Interstellar Objects and Sample Returns

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The i4is Project Lyra team have worked with international colleagues to deliver *Interstellar Now! Missions to and Sample Returns from Nearby Interstellar Objects* and *Exobodies in Our Back Yard: Science from Missions to Nearby Interstellar Objects* a Science White Paper submitted to the 2023-2032 Planetary Science and Astrobiology Decadal Survey.

Principium readers will be familiar with the work of Adam Hibberd in Project Lyra. Here he walks us through the basics of missions to Interstellar Objects (ISOs) including the possibility of a sample return - and the additional challenges it poses.

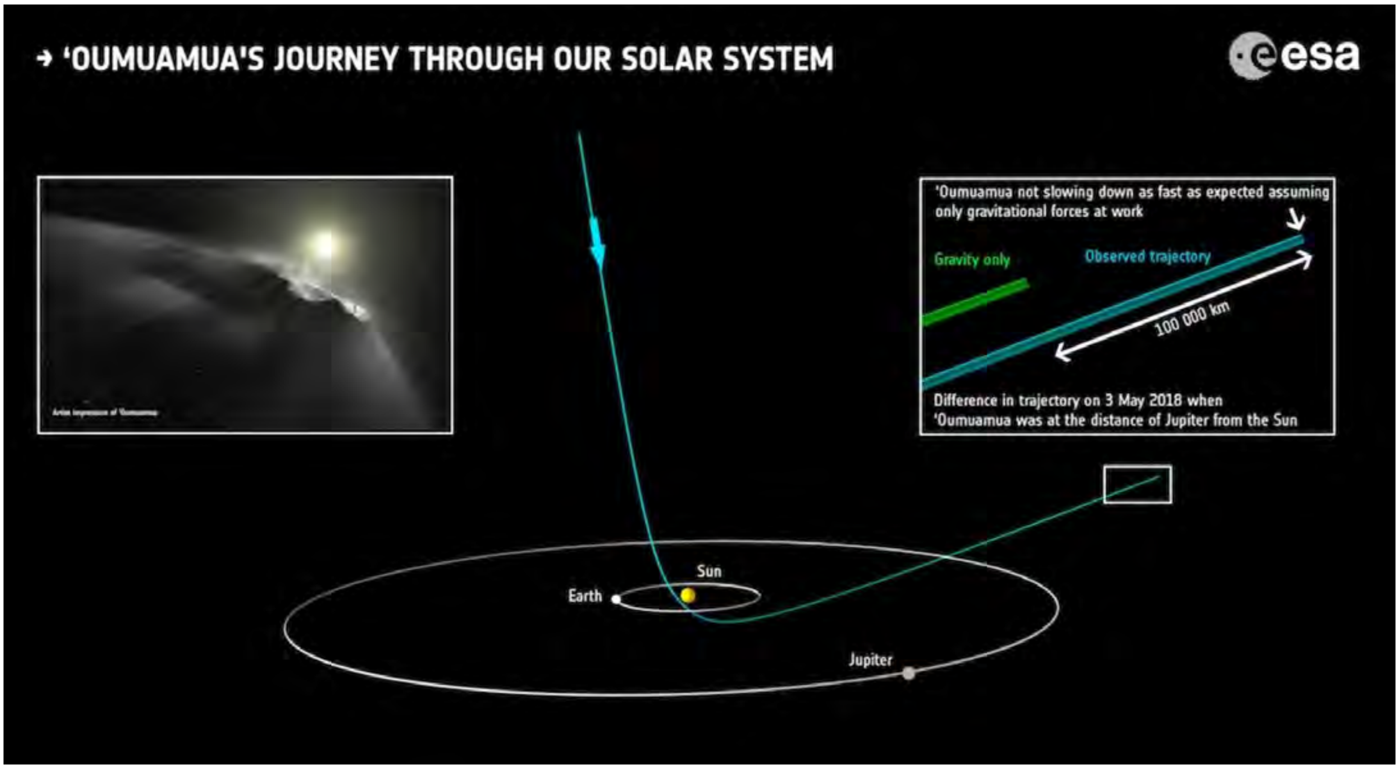
Introduction

What do we know of the Solar System to which our planet Earth belongs? Well we know Earth is not alone - in our Solar System it is surrounded by other celestial bodies. For example, most of us are aware that there are seven other known planets, and they can be considered our siblings - born and brought up in the same familiar surroundings, formed from the same proto-planetary disc which surrounded our host star, the Sun. How do we know this? There is an abundance of scientific evidence which allows us to reach this inescapable conclusion. Two of the most compelling pieces of evidence are firstly that they are in orbits bound to the Sun. In fact the orbits are elliptical so that each planet has its own unique 'orbital period', the time taken for it to return to the same point in its orbital path around the Sun. Secondly, they all follow an anticlockwise rotation around the Sun (looking down on the Solar System from above the Earth's North Pole). This direction is known as prograde. This is too much of a coincidence to happen randomly and originates in the spin orientation of the Sun's proto-planetary disc. Indeed if we change our perspective and look at objects at smaller scales then we generally observe them to follow the same sorts of orbits, elliptical and bound to the Sun and also with the same orbital spin orientation, anticlockwise (a notable exception will be discussed later). The orbital path of an object under the influence of some dominant gravitational force is characterized by a set of 5 or 6 numbers known as its orbital parameters (or orbital elements) each of which say something different about the orbit and stay pretty well fixed. Given a series of observations of the location of an object in the night's sky and using equations derived long ago by scientific mavericks and geniuses, the object's associated orbital parameters can be determined. Amongst these is a parameter known as eccentricity (a unitless parameter given the symbol e). For an elliptical orbit, e has a value somewhere between zero and one. Historically, save for a small number of exceptions (like certain comets which actually originate in the distant reaches of the Solar System called the Oort Cloud), when an object is discovered and the value of its parameter e is calculated, the solution has inevitably and consistently confirmed to lie within this range of values. Conclusion? Ostensibly, it would seem that everything we can observe in our Solar System originates therein.*

