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Interstellar now! Missions to explore nearby interstellar objects

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Abstract

The recently discovered first high velocity hyperbolic objects passing through the Solar System, 1I/'Oumuamua and 2I/Borisov, have raised the question about near term missions to Interstellar Objects. *In situ* spacecraft exploration of these objects will allow the direct determination of both their structure and their chemical and isotopic composition, enabling an entirely new way of studying small bodies from outside our solar system. In this paper, we map various Interstellar Object classes to mission types, demonstrating that missions to a range of Interstellar Object classes are feasible, using existing or near-term technology. We describe flyby, rendezvous and sample return missions to interstellar objects, showing various ways to explore these bodies characterizing their surface, dynamics, structure and composition. Interstellar objects likely formed very far from the solar system in both time and space; their direct exploration will constrain their formation and history, situating them within the dynamical and chemical evolution of the Galaxy. These mission types also provide the opportunity to explore solar system bodies and perform measurements in the far outer solar system.

Keywords: Interstellar objects; Missions; Trajectories

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1. Introduction

It is not an exaggeration to contend that we live in a special epoch in which, after centuries of speculation, the first exoplanets have been detected (Perryman, 2018). One of the most compelling reasons for studying exoplanets is that discerning and characterizing these worlds holds the potential of revolutionizing our understanding of astrophysics and planetary science, as well as astrobiology if they are determined to harbor "alien" life (Schwieterman et al., 2018; Lingam and Loeb, 2019). Terrestrial telescopes and even futuristic very large instruments in space, such as the Labeyrie Hypertelescope (Labeyrie, 2016), will not be sufficient to characterize and understand local geology, chemistry and possibly biology of extrasolar objects at small scales. Even minuscule gram-scale probes,

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laser-launched from Earth to relativistic speeds, are unlikely to return science data from other stellar systems much sooner than 2070 (Perakis et al., 2016; Hein et al., 2017; Parkin, 2018; Häfner et al., 2019).

However, these are not the only two avenues open to humanity. Extrasolar objects have passed through our home system twice now in just the last three years: 1I/'Oumuamua and 2I/ Borisov (Meech et al., 2017; Jewitt and Luu, 2019). These interstellar objects (ISOs) provide a previously inaccessible opportunity to directly, and much sooner, sample physical material from other stellar systems. By analyzing these interstellar interlopers, we can acquire substantial data and deduce information about their planetary system of origin (Feng and Jones, 2018; Portegies Zwart et al., 2018; Moro-Martín, 2018; Jackson et al., 2018), planetary formation (Trilling et al., 2017; Raymond et al., 2018; Rice and Laughlin, 2019), galactic evolution, and possibly molecular biosignatures (Lingam and Loeb, 2018) or even clues about panspermia (Ginsburg et al., 2018).

Previous papers have investigated flyby missions to ISOs either in the context of specific objects such as 1I/'Oumuamua and 2I/Borisov (Hibberd et al., 2019; Hein et al., 2019; Hibberd et al., 2020) or objects passing through the Solar system which have been discovered early enough (Seligman and Laughlin, 2018; Moore et al., 2020). Furthermore, the Comet Interceptor mission, which has been selected as a Fast Class mission by the European Space Agency (ESA), aims to intercept a long-period comet (Snodgrass and Jones, 2019). In case this primary objective is not fulfilled, alternative candidates include not just short-period comets but also interstellar objects (ISOs) (Schwamb et al., 2020), provided that the appropriate Delta-V requirements are met for the latter. Furthermore, sample return missions to outer solar system objects have also been proposed, which may face similar challenges as chasing ISOs (Mori et al., 2020). In contrast, during the course of this paper, we map various ISO classes to mission types, demonstrating that missions to a range of ISO classes are feasible, all through the usage of existing or near-term technology.

2. ISO Mission Science Objectives

ISOs passing through the solar system are the only interstellar objects we have a chance of directly exploring in the near future. The Rosetta mission has illustrated the limits of remote astronomical observations in characterizing a cometary body, and what can be achieved through direct exploration (Drozdovskaya et al., 2019). Extending *in situ spacecraft exploration to ISOs ought to enable the determination of their surface, structure, and chemical and isotopic composition in detail. Initial studies have shown the existence of possible missions, solely reliant on existing technology, to 1I and 2I (*Hein et al., 2019*;* Hibberd et al., 2019*;* Hibberd et al., 2020*), and to additional, yet-to-be-discovered, ISOs (*Seligman and Laughlin, 2018*;* Moore et al., 2020*). In addition, work is ongoing on interstellar precursor missions deep into the outer solar system (*Brandt et al., 2017*;* Heller et al., 2020*), which are distinguished by similar trajectories (*McAdams and McNutt, 2020*) and could therefore be sent to intercept ISOs as a secondary objective.*

A mission designed to target ISOs can yield valuable scientific return both prior to and after interception. Before the encounter, the probe could analyze interplanetary dust (Grün et al., 2001) and the solar wind plasma (Bruno and Carbone, 2013). Furthermore, much like the *Spitzer* telescope, the mission may be suitable for microlensing studies, which yield information about the mass, distance and parallax vector of extrasolar objects (Udalski et al., 2015; Zhu et al., 2016).

