interstellar probes and Earth. We have also submitted a NIAC proposal concerned with the realisation of a technology known as ‘flat or folded optics’. This has already been mentioned briefly in our previously published preprint about swarming our Sun’s nearest neighbouring star, Proxima Centauri with interstellar laser sails, this paper can be found in Eubanks et al, *Swarming Proxima Centauri: Optical Communication Over Interstellar Distances* (arxiv.org/abs/2309.07061), and the relevant section is 3.2.

A flat optical device would be 1,000th the mass of a LORRI, and around one 10th of the LORRI area, but would be able to achieve the same resolution. This introduces the possibility of using a small probe instead of a large one. We can calculate the distance this probe would have to be from ‘Oumuamua to resolve the object if it had the flat optics technology (ie 1 pixel < 250 m) and it turns out to be ~50,000 km. But even so, on its own it could never get that close since we have seen that a ΔV above 3.2 km/s would probably be unrealistic. But now what happens exactly when we contemplate the possibility of more than one, or even a swarm of spacecraft for Project Lyra?

For the moment let us consider the possibility of just two spacecraft, both chemically propelled. Furthermore, we shall discard the SOM route to ‘Oumuamua, identified in (1) above, since it is simply too complex and technologically demanding. Which of the remaining trajectory options would be optimal?

I have done a lot of research on this problem and have discovered that for chemical missions, we should reject both the single JOM (alternatively called a ‘powered’ Jupiter gravitational assist - GA) and the double (ie the DJGA). As far as the latter is concerned it turns out that the extra 6-year delay in returning to Jupiter for a second GA, after already having conducted the first, renders this a significantly suboptimal route. It is also deficient in that it is a far more complex alternative to the straightforward single GA. However why should we reject the JOM option, surely one would expect this to be more effective than the PJGA option as it delivers more kick at periJove?
Surprisingly enough, and I reiterate I have investigated this extensively, it is nonetheless more efficient to fire any extra rocket boosters the Lyra craft might have immediately on the Earth-escape leg of the journey and none at Jupiter, than delay the booster's thrust until Jupiter is reached - this is the optimal solution based purely on the mechanics of the system. But there is no surprise here, this is precisely the solution preferred by the Interstellar Probe study which was conducted by the Johns Hopkins University (JHU), into a chemical mission beyond the heliopause and into the Interstellar Medium (ISM).

But there are other issues with the Jupiter Oberth option which would also make the JOM challenging. First of all, in the case of a liquid cryogenic Centaur stage, there would be leakage and boil-off of LH$_2$/LOX during the lengthy Earth-to-Jupiter transfer; and second, there would also potentially be significant degradation of solid stage performance from prolonged exposure to space. Moreover the use of the Centaur stage only becomes tenable when it is exploited as soon as possible after lift-off, waiting until Jupiter would clearly not be plausible.

With all this preamble over, let us now come to the knub of this article, and that is using a SpaceX Starship to reach ‘Oumuamua.

Many papers have been written on the possibility of exploiting the NASA Space Launch System (SLS) for Project Lyra, but the question is: ‘will this be at all likely?’ The quick and most likely answer is ‘no’. The SLS is booked up to ARTEMIS 5 in 2030, and in my opinion, with a PJGA launch year in either 2031 or 2032, it would be difficult to persuade NASA to dedicate a full SLS to Project Lyra. The easier and more sensible strategy is to concentrate on the SpaceX Starship, a far more likely prospect, especially with Elon Musk’s plans to ramp up production of this powerful launch vehicle to support his lunar and interplanetary ambitions.

Furthermore, he intends to introduce the infrastructure necessary for LEO refuelling of a Starship, and the current planned transfer of 1,000 metric tons (mt) of propellant opens the possibility of Earth-escape missions, unattainable by a single un-refuelled Starship. I decided to derive the Earth Characteristic Energy, $C_3$, achievable by a Starship in LEO refuelled with 1,000 mt of propellant. Refer to Figure 1.

---

**Figure 1**

Characteristic Energy, $C_3$, of a SpaceX Starship in LEO Refuelled with 1000 mt Propellant against Mass of Payload

---
We can see that a refuelled Starship can carry up to 110 mt of mass payload to Jupiter. Moreover, a Starship payload bay is 17 m x 8 m, which is quite a capacity, so what about adding some stages onto the Project Lyra payload to give an extra kick where the Starship has finished off? I tried up to three extra stages and a range of different rocket stages, summarised in the Table below.

| Booster Stage | Exhaust Velocity (km/s) | Total Mass (kg) | Dry Mass (kg) | Propellant Mass (kg) | Length (m) |
|---------------|-------------------------|----------------|--------------|---------------------|-------------|
| STAR 48B      | 2.8028                  | 2137           | 124          | 2013                | 2.03        |
| ORION 50XL    | 2.8647                  | 4306           | 367          | 3939                | 3.07        |
| CASTOR 30B    | 2.9649                  | 13971          | 1000         | 12971               | 3.5         |
| CASTOR 30XL   | 2.8866                  | 26406          | 1392         | 25014               | 6.0         |
| CENTAUR D     | 4.3512                  | 16458          | 2631         | 13827               | 9.6         |
| CENTAUR III   | 4.009                   | 20830          | 2247         | 18583               | 12.68       |