On October 19th 2017 an object was discovered in the Solar System with an e calculation of significantly greater than one. What does this mean? It means that the object is not in an ellipse, it is not bound to the Sun, it therefore does not have an orbital period. It did not originate in our Solar System, it is in fact in a hyperbolic orbit and approached the Sun from a great distance and will necessarily depart with the same speed with which it approached, around 26 km/s. This value is known as the heliocentric hyperbolic excess of the object, generally given the symbol V_∞. It thus probably started its life born in some planetary system somewhere else in our galaxy, from which it

*However an important caveat should be inserted at this point in that although this is generally the case, the stability over time of the Solar System is actually uncertain and it is perfectly possible for objects to encounter our Solar System and be captured into it, by gravitational influences such as that of Jupiter. We shall touch on this possibility later. Conversely, it is also possible that the accumulation of gravitational resonances acting on a Solar System object over time could eventually lead to it being ejected out into interstellar space.

was expelled by a gravitational perturbation. It eventually encountered our own system, drawn in by the pull of the Sun and some days after passage through its perihelion (its closest approach to the Sun) it was spotted by a telescope in Hawaii and eventually given the Hawaiian name ‘Oumuamua, receiving the official designation 1I (one eye), the first interstellar object known.



‘Oumuamua’s journey through our Solar System
Credit: ESA

Project Lyra

Project Lyra, a campaign to research the viability of spacecraft missions to 1I/’Oumuamua was instigated by the Initiative for Interstellar Studies, i4is, soon after its discovery and by this time in the same year I had developed my Optimum Interplanetary Trajectory Software (OITS) and had begun using it to conduct my own separate research into missions to 1I/’Oumuamua. These two parallel lines of research progressed entirely independently until my discovery of Project Lyra, and for that matter i4is, via a Google of ‘Oumuamua on the internet. I then contacted Andreas Hein of i4is and things progressed from there. Now several papers have been published on the subject, with me as part of the i4is Project Lyra team. Since that time, a second interstellar object was discovered in 2019, designated 2I/Borisov, and needless to say an article has been published on missions to this also.