2.1. ISO Taxonomy

To date, two different ISOs have been discovered. Their observed properties vary substantially: the hyperbolic interstellar asteroid (1I/'Oumuamua) and interstellar comet (2I/Borisov). Hyperbolic visitors that will not return to the Solar system are readily classifiable in terms of their composition and excess velocity at infinity (v_∞); furthermore these parameters may exhibit some degree of correlation (Eubanks, 2019a; Eubanks, 2019b). We can reasonably expect other interstellar objects in the coming years, especially as astronomical surveys improve (Trilling et al., 2017; Portegies Zwart et al., 2018; Rice and Laughlin, 2019; Yeh et al., 2020). In addition, captured ISOs in our solar system might already exist (Torbett, 1986; Gaidos, 2018; Lingam and Loeb, 2018; Siraj and Loeb, 2019; Namouni and Morais, 2018) – some with very low original excess velocities that readily facilitated capture (Belbruno et al., 2012; Hands and Dehnen, 2020; Pfalzner et al., 2020) – although Morbidelli et al. (2020) have challenged this origin for Centaurs.

Distinguishing ISOs passing through our Solar system can be done via dynamical considerations, e.g., by measuring their speeds and thereby calculating their excess velocities; this method is valuable for objects with v_∞ of at least a few km/s. In the case of captured ISOs, there are more ambiguities surrounding their existence and means of detecting them. If captured ISOs do exist in significant numbers, they may be discernible through their orbital parameters (especially the inclination), although the estimates vary from study to study (cf. Siraj and Loeb, 2019; Namouni and Morais, 2018; Hands and Dehnen, 2020; Morbidelli et al., 2020). Furthermore, if the isotopic ratios (e.g., of the three oxygen isotopes) of putative captured ISOs diverge significantly from those of Solar system values, that would provide another means of distinguishing them (Gaidos, 2018; Lingam and Loeb, 2018). Further measurements of isotopic ratios and other chemical properties of ISOs passing through our Solar system will enable us to gain a better understanding of their properties, which may then be utilized in identifying captured ISOs. On account of the inherent uncertainties concerning captured

Table 1
The InterStellar Object Taxonomy; types of ISOs, the associated science and potential near-term mission types. All missions, and especially rendezvous or sample return missions, are facilitated for ISOs having low inclinations, low v_∞, and for ISOs discovered well before their perihelion passage.

ID	Type	Examples	Mission Type
(1)	Clearly hyperbolic galactic thin disk objects, which have 1 km/s $\ll v_\infty \lesssim$ 100 km/s relative to the Sun.	1I/'Oumuamua & 2I/Borisov. Currently detection limited. ~92% of arrivals in kinematic model.	Flyby/Impactor, in fortuitous cases (especially with early pre-perihelion detection) rendezvous or sample return.
(2)	Galactic thick disk objects, with lower spatial density and higher velocities, roughly 100 $\lesssim v_\infty \lesssim$ 200 km/s.	None known so far. ~6% of arrivals in kinematic model.	Only flyby missions are possible, and only if discovered before perihelion.
(3)	Galactic halo objects, with an even lower spatial density and $v_\infty \gtrsim$ 200 km/s.	None known so far. ~1% of arrivals in kinematic model.	Probably not feasible even for flybys; would pass through the Earth's orbit in a few weeks or less.
(4)	Bodies not bound to our galaxy. An very low spatial density and a galactic velocity $\gtrsim$ 530 km/s.	None known so far. ~0.4% of arrivals in kinematic model.	Probably not feasible even for flybys; would pass through the Earth's orbit in less than 1 week.
(5)	Similar to Type 1 objects, but with $v_\infty \lesssim 1$ km/s. This category is separated as these objects may be confused with the "Oort spike" of long period comets.	C/2007 W1 Boattini. Note that apparent interstellar comets at these velocities may be recaptured Oort cloud comets.	Flyby/Impactor/Rendezvous/Sample return
(6)	Comets captured in the Oort cloud at the formation of solar system, and later perturbed into the inner system with other long period comets.	Population unknown, possibly a significant fraction of the long period comets.	Impact sampling or sample return, isotope analysis needed for confirmation.
(7)	Objects (planetesimals) captured primordially by gas drag in early inner solar system.	Unclear if any has survived until now.	Rendezvous depending on inclination. Distinguishing them remotely will be hard.
(8)	Captured objects in retrograde and other unusual orbits; see, e.g., Siraj and Loeb (2019, 2018, 2020). These orbits are typically not stable and so these objects would be relatively recent captures.	Some Centaurs; retrograde objects such as (514107) Ka'epaoka'awela. Work is needed to find orbits most likely to contain ISOs.	These objects are now in solar orbits, and rendezvous or sample return is possible depending on their inclination.
(9)	Sednoids, three body traded objects, special case of case #6 or case #8. The difference is that these objects are thought to have been captured in a 3-body interaction with the Sun and a passing star or planet.	Sedna, 2014 UZ224, 2012 VP113, 2014 SR349, 2013 FT28	Large distances, but low velocities, would facilitate rendezvous or sample return.

ISOs, we emphasize that the entries (6) to (9) delineated in Table 1 as well as the specific examples investigated in more detail such as Ka'epaoka'awela (514107) should be regarded as *potential* candidates; in other words, these objects have not been unequivocally confirmed to be captured ISOs.

In order to truly determine whether objects are truly ISOs or not, visiting them is of paramount importance. Type 2 ISOs in Table 1, with $v_\infty \lesssim 1$ km/s, have been separately classified because the problem lies not just in finding but also in distinguishing them from long-period Oort Cloud comets (see, e.g., Belbruno et al., 2012; Królikowska and Dybczyński, 2013; Hands and Dehnen, 2020). Ultimately, settling this issue necessitates compositional and isotopic analysis, which can be performed in fast flybys sampling the coma directly or collecting ejecta from impactors (see Eubanks et al., 2020). The different mission categories and accompanying objectives are described in more detail in following sections.