In order to translate these spacecraft and rocket combinations into optimal trajectories to `Oumuamua, we must apply my software known as OITS (Optimum Interplanetary Trajectory Software), NOT in minimum `ΔV` mode, but instead in minimum `total flight duration` mode, since we KNOW the precise ΔVs at Earth and Jupiter - the former is simply a question of applying the famous rocket equation of Tsiolkovsky, and the latter is naturally set to zero or a negligibly small upper bound - as articulated already, we need to follow a PJGA trajectory, as this is the optimal route.

I did precisely this investigation with three Project Lyra masses, 100 kg, 500 kg and 860 kg (refer Figures 2 to 4). The logic behind the selection of 500 kg (Figure 3) is that is about the same as the New Horizons spacecraft to Pluto and further the reason for 860 kg (Figure 4) is that this is about the mass of the proposed interstellar probe. The 100 kg value (Figure 2) is so that we have a handy theoretical baseline as to what is achievable by a refuelled Starship.
To this end we find that in principle, with a PJGA and a Starship, we can achieve arrival times at ‘Oumuamua as early as 2051, which is one year sooner than the nominal Project Lyra SOM mission which assumes 6SR perihelion. The 500 kg and 860 kg missions have slightly later ETAs in 2056 and 2059 respectively. In all cases the Centaur III is only slightly preferred over the Centaur D, though the requirement to fit inside the cargo bay (length ~17m) with any additional stages attached lengthwise, would seem to make the latter stage preferable as it is quite considerably shorter.
But what, in practice would the mass of the Lyra craft be? The following analysis endeavours to investigate this.

If we have a flat optics device capable of achieving what the LORRI can achieve with 1,000th of the mass, let us also downsize the overall spacecraft mass of New Horizons (~500 kg) by a similar ratio giving a mass of the spacecraft of ~0.5 kg, that is quite small and introduces the possibility of that 100 kg overall payload mass discussed above, potentially holding ~200 of these putative 0.5 kg craft in all. If we assume they are distributed across a plane in a hexagonal close packed arrangement, how far apart must this swarm of spacecraft be in order that three, say, must detect ‘Oumuamua?

First, as we have seen, for a probe to resolve ‘Oumuamua by a pixel, it needs to be within \( d = 50,000 \text{ km} \) of ‘Oumuamua. Assuming hexagonal close packing of the swarm, the distance between adjacent probes so that three are able to resolve ‘Oumuamua, turns out also to be \( R = 50,000 \text{ km} \). This corresponds to an areal number density, \( \rho \), as follows:

\[
\rho = \frac{2\sqrt{3}}{3R^2}
\]

which in turn gives \( \rho = 4.6 \times 10^{-10} \text{ km}^{-2} \). For \( N=200 \) probes, that translates to a circular swarm diameter of ~0.75 million km, or 0.005 au. Figure 5 gives the dependency of swarm diameter on number of probes. If we examine Figure 5 we see that in order to achieve an overall swarm diameter of around 500,000 km (which as already mentioned is ‘Oumuamua’s positional uncertainty), we would need as few as \( \text{N} \sim 90 \) probes. However let us proceed with the assumed \( \text{N}=200 \), with a swarm diameter of ~0.75 million km, because that means we are building into our mission design some tolerance to larger errors in ‘Oumuamua’s position.

As already mentioned, at a distance of 5 million km from closest approach, and with an 11 hour exposure time, the swarm should be capable of detecting ‘Oumuamua. For our Starship mission with 100 kg payload, that turns out to have a spacecraft arrival speed of 21.4 km/s wrt ‘Oumuamua, thus imaging would take place at ~65 hours before closest approach.

The closest probe to ‘Oumuamua in the lateral hexagonal-packed plane arrangement would be at most displaced laterally from ‘Oumuamua by ~22,000 km. Figure 6 gives the apparent lateral velocity of ‘Oumuamua as observed by this probe.
As previously mentioned at 65 hours out, a pixel in our flat-optical device would be ~25 km at this distance, and it turns out ‘Oumuamua would take only about 271 seconds to traverse this pixel. Compare this with the exposure time of 11 hours, one would be surprised if ‘Oumuamua could be resolved at all at this distance. Plot 7 gives the ratio of pixel transit time against exposure time as the probe approaches ‘Oumuamua, and from this figure we can conclude that the most likely time we could observe ‘Oumuamua would be from around quarter of an hour before closest approach.
However if you reference this Figure 7, it seems this ratio is always much less than 1, does this suggest our flat-optical device is not up to the job? It turns out, not so! With the implementation of high dynamic range imagery - taking lots of short pictures with good quantum efficiency, and then combining them to get the needed exposure time, the apparent problem is resolved.