But why are missions to interstellar objects so important? Well ask yourself, how else would a scientist be able to study material from another planetary system up close? A journey to the nearest star to our Sun would take tens of thousands of years using current chemical rocket technology, and that ain’t gonna happen! These interstellar visitors have been kind enough to spare us the trouble and in addition arrive with great gifts of tales to tell, waiting for scientists to uncover. Questions which could be answered:

1) Where might they have originated?

2) What is their composition?

3) Do they contain simple and/or complex organic compounds?

4) How were they formed?

5) What has been the effect on them of travelling long distances through the Interstellar Medium?

6) Specifically in the case of 1I/’Oumuamua, what was the cause of the non-gravitational force detected on it as it encountered the inner Solar System?

7) Etc.

Decadal Survey

This is all very well in theory, but exactly how is a mission going to happen? Would a space agency like NASA take on the challenge? Well no doubt space scientists around the world, with all kinds of expertise, are clamouring for the attention of NASA, trying desperately to receive much-needed funding for their particular line of research. At this point, in weighs a publication known as the ‘Decadal Survey of Planetary Science and Astrobiology’ which is a report undertaken by the National Academy of Sciences in the US every ten years (as you might expect). You could be forgiven for thinking that this sounds very much like another unnecessary layer of bureaucratic red tape. However its purpose is extremely important, it is exactly to prioritise the fields of interest in the planetary sciences, in order that NASA and indeed other US government agencies can better decide which areas of research (conducted either on Earth or in space, in the form of spacecraft missions) are most salient and could therefore potentially be ear-marked for investment. The process is to solicit white papers from the scientific community. Each scientist or group of scientists submitting a white paper must elaborate on the precise nature of their scientific research, the knowledge they wish to acquire, their mission goals, and they may of course wish to justify why precious funding should be channelled towards their specific line of research. Clearly a positive result from the Decadal Survey does not guarantee funding but does make this funding far more likely.

Since the discovery of 1I/’Oumuamua, interstellar objects (ISOs) have been the topic of the moment, the subject of intense scientific enquiry and even heated debate. With the work of Project Lyra under the banner of i4is, it seemed to various scientists associated with this research, as well as some more from various other prestigious organisations, that one way of increasing the likelihood of a mission to an ISO and realising what up to that point had only been words on paper, would be to construct between them a white paper for the Decadal Survey. In fact, this goal was accomplished with two submissions, one for the science category and the second for the mission category, my main contribution was for the latter. In what follows, I shall elucidate on the content of the mission white paper, entitled ‘Interstellar Now! Missions to and Sample Returns from Nearby Interstellar Objects’.

What is an ISO?

So firstly what is an ISO? Before careering head-long into a spacecraft mission definition, it may be worth gathering our wits and systematically subdividing ISOs into various categories. Table 1 is based on the white paper and attempts to do exactly this.

Type	Definition	Orbital Characteristics	Examples/Candidates
1	Clear extrasolar origin with definite hyperbolic orbit.	Value of e much larger than 1 and V∞ 1 km/s	1I/’Oumuamua, 2I/Borisov
2	Extrasolar origin but with weakly hyperbolic orbit.	Value of e only slightly larger than 1 and V∞ around 1 km/s	C/2007 W1 Boattini?
3	Galactic Stellar Halo objects, low spatial density, of order ≤1% of Galactic Disk ISOs.	e & V∞ are extremely large	Yet to be detected
4	Comets captured in the Oort cloud at the formation of solar system.	Semi-major axes of 1,000 AU – 200,000 AU, e < 1	Population unknown, possibly a significant fraction of the long period comets (which originate in the Oort Cloud).
5	Material captured primordially by gas drag in early inner solar system.	e < 1	Unclear if any has survived until now.
6	Captured objects in retrograde and other unusual orbits.	e < 1	Some Centaurs; retrograde objects such as (514107) Ka'epaoka'awela.
7	Sednoids, three body traded objects, special case of case 4 or case 6.	Perihelion 50 AU and a semi-major axis 150 AU.	Sedna, 2014 UZ224, 2012 VP113, 2014 SR349, 2013 FT28.