2.2. Overview of mission and science objectives

There are three broad mission categories that naturally come to the fore, and their scientific potential (along with accompanying pros and cons) is described in more detail below. Unless explicitly noted otherwise, it may be assumed that all scientific objectives possible for a simpler mission can also be accomplished by more complex missions.

An **ISO flyby** provides opportunities for close-up observations and surface characterization as well as sample collection, either from the object's plume or coma (for an active comet), or by liberating material through an impactor(s). Assuming a hypervelocity impact, radiation and detritus from the ionized plume could be analyzed using a high resolution UV spectrometer or mass spectrometer (Mahoney et al., 1991; Tandy et al., 2014; Eubanks et al., 2020). Recommended strike velocities are in the narrow range of 3-6 km/s; higher velocities could lead to over-fragmentation of biomolecular building blocks, whereas lower velocities render the method ineffective (Klenner et al., 2020). Collected samples can be analyzed in flight by means of an onboard mass spectrometer, yielding information about composition and isotope ratios (New et al., 2020). For more massive ISOs, detailed spectroscopic measurements of the target could yield further clues about the object's composition and potentially even its history and origin in the galaxy. For instance, if the ratio of $^{12}CO/^{13}CO$ is higher than the local interstellar medium value, it may indicate that the ISO in question spent a significant fraction of time in the vicinity of solar-type Young Stellar Objects (Smith et al., 2015). Oxygen isotope ratios are also heterogeneous in different regions of the Galaxy (e.g. Nittler and Gaidos, 2012), and might therefore be indicative of where the ISO had originated.

An **ISO rendezvous with an Orbiter** would provide scientists with significantly more time for an in-depth and close-up study with a suite of instruments on board the orbiter or lander; analogous to, e.g., the Dawn and Rosetta missions (e.g., Glassmeier et al., 2007; Russell et al., 2015; Taylor et al., 2017). Besides the object's mass, density, mass distribution and composition, such a mission could perform seismologic experiments unveiling the deep interior structure of the ISO. Mass, density and crystalline structure (via microscopy) may be potentially determined for near-surface materials. Detailed measurements made possible by this type of mission might also yield information regarding the evolution of the originating stellar system. Depending on the instrumentation onboard the spacecraft, spectrophotometric, magnetometric, and radio measurements can be executed. Additionally, an **ISO rendezvous including a lander** could exploit advances in miniaturizing diagnostic equipment (e.g. lab-on-a-chip) and leverage the capabilities of a lander to return a large amount of data about the ISO over an extended period of time to scientists on Earth, including but not limited to composition, and possible volatile and organic molecules; these putative landers could leverage existing concepts developed for the likes of Enceladus and Europa (Konstantinidis et al., 2015). Since the interstellar object will subsequently leave the Solar System and perhaps pass through another planetary system, a lander as a technological object would be a signpost of our technological achievements for an alien "civilization", should one exist. It would represent an interstellar version of the "Message from Earth" on board Pioneer 10 (Sagan et al., 1972).

ISO sample return via high-velocity impacts is the most complicated and audacious strategy, akin to what was accomplished by the Genesis and Stardust missions (Burnett et al., 2003; Brownlee, 2014). In general, this mission type would utilize available ΔV not to rendezvous, but to return back to Earth. Besides some of the aforementioned science objectives, returning samples to earth allows for much more detailed analysis essentially unconstrained by mass, size, resolving power, operating power, and time (Neveu et al., 2020). Molecular composition and microcrystalline structure can be deduced from vaporised ejecta and dust. Determining mineralogic, mechanical and structural properties would need centimeter-sized samples, either collected in the plume/coma of the ISO or from ejecta generated by an impactor. Laboratories back on Earth could readily undertake analysis of the isotope ratios of heavy elements, molecular chemistry, nuclear chemistry, and neutron activity. Diagnostic equipment is self-evidently not subject to mass constraints of the spacecraft and can provide, among others, higher-resolution spectroscopy, spectrophotometry, electron- and atomic force microscopy. One trade-off is that a sample return mission may yield less information about basic mass, density and seismology of the target. Furthermore, with existing sample return technologies, the returned samples are limited to solid dust grains, which limits the understanding of comet-like objects containing volatiles.

Additional non-ISO science objectives: In addition to scientific objectives associated with the ISOs themselves, interesting measurements can also be performed en-route, including but not limited to the collection and analysis of interplanetary dust and ions and close-up observation of outer Solar system phenomena, e.g., the IBEX ribbon (McComas et al., 2017). In case the mission is tailored toward a flyby of the ISO, it will continue on its prescribed trajectory and will eventually traverse and move beyond the heliosphere. In this process, it could yield a wealth of information about the heliosphere and interstellar medium (ISM), just as the *Voyager* spacecraft do.

Further scientific objectives include the shape of the heliosphere (Dialynas et al., 2017), the propagation of galactic cosmic rays (Stone et al., 2013; Cummings et al., 2016), and the interaction with the ISM (Zank, 2015). Some examples of ISM physics and characteristics worthy of further study are the radial large-scale gradient (Kurth and Gurnett, 2020), interstellar plasma and magnetic fields (Gurnett et al., 2013; Burlaga and Ness, 2014), and magnetic turbulence (Burlaga et al., 2015). One concrete example of each of the three mission categories, outlined above, follows. We will not comment on the instrumentation, because it is not the thrust of this paper. Minimum instrumentation should, however, include a camera and mass spectrometer for each of the missions.