So we now have a fix on 'Oumuamua from three probes, it is time now to communicate this, but to whom? Let us say we have a second interstellar probe of 500 kg following on behind the 100 kg spacecraft. Referring to the relevant plot, we see that a mission with a Centaur D, would arrive in ~ 2057. This would have been launched around the same time as the 100 kg spacecraft but would take a longer time to arrive, due to its larger payload. Having received the trajectory data from the probes, it would be able to make a sufficient alteration to its path so that after six years it would intercept 'Oumuamua and establish exactly what this strange object is.

This is all rather straightforward in theory, however in practice, will this flat-optics technology so important to the mission architecture elucidated above, have been developed by the PJGA launch year of 2032? If the necessary advancements do not come to fruition by then it would appear we have a problem. So let us now examine the game-changer of Nuclear Thermal Propulsion (NTP) in the context of Project Lyra.

I have already researched missions to 'Oumuamua using NTP, written-up both in an Acta Astronautica paper with Andreas Hein which can be found here [1], and in a subsequent additional preprint which further addresses use of a SpaceX Starship holding an NTP spacecraft payload (which is here [2]).

It turns out from this latter preprint, and contrary to the findings of the first Project Lyra paper (which on this particular point was applicable to chemical propulsion only), that if we adopt a Starship Expendable launch vehicle to launch the NTP craft, then this offers the possibility of a direct flight straight from Earth orbit to 'Oumuamua.

The details can be found in the latter preprint, but the essentials are that we have a 3 metric ton NTP spacecraft, with an extra 500 kg payload mass and furthermore with Liquid hydrogen (LH₂) cryogenic propellant, a specific impulse of 900 seconds can be generated.

Refer to figure 8 for the arrival date against launch date for this direct Starship Expendable + NTP mission. To generate this plot, and to maintain consistency with the analysis already performed above for chemical, I have replaced that 500 kg payload adopted in the preprint by a 100 kg one.

Figure 8

![Project Lyra: Direct Missions to 'Oumuamua using NTP with Launch on a Starship Expendable from a 2000 km Earth Expendable Orbit](image)

Launch Date is June 18th/19th of corresponding year with relative arrival speed of 'Oumuamua of 27 km/s in all cases

---

[1] Project Lyra: Catching 1I/'Oumuamua Using Nuclear Thermal Rockets, Hibberd et al arxiv.org/abs/2008.05435
[2] Initiative for Interstellar Studies Project Lyra with Nuclear Thermal Propulsion II Project Lyra with Nuclear Thermal Propulsion, Hibberd. www.researchgate.net/publication/376190502_Initiative_for_Interstellar_Studies_Project_Lyra_with_Nuclear_Thermal_Propulsion_II_Project_Lyra_with_Nuclear_Thermal_Propulsion
When we look at this Figure 8 plot, we see that for yearly launch dates from 2031 to 2040, the arrival years at ‘Oumuamua happen from 2045 to 2063 respectively, with mission durations increasing by 1 extra year for every year the launch is delayed. For information that the relative arrival velocity wrt ‘Oumuamua for all these missions is ~27 km/s.

But how do these results impact on the preceding discussion? To this end, let us propose an alternative yet similar mission design, something along the following lines.

We suppose an 860 kg mass Interstellar Probe following a PJGA trajectory, and launched in 2032 on board a Starship. This chemical-propelled mission is along the lines JHU has proposed already but although their design also assumes a PJGA, nevertheless their trajectory analysis obviously neglects ‘Oumuamua as a target. However, let us now, in what follows, rectify that.

Refer to Figure 4 for the relevant results for a mission to ‘Oumuamua with 860 kg payload and assuming chemical propulsion, and we see that a Centaur D followed by Castor 30B and STAR 48 would arrive at ‘Oumuamua via Jupiter in 2060. But this mission would still have that inherent and unresolved uncertainty in ‘Oumuamua’s position at intercept. This is where NTP steps in.

Let us say in addition to this chemical mission, we launch a separate Lyra craft onboard an expendable Starship with NTP and 100 kg payload, the latter comprising the N=200 probes each of mass 500 grams, as we assumed for our chemical mission earlier. This NTP craft is sent on its way much later than the Interstellar Probe, say in the year 2037 or 2038, by which time NTP will have been qualified and fully operational, and moreover the technology for the flat optics will also have been accomplished, together with the capability to miniaturize other important electronic components, etc.

This swarm of probes will arrive at ‘Oumuamua at least 1 year before the Interstellar Probe and would allow, as articulated above, determination of ‘Oumuamua’s position with sufficient accuracy so that the data can be relayed back to the approaching 860 kg craft. Armed with this important trajectory data, it would then adjust its own trajectory to ensure a close flyby of ‘Oumuamua.

I have elucidated two architectures which would work for Project Lyra, but there are many more which can equally well be examined, for example we may wish to use a single mothercraft with a deployable swarm of probes onboard to be sent on in advance of the main craft. I suppose the problem with Project Lyra is NOT whether this project would succeed or not, it is rather how apathetic is humanity?