The layperson may have difficulty in totally comprehending Table 1 but let us, for the moment, take it as read that there are seven categories of ISO. Let us instead negotiate the issue of what different types of spacecraft mission can be conducted to an ISO. Well the white paper mentions three sorts of mission which in order of ascending level of scientific return are as follows:

A) Intercept

B) Rendezvous

C) Sample Return

Intercept (A) is defined as a spacecraft mission which eventually arrives at the ISO but does NOT change its velocity in order to stay with it and proceeds to leave the ISO with a departure velocity equal to the approach velocity.

Rendezvous (B) is defined as a spacecraft mission which eventually arrives at the ISO and then applies thrust as it approaches (generally to slow down) in order that the spacecraft stays with the ISO in its journey either through and out of the Solar System (ISO types 1, 2 & 3), or around the Sun (ISO types 4, 5, 6 & 7).

Sample Return (C) is defined as a spacecraft mission which encounters the ISO, in some way extracts material from the ISO and then returns to Earth with a sample of the ISO onboard for scientists to study.

(C) is clearly the holy grail of scientific outcomes. Imagine! – particles of material from some distant planetary system, on Earth for scientists to analyse with the full might and multiplicity of scientific instruments at their disposal. But how can this be achieved? I decided to use OITS to conduct some research into how a sample return might be undertaken to a type 1 ISO such as 1I/'Oumuamua or 2I/Borisov.

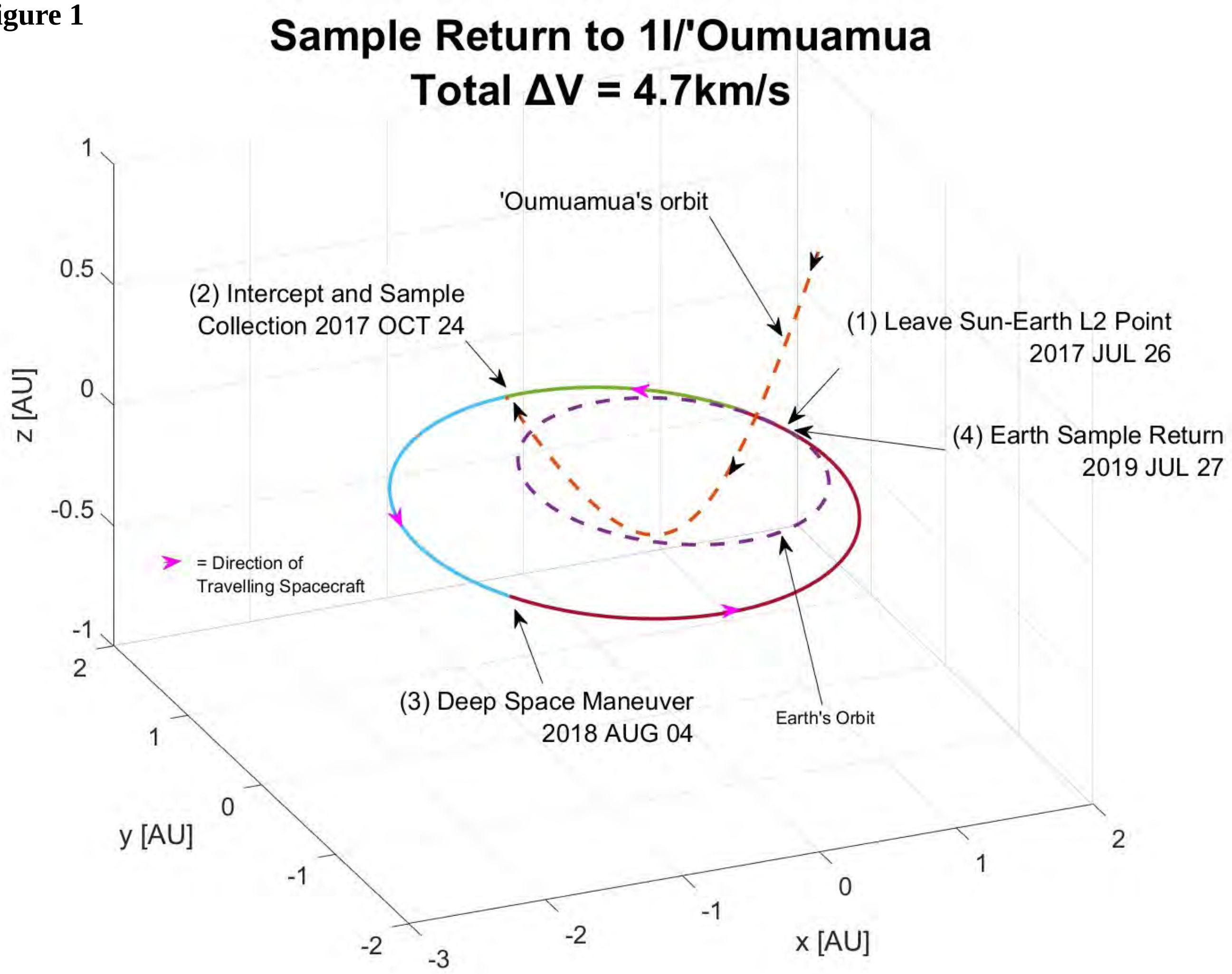
Sample Return to a Type 1 ISO like 1I/'Oumuamua