3. Types of ISO Missions

ISO missions can be characterized by the resources required to perform them, which are closely related to how the ISO came to be in the solar system, and whether a mission is able to interact with it before its perihelion or afterwards (see Table 2). ISOs are either unbound, passing through the solar system on a hyperbolic orbit, or bound, in some elliptical orbit about the Sun or even one of the planets. Unbound ISOs will generally be clearly of interstellar origin, but will only pass through the solar system once. If a mission can be launched before or around the time of the ISO's perihelion passage, then travel times can be reduced, especially if the ISO passes close the Earth, and a fast sample return (capture of cometary coma or impact probe ejecta material) may be possible.

3.1. Flyby Missions

Flyby missions are of particular relevance where the distance of the target ISO from the sun is large and/or the ISO is travelling at a high heliocentric speed. The former may be for one of the following two reasons:

Table 2
Types of missions to InterStellar Objects.

Target	Mission Type	Exploration Type	Notes
ISOs Entering the Solar System	Loiter Missions	Fast Sample Return	Requires Prepositioning of Spacecraft
ISOs Leaving the Solar System	Chase Missions	Fast Flyby	High ΔV, Long Duration
Captured ISOs	Preplanned Missions	Orbiters, Landers	Similar to other asteroid/comet missions.

1. The perihelion is high, so minimum possible encounter distances are still extremely large (e.g. type (7) ISOs in Table 1).
2. The perihelion is small, but the detection of the ISO occurs too late to take full advantage of this fact; for example, the type (1) ISO, 1I/'Oumuamua, in Table 1.

A high intercept distance means that a large sun-radial velocity component must be generated in order to constrain the flight duration to a practically acceptable value. For chemical propulsion to 1I, extensive research has been conducted (Hein et al., 2019; Hibberd et al., 2020). The mission shown in Fig. 1 is a launch in 2030 and a 'V_∞ Leveraging Maneuver', a reverse gravity assist (GA) at Jupiter, followed by a Solar Oberth (SO) maneuver at 6 solar radii (Blanco and Mungan, 2020), and 2-stage sample return mission at the SO which enables intercept at 200AU. Using the Space Launch System (SLS), depending on the version, a probe mass up to ~ 900 kg is possible. More generally, launchers such as the Falcon Heavy and SLS can be used to throw spacecraft with masses up to 1000 kg to ISO targets depending on launch date, mission duration, and maneuvers (Hein et al., 2019; Hibberd et al., 2020).

For the SO maneuver, at 6 solar radii, heatshield technology similar to the Parker Solar Probe can be used to protect against solar heating (Hibberd et al., 2020; Brandt et al., 2017). Due to uncertainty in 1I's orbit, at 200AU there is a possible displacement on the order of 10^5 km from its estimated solar escape asymptote, assuming a positional uncertainty of 10^{-5} rad (Trilling et al., 2018). At an approach speed of 30 km.s^{-1}, observations from the spacecraft would require a New Horizons LORI-type telescope (apparent magnitude of 17 at 10 s exposure time (Cheng et al., 2008). Assuming an apparent magnitude of 26 of the object and 11 h of exposure time, the object could be detected at a distance of about 4.6×10^6 km, which translates to a timescale of 43 h before closest approach for the specified speed of 30 km.s^{-1}.

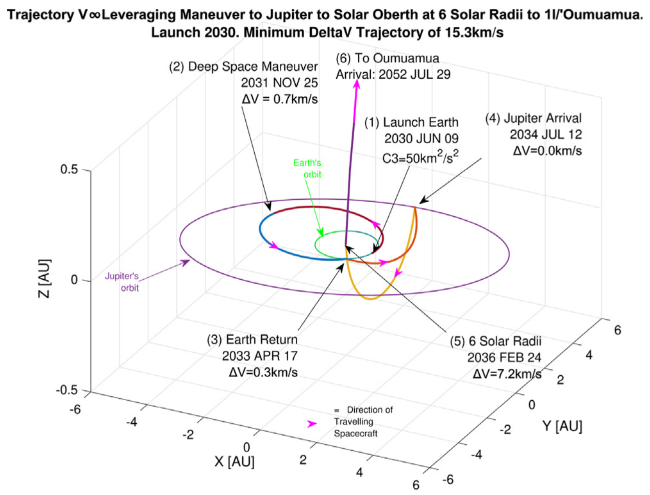

Fig. 1. Trajectory to 1I/'Oumuamua.

The horizontal maneuver would require a velocity increment on the order of hundreds of ms^{-1}. As a more advanced approach, a swarm of chipsats could be dispensed around 1I's estimated escape asymptote and travel in the vanguard of the probe, returning data which would allow the main craft to adjust its velocity accordingly to ensure intercept. The main craft would then release an impactor and analyze the isotopic composition of 1I via spectroscopic methods. However, the consequently smaller telescope size renders detection more challenging, as might the data return to Earth. The potential to sequentially launch the chipsats at velocities of 300 kms^{-1} or higher, such as with the Starshot precursor architecture (Parkin, 2018) may merit further research.

Our brief analysis (and its attendant caveats) should not be regarded as exhaustive. Other issues that we have not delineated include the difficulties posed by long CCD exposure times (11 h in our scenario) such as the cumulative impact of cosmic rays and the necessity of accounting for parallax motion of the object during this period. Obstacles with respect to measuring the position of the object, calculating offsets, and relaying it to the spacecraft may also arise. Hence, we acknowledge that there are significant (but not necessarily insurmountable) and outstanding challenges that are not tackled herein, as they fall outside the scope of this particular paper.

For nuclear thermal propulsion (NTP) to 1I, Hibberd and Hein (2020) have shown that a direct trajectory leaving low Earth orbit (LEO) in 2030, to fly by 1I, is achievable using a small nuclear rocket engine (derived from the government-sponsored Rover/NERVA programs) and an SLS Block 2. Utilizing a Oberth maneuver at Jupiter to reach 1I drastically reduces flight time. Launching in 2031, a "Pewee"-class NTP system (also researched in the Rover/NERVA programs) can deliver 2.5 t on target in a 14 year flight. The flight segment from LEO to Jupiter would take 5 months and, thus, needs a zero-boil-off cryocooler and zero-leakage liquid hydrogen (LH2) tanks. Other existing/near-term technologies could also be applied to drastically reduce this mission's duration, e.g., solar sails, electric sails, and multi-grid electric thrusters

(Dachwald, 2004; Loeb et al., 2008; Loeb et al., 2011; Hein et al., 2019; Brandt et al., 2017).

3.2. Rendezvous Missions

For **rendezvous missions to hyperbolic ISOs**, The high radial velocity required to achieve an acceptable flight duration, as discussed in Section 3.1, would then need to be removed in order to achieve a rendezvous mission, thereby imposing severe constraints on the on-board propulsion system (hence the New Horizons flyby of Pluto for example). However, it should be noted that, although the technology would require some further research and development, rendezvous missions could utilise electric or magnetic sail propulsion schemes to slow down and stay with the target. Solar sails based on the statite concept have also been proposed as viable alternatives for rendezvous missions (Linares et al., 2020). The specifics for a rendezvous mission were described for 1I/'Oumuamua as a target in Hein et al. (2019).

In a similar vein, it is instructive to further delve into a couple of representative examples for other ISOs, notably **rendezvous missions to captured ISOs**. Type (6) ISOs (Table 1) in elliptical orbits (as opposed to hyperbolic orbits of types (1) and (2)) follow periodic optima, and so can spacecraft. This opens the possibility of rendezvous missions with reasonable ΔV of approximately 10 km/s. Rendezvous missions require a thrust from the spacecraft as the target ISO is approached to slow down and stay with the ISO in its path around the sun. The two objects studied in more detail here are both potentially type (6) ISOs, namely (514107) Ka'epaoka'awela (which is in retrograde motion and co-orbital with Jupiter), and the highly inclined centaur 2008 KV42.

In the case of 514107, there are two relatively near-term rendezvous mission candidates launching in 2024 and in 2030. These are shown in Figs. 2 and 3, respectively. The latter opportunity has the advantage of a marginally lower ΔV and a later launch date to enable more time for mission preparation. The pertinent data is provided in Table 4. Hence the launch is in 2030 with a V_∞ Leveraging Manoeuvre of $n = 1$ year. A Jupiter Oberth in Jan 2032 applied at an altitude of 77,198 km results in a retrograde heliocentric orbit. In this orbit the spacecraft travels on a long cruise, eventually catching up with 514107 and applying a ΔV of 2.5 km.s^{-1} to slow down and rendezvous. For completeness, the long spacecraft cruise arc from Jupiter to 514107 subtends an angle of 272.6° at the sun.

To give an idea of the long term feasibility of performing a rendezvous missions with 514107, trajectories are provided for the years 2024 to 2038 in Fig. 4. The upper blue line shows ΔVs for missions without a 1 year V_∞ Leveraging Maneuver, and revealing a periodicity of around 4 years between consecutive minima or maxima. If we take maxima or minima ΔV missions and introduce a preceding V_∞ Leveraging Maneuver, we obtain the ΔV requirements indicated by the red squares below the blue line. Thus, a preceding V_∞ Leveraging Maneuver can yield a reduction in ΔV of around 40%. In the case of the highly inclined centaur 2008 KV42, a rendezvous mission seems feasible with a launch in 2029 and flight duration of 15 years from launch to rendezvous, see Fig. 6 and Table 5.

3.3. Sample Return Missions

With NTP, sample returns are feasible from type (1), (2) & (4) ISOs, beginning with a pre-positioned interceptor loitering at the Sun/Earth L2 (SEL2) point, where the probe awaits a dispatch order upon detection of an ISO. Not all, but some, weakly hyperbolic comets have orbits appropriate for a direct return to Earth. A sample loiter/interceptor mission to C/2020 N1, serving as a surrogate for a type (2) object & and possibly a type (4) ISO, is shown in Fig. 5. A future discovery of such an object would have an identical general sample return mission architecture to that shown but different values for mission duration, ΔV and launch date.

When an ISO conducive to sample return is discovered, a heliocentric ellipse from Earth is computed. Requirements for this ellipse are (a) it intercepts the comet with relative velocity < 6 km.s^{-1} (b) its time period is a whole number of n years, (c) it minimizes ΔV required at SEL2 departure. Note that (b) ensures free return to Earth without any plane changes or any other ΔVs along this ellipse. For the chosen target, the departure ΔV is applied at the optimal launch time using NTP or solar electric propulsion with arcjets. As the target is approached, an impactor is deployed and the spacecraft travels through the plume. If the plumes are anticipated to be hazardous (e.g., based on prior spectroscopy), a swarm of subprobes can be released and sent in advance of the main craft to sample the plume, returning to the main craft at a safe standoff distance after the encounter.