With a type 1 ISO there are two characteristics of its trajectory which are relevant. Firstly the trajectory entails the ISO to be travelling at a high heliocentric speed and secondly its orbital plane is at a high inclination to the ecliptic (the plane defined by Earth's orbit around the Sun). This high inclination essentially means that the ISO spends a good extent of its time significantly displaced from the ecliptic, although it crosses the ecliptic at two points known as the ascending node and descending node. Efficient trajectories to encounter a type 1 ISO must take maximum advantage of Earth's orbital velocity and as a result of this velocity lying in the ecliptic plane (by definition) results in the spacecraft encountering the ISO at one of its nodes. There is in fact an infinity of possible Earth launch dates and flight durations which would allow an encounter with a particular type 1 ISO, let us call the set of such combinations, S. There turns out to be only one member of S (so one combination of launch date and flight time) requiring least velocity increment, ΔV, from the travelling spacecraft's rocket engines.

This is all fair and well but so far we have only considered how the spacecraft might achieve an intercept, how might it return to Earth? Well if we examine S and for the moment exclude the member with minimum ΔV, there are in fact other members of this set S which have a particular yet useful characteristic. If we take a random member of this set, this has an associated launch date and flight time to encounter, as mentioned. This turns out to be quite sufficient information to work out the time period T of the spacecraft's orbit (please be reassured that it also turns out generally this will be an ellipse, bound to the Sun with $e < 1$ as has been discussed). Now certain members of S will have a time period, T, with a whole multiple n, of Earth's orbital period, which is 365.25 days, one Earth year. Why is this relevant? It is because, without any subsequent application of thrust from the spacecraft's engines (so a free ride) the spacecraft will rather neatly return back to Earth a whole number n years after launch, where Earth will be conveniently located at almost the exact same point in its orbit around the Sun as it was when the launch originally took place. Eureka! We have achieved a sample return!

For 1I/’Oumuamua a sample return trajectory utilising this technique is provided in Figure 1. There are four notable features to be considered. Firstly, the spacecraft begins its journey to 1I/’Oumuamua from the Sun/Earth Lagrange 2 Libration Point (L2). This is a point where the gravitational influences of the Sun and Earth combine with the centrifugal force to effectively cancel out, providing a comfortable point at which a spacecraft, for example, can sit and wait for an ISO to be discovered. For the Sun/Earth system the L2 point extends in a line outward from the Sun, at 1.5 million kilometres beyond Earth. Secondly there follows after launch an intercept and sample collection of material from 1I/’Oumuamua when 1I is crossing from below to above the ecliptic plane, ie at the ascending node. Thirdly there is an optional Deep Space Manoeuvre (DSM) at the spacecraft’s aphelion after the sample collection has taken place (this can be considered effectively as a minor course correction). Fourth and finally there is an Earth return on July 27th 2019, almost exactly 2 years after launch from L2, which happened on July 26th 2017 (so n = 2).

Figure 1



This is all very fine and dandy in theory, but is it practicable in reality? There are two reasons why not. Firstly, look at that launch date again: July 26th 2017. If we look back to when 1I/’Oumuamua was discovered, this was October 19th 2017. So immediately we have an issue in that the optimal launch date was actually before 1I/’Oumuamua was discovered! The second reason is slightly less evident and one needs to analyse the spacecraft’s trajectory in more detail for it to be revealed. It is this: as the spacecraft approaches 1I/’Oumuamua, its task is to collect a sample. To do this the spacecraft uses a very low density substance which has been tried and tested for sample return missions known as aerogel. This collection may be a complex procedure, possibly involving a subprobe to use as an impactor, but it is achievable with the right encounter conditions. What are these? The main condition is that, in order that the collected material does not undergo significant alteration or degradation, the relative velocity of the spacecraft with the target body, Vrel, must be less than 6 km/s. But we find for the trajectory to 1I/‘Oumuamua it is much higher - around 50 km/s.

The first of these issues, the launch date, may be resolved in the future for type 1 ISOs by the arrival on the scene of more powerful telescopes with higher data collection rates, such as the Vera C Rubin Telescope (also known as the LSST), and will allow earlier detection of ISOs. The second is a fundamental consequence of the orbit of a type 1 ISO (its high heliocentric speed and high inclination). This cannot therefore be realistically overcome.

However, let us not give up hope at this point. There are other categories of ISO, like for example type 2 & 4 ISOs in Table 1. How are these defined? In order to do this we must have some background knowledge.

What are Type 2 & 4 ISOs?

Most of us are aware of the particular type of celestial body known as a comet. Their tails can light up the night's sky and indeed often the sky in daytime also. Generally their orbits have e values less than one, meaning they have a finite orbital time period, and so they are bound to the Sun and originate in our solar system, as we have already discussed. In fact comets can be separated into two categories, these are short period comets and long period comets. Their key point of distinction however is that the long period ones are thought to originate in a cloud of proto-comets orbiting a huge distance from the Sun (somewhere between 2,000 AU-200,000 AU, where an AU is the distance between the Sun and Earth), the Oort Cloud, whereas short period comets may well have come from the Kuiper Belt, a disc extending beyond the orbit of the planet Neptune, but much closer to us than the Oort Cloud.

How does a proto-comet in the Oort cloud become a fully-fledged comet? It is generally believed this is caused by a gravitational perturbation, a nudge of encouragement, presumably as a result of some passing ISO grazing our solar system, at a great distance from the Sun. Essentially this nudge has the effect of dramatically reducing the Oort cloud Object's perihelion (the closest distance the comet gets to the Sun) so that it eventually encounters the inner solar system and is observed on Earth. Thus the consequence of this perturbation is to increase the e value from around zero (circular) to a value just less than one (highly elliptical). However there are some comets, known as weakly hyperbolic comets, which have e values slightly larger than one. As discussed above, this would seem to indicate the comet is an ISO, but in fact it has been found to be perfectly possible for a body in the Oort Cloud to be perturbed from its orbit with $e < 1$ into a weakly hyperbolic orbit with $e > 1$.

As a result of all this, we find that a type 2 ISO, defined as a weakly hyperbolic ISO (with V_∞ around 1 km/s), could easily be an object originating in the Oort Cloud, with obvious potential for confusion.

But there is another layer of complexity to this. There are very likely to be Oort Cloud objects which are actually ISOs, in other words they have journeyed from some far distant planetary system and upon arriving at our Oort Cloud have become resident, again through gravitational interactions. Thus we have the definition of type 4 objects. Furthermore to follow the logic and to add even further complexity, it is more than likely that some long period comets were originally type 4 ISOs.

Sample Return to Type 2 & 4 ISOs

The overall consequence of this complexity is that a mission to a weakly hyperbolic comet should be considered as they are quite possibly type 2 or type 4 ISOs. Indeed this is a far more fruitful line of research for a sample return mission because such ISOs have much lower heliocentric speeds than type 1 ISOs therefore potentially reducing the encounter velocity of a putative spacecraft. With this in mind I examined sample return trajectories to weakly hyperbolic comets and Table 2 (after References below) is the result.