The spacecraft arrives back at Earth for aerocapture and eventual return to Earth's laboratories. For three currently known, weakly hyperbolic comets, which would have been suitable for this sort of sample return during their passage through the inner solar system (optimal launch dates have lapsed), ΔVs is predicted to range from 17.4 km.s^{-1} to 24.4 km.s^{-1}, n from 10–17 years, and intercept distance from 4.5–10AU. Using NTP, payload masses on the order of several metric tonnes are achievable, assuming the availability of an SLS Block 2 and two zero-boil-off and zero-leakage LH2 tanks, of the kind assumed in NASA's Manned Mars Mission Design Reference Architecture, with optimal mass ratio.

Table 3 gives a list of some more weakly hyperbolic comets used as surrogates for type (4) objects, but note that any of these also could be a type (2) ISO. It can be seen that three such objects are candidates for sample returns of the kind described, C 2020 N1 P, C 2018 C2 'Lemmon' and C 2014 Y1. If we constrain the spacecraft departure date to be after the discovery date (which was 28/01/2018), focus our intention, for example, on C 2018 C2, and use Opti-

Table 3
Sample Return from Several Weekly Hyperbolic Comets and Also 1I/'Oumuamua and 2I/Borisov.

Object	Total Delta-V km/s	n	Discovery	Launch from S/E L2	Encounter	Return	R encounter AU	Vrel encounter $km.s^{-1}$	Vrel return $km.s^{-1}$	Delta-V at L2 $km.s^{-1}$	Delta-V Object $km.s^{-1}$	Flight D. days	Flight D. yrs
C 2019 Y4 Atlas	16.1	n/a	28/12/2019	04/03/2020	31/05/2020	10/04/2021	0.25	67.00	25.70	12.5	3.6	402	1.10
C 2020 N1 P	6.7	n/a	03/07/2020	30/07/2020	04/03/2021	18/10/2021	1.32	19.80	11.60	3.40	3.30	445	1.22
C 2020 N1 P	5.7	n/a	03/07/2020	03/07/2020	04/03/2021	20/10/2021	1.33	19.60	11.60	2.00	3.60	474	1.30
C 2020 N1 P*	20.4	10	03/07/2020	09/01/2021	01/03/2022	10/01/2031	4.55	5.9	20.6	20.4	0.0	3652	10.0
C 2017 S6	18.4	14	30/09/2017	18/02/2018	31/10/2018	20/02/2032	3.45	26.80	17.40	18.4	0.00	5115	14.00
C 2018 U1	8.5	6	27/10/2018	27/12/2019	27/10/2021	25/12/2025	5.00	23.00	8.90	8.5	0.00	2190	6.00
C 2019 F1 Atlas	10.2	15	29/03/2019	07/05/2019	18/01/2025	07/05/2034	10.70	10.20	10.60	10.2	0.00	5479	15.00
C 2014 AA 52	9.1	3	04/01/2014	11/02/2014	27/08/2015	14/02/2017	2.90	20.70	7.00	6.00	3.10	1099	3.01
C 2014 Y1*	17.2	17	16/12/2014	30/03/2015	27/01/2019	04/04/2032	10.0	6.0	16.8	16.4	0.8	6215	17.0
C 2015 V2 Johnson	4.6	2	11/01/2015	30/01/2017	04/07/2017	31/01/2019	1.67	25.10	5.00	4.6	0.00	731	2.00
C 2015 H2*	23.9	16.5	20/05/2015	28/05/2017	29/11/2020	15/12/2033	11.7	6.0	35.2	17.4	6.5	6045	16.5
C 2013 V1 Boattini	16.3	12	04/11/2013	19/01/2014	11/09/2015	19/01/2026	5.80	9.20	16.40	16.3	0.00	4383	12.00
C 2013 V1 Boattini	11.5	30	04/11/2013	05/01/2014	19/09/2016	06/01/2044	8.80	6.50	11.80	11.5	0.00	10958	30.00
C 2018 C2 Lemmon	7.5	3	28/01/2018	01/02/2018	06/09/2018	29/01/2021	2.30	15.20	7.30	7.5	0.00	1093	2.99
C 2018 C2 Lemmon	18.7	6	28/01/2018	17/04/2018	01/03/2019	17/04/2024	3.67	10.0	18.6	18.6	0.1	2191	6.0
C 2018 C2 Lemmon *	24.4	14	28/01/2018	08/05/2018	05/11/2019	08/05/2032	5.8	6.0	24.2	24.2	0.2	5114	14.0
C 2020 K5 PanSTARRS	8.2	5	25/05/2020	30/06/2020	14/06/2022	30/06/2025	4.70	17.00	8.80	8.2	0.00	1826	5.00
2I Borisov	6.2	n/a	30/08/2020	12/07/2018	26/10/2019	18/09/2020	2.20	33.00	12.20	5.00	1.20	799	2.19
1I 'Oumuamua	4.7	2	19/10/2017	23/07/2017	24/10/2017	19/07/2019	1.35	49.80	5.20	4.7	0.00	726	1.99

n indicates the number of years from launch to return of the sample.
Rows with * are missions with Encounter Vrel $< 6 km.s^{-1}$
In addition gray missions have Vrel $< 6 km.s^{-1}$ and no ΔV at the object, and so n is an integer number of years

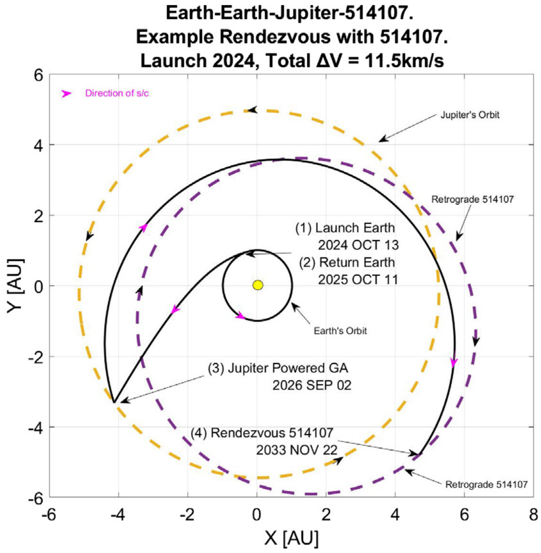

Fig. 2. Trajectory to Ka’epaoka’awela (514107) Launch 2024.

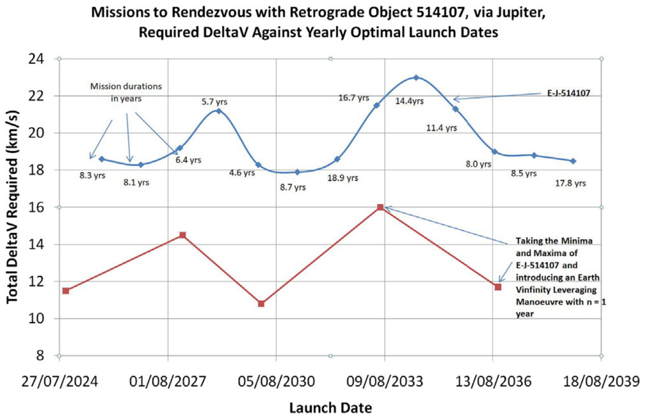

Fig. 4. ΔV Dependency on Launch Date for a Rendezvous Trajectory to Ka’epaoka’awela (514107).

mum Interplanetary Trajectory Software to solve such trajectories, there turns out to be several sample return solutions with different values of n, i.e. $n = 10, 11, 12, 13$

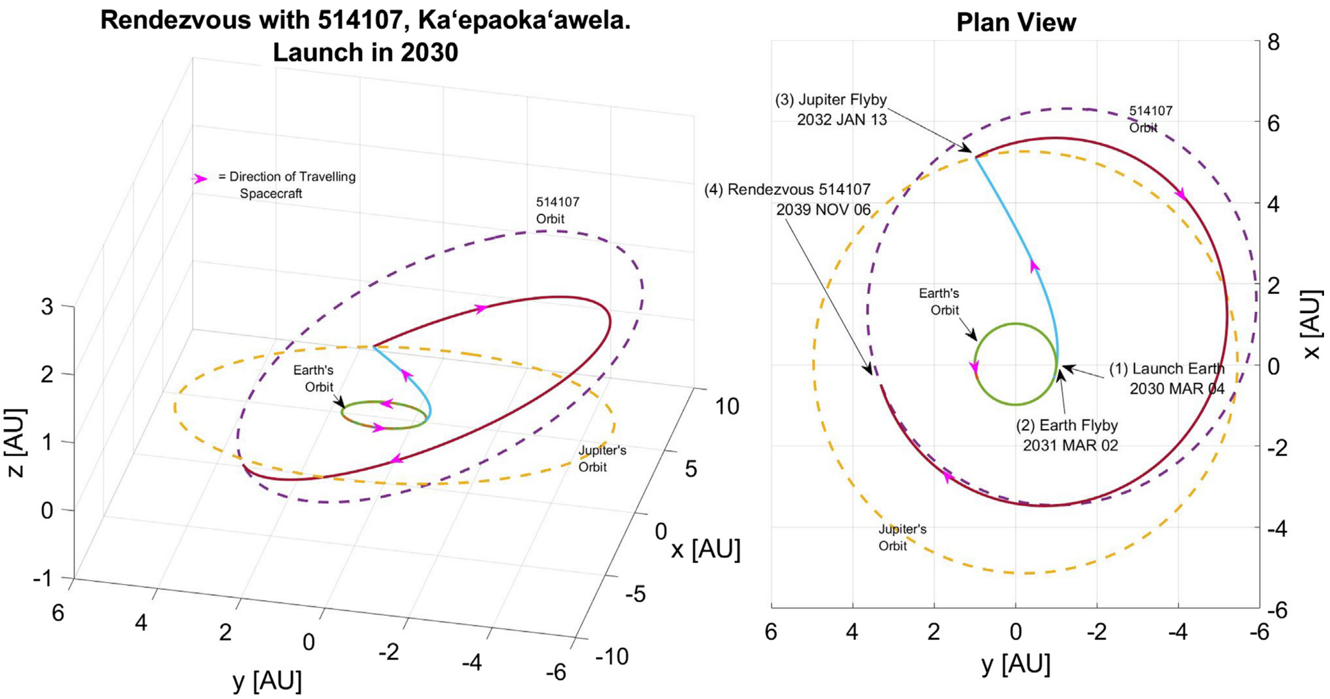

Fig. 3. Trajectory to Ka’epaoka’awela (514107) Launch 2030.