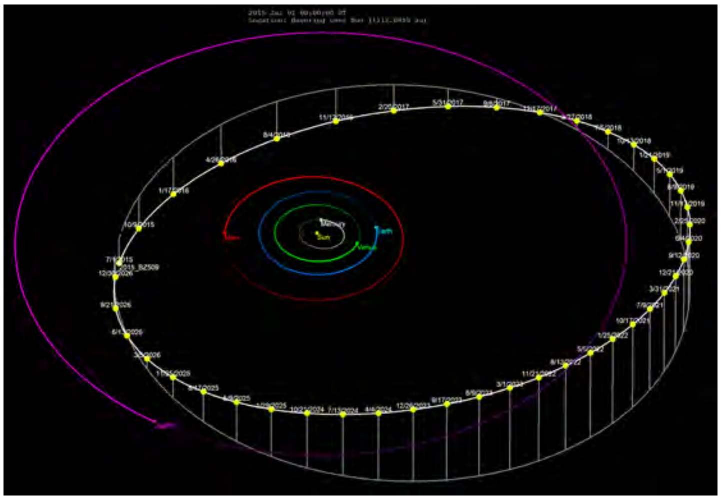
We find some comets are duplicated in order to take into account different values of n. It can be observed that three such weakly hyperbolic comets were contenders for sample return missions because the spacecraft's Vrel would have been less than 6 km/s. The total ΔV for these missions, the second column, were unfortunately large and as stated in the white paper, could be achieved by either Nuclear Thermal Propulsion (NTP) or by Solar Electric Propulsion (SEP) with arcjets. This is all very encouraging for the future and for possible missions loitering at L2, ready to be deployed for a sample return of a convenient weakly hyperbolic comet, possibly detected by the Vera C Rubin Telescope.

All this may be a long shot but the prize is enormous – a sample of material from somewhere outside our solar system – a fantastic reward for scientists and maybe worth the risk? And if the object turns out to be a bona fide Oort Cloud object and not an ISO, a sample return would still be a massive accomplishment and a valuable gift for scientists.

Rendezvous with Ka'epaoka'awela

Let us finish by examining a particular mission of type (B), a rendezvous, in fact one which is expounded in the white paper. The target in question is a celestial body called Ka'epaoka'awela (514107). What is it? It is an object co-orbital with Jupiter, so in other words having a very similar orbital period to Jupiter's and with a very similar mean distance from the Sun as Jupiter's. Clearly therefore, it has an e value less than one, so bound to the Sun and not a candidate for an ISO you might think. There is however an additional unusual feature of 514107 which needs to be explained: it is actually in a retrograde orbit around the Sun. Referring back to the beginning of this article the prograde nature of a body in the solar system was the second piece of evidence which allowed us to attribute a body as belonging to and originating in our solar system. What therefore is the consequence of 514107 being retrograde? Is the implication that it doesn't belong to our solar system? Is it in fact an ISO (a type 6 ISO)? It could well have entered our solar system in the dim and distant past, been pulled in by Jupiter's huge gravitational mass and become bound to the Sun, in an otherwise very unlikely retrograde motion. An animation produced by OITS of a rendezvous mission to find out whether 514107 is an ISO can be found here:

adamhibberd.com/interstellar-objects/



Retrograde orbit of Ka'epaoka'awela
Credit: Tomruen/Wikipedia

en.wikipedia.org/wiki/514107_Ka%CA%BBepaoka%CA%BBawela

Conclusion

So in conclusion, will there ever be a mission to an ISO? Well let's see what the Decadal Survey for Planetary Science and Astrobiology makes of it. The team at i4is has done their bit towards the endless pursuit of knowledge. It is so easy for this pursuit to be concerned only about the parochial, the now, the ephemeral. It is time humanity broadened its horizons a bit and Interstellar Objects are a convenient and timely stepping stone towards accomplishing this.

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About the Author

Adam Hibberd is a key member of the i4is Project Lyra team. Most recently he was also a major contributor to the i4is proposal for a near term missions to Venus (i4is.org/missions-to-venus/). See *News Feature: Hints of life on Venus* elsewhere in this issue.

Table 2

Flight D. /yrs	Flight D./ Days	Delta-V at Object /km/s	Delta-V at L2/ km/s	Vrel return/ km/s	**Vrel encounter km/s**	R encounter/ AU	Return	Encounter	Launch from S/E L2	Discovery	n	Total ΔV km/s	Object
1.1	402	3.6	12.5	25.7	**67**	0.25	10/04/2021	31/05/2020	04/03/2020	28/12/2019	n/a	16.1	C 2019 Y4 Atlas
1.22	445	3.3	3.4	11.6	**19.8**	1.32	18/10/2021	04/03/2021	30/07/2020	03/07/2020	n/a	6.7	C 2020 N1 P
1.3	474	3.6	2	11.6	**19.6**	1.33	20/10/2021	04/03/2021	03/07/2020	03/07/2020	n/a	5.7	C 2020 N1 P
10	**3652**	**0**	**20.4**	**20.6**	**5.9**	**4.55**	**10/01/2031**	**01/03/2022**	**09/01/2021**	**03/07/2020**	**10**	**20.4**	**C 2020 N1 P***
14	5115	0	18.4	17.4	**26.8**	3.45	20/02/2032	31/10/2018	18/02/2018	30/09/2017	14	18.4	C 2017 S6
6	2190	0	8.5	8.9	**23**	5	25/12/2025	27/10/2021	27/12/2019	27/10/2018	6	8.5	C 2018 U1
15	5479	0	10.2	10.6	**10.2**	10.7	07/05/2034	18/01/2025	07/05/2019	29/03/2019	15	10.2	C 2019 F1 Atlas
3.01	1099	3.1	6	7	**20.7**	2.9	14/02/2017	27/08/2015	11/02/2014	04/01/2014	3	9.1	C 2014 AA 52
17	**6215**	**0.8**	**16.4**	**16.8**	**6**	**10**	**04/04/2032**	**27/01/2019**	**30/03/2015**	**16/12/2014**	**17**	**17.2**	**C 2014 Y1***
2	731	0	4.6	5	**25.1**	1.67	31/01/2019	04/07/2017	30/01/2017	11/01/2015	2	4.6	C 2015 V2 Johnson
16.5	6045	6.5	17.4	35.2	**6**	11.7	15/12/2033	29/11/2020	28/05/2017	20/05/2015	16.5	23.9	C 2015 H2*
12	**4383**	**0**	**16.3**	**16.4**	**9.2**	**5.8**	**19/01/2026**	**11/09/2015**	**19/01/2014**	**04/11/2013**	**12**	**16.3**	**C 2013 V1 Boattini**
30	10958	0	11.5	11.8	**6.5**	8.8	06/01/2044	19/09/2016	05/01/2014	04/11/2013	30	11.5	C 2013 V1 Boattini
2.99	1093	0	7.5	7.3	**15.2**	2.3	29/01/2021	06/09/2018	01/02/2018	28/01/2018	3	7.5	C 2018 C2 Lemmon
6	2191	0.1	18.6	18.6	**10**	3.67	17/04/2024	01/03/2019	17/04/2018	28/01/2018	6	18.7	C 2018 C2 Lemmon
14	**5114**	**0.2**	**24.2**	**24.2**	**6**	**5.8**	**08/05/2032**	**05/11/2019**	**08/05/2018**	**28/01/2018**	**14**	**24.4**	**C 2018 C2 Lemmon ***
5	1826	0	8.2	8.8	**17**	4.7	30/06/2025	14/06/2022	30/06/2020	25/05/2020	5	8.2	C 2020 K5 PanSTARRS
2.19	799	1.2	5	12.2	**33**	2.2	18/09/2020	26/10/2019	12/07/2018	30/08/2020	n/a	6.2	2I Borisov
1.99	726	0	4.7	5.2	**49.8**	1.35	19/07/2019	24/10/2017	23/07/2017	19/10/2017	2	4.7	1I 'Oumuamua

Rows with * are missions with Encounter Vrel < 6 km/s. In addition yellow missions have Vrel < 6 km/s and no ΔV at the object, and so n is an integer number of years.