Table 4
Rendezvous Mission to 514107 (Possible Type 6 ISO).

Number	Body	Time	Arrival speed km.s^{-1}	Departure speed km.s^{-1}	ΔV km.s^{-1}	Cumulative ΔV km.s^{-1}	Periapsis altitude km
1	Earth	2030 MAR 04	0.00	0.01	0.01	0.01	N/A
2	Earth	2031 MAR 02	0.01	15.88	8.31	8.32	200
3	Jupiter	2032 JAN 13	24.80	24.93	0.07	8.39	77197.6
4	514107	2039 NOV 06	2.49	0.00	2.49	**10.88**	N/A

Table 5
Rendezvous Mission to 2008 K4V2 (Possible Type 6 ISO).

Number	Body	Time	Arrival speed km.s^{-1}	Departure speed km.s^{-1}	ΔV km.s^{-1}	Cumulative ΔV km.s^{-1}	Periapsis altitude km
1	Earth Launch	2029 FEB 22	0.00	0.11	0.11	0.11	N/A
2	Deep Space Maneuver at 1.0AU	2029 AUG 07	29.68	29.65	0.59	0.69	N/A
3	Earth Powered Flyby	2030 JAN 20	0.48	8.93	3.16	3.85	200
4	Jupiter Flyby	2032 JAN 26	7.48	9.95	0.78	4.63	302223.2
5	2008 KV42	2044 FEB 19	9.01	0.00	9.01	**13.65**	N/A

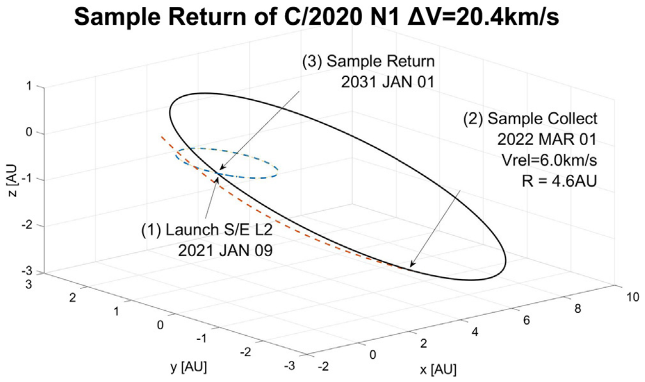

Fig. 5. Sample Return from C/2020 N1.

and 14 years. We also find that the departure date is always very close to 08/05/2018 and the thrust directions lie within around 1° of each other. The ΔV at departure stays just about constant as the value of n increases, but there arises a gradually increasing ΔV at intercept. The combined effect is to increase the total ΔV requirement as n increases. All this information is provided in the Fig. 7. Note that this assumes a departure from the SEL2 point directly into the heliocentric ellipse, although a gravitational assist on Earth would possibly be more efficient.[1,2]

3.4. Discussion of Mission Findings

Missions to ISOs might resolve many vital questions about our and other star systems, are technologically feasible, but some mission types face noteworthy challenges regarding technology maturity. To be specific, it is expected that further development and deployment of heavy launcher and NTP systems would benefit the exploration of potential ISOs greatly.

Our results indicate that most mission types elucidated herein, except for sample return, could be realized with existing technologies or modified versions of existing technologies, such as chemical propulsion and a Parker Solar Probe-type heat shield (Hein et al., 2019; Hibberd et al., 2020). Collisions with dust, gas, and cosmic rays and spacecraft charging in the interplanetary or interstellar medium will engender deflection of the spacecraft trajectory and cause material damage to it, but both effects are likely minimal even at high speeds (Hoang et al., 2017; Hoang and Loeb, 2017; Lingam and Loeb, 2020; Lingam and Loeb, 2021), and the former can be corrected by onboard thrusters. However, for sample return missions, technologies which currently have a low Technology Readiness Level (TRL) would be required, such as NTP, for which TRL ranges from 2 to 6, depending on the reference (e.g., NASA Technology Taxonomy, NASA Technology Roadmap), as well as zero-boil-off and zero-leakage LH2 tanks. [3] Moreover, missions involving a Solar Oberth maneuver are particularly sensitive to uncertainties in the perihelion burn and might be difficult to accurately steer towards the ISO in actuality. Perihelion burn uncertainties are relevant for solid-propellant rockets. This issue may be particularly applicable to ISOs which are on their way out of the solar system, given the variability accompanying the position determination of such ISOs (Hein et al., 2019). Hence, although the Solar Oberth maneuver accords considerable advantages in terms of performance, it still needs to be proven in practice.

As a consequence, for now, we are left with the conundrum of either waiting for the next ISO to be discovered via a loiter mission, to chase an ISO already on its way out of the solar system, or to develop NTP for facilitating access to a greater variety of ISOs.

4. Conclusions

There are many mysteries that remain unresolved about the Solar system, which can be distilled down to a single question: Is the Solar system typical? In other words, does it obey the Copernican Principle sensu lato? The detection of exoplanets has, thus far, enabled us to address this issue to an extent insofar as the architecture and general makeup

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[1] https://www.nasa.gov/pdf/373665main_NASA-SP-2009–566.pdf

[2] https://github.com/AdamHibberd/Optimum_Interplanetary_Trajectory/blob/master/doc/Optimum%20Interplanetary%20Trajectory%20Software%20by%20Adam%20Hibberd.pdf

[3] https://www.nasa.gov/offices/oct/taxonomy/index.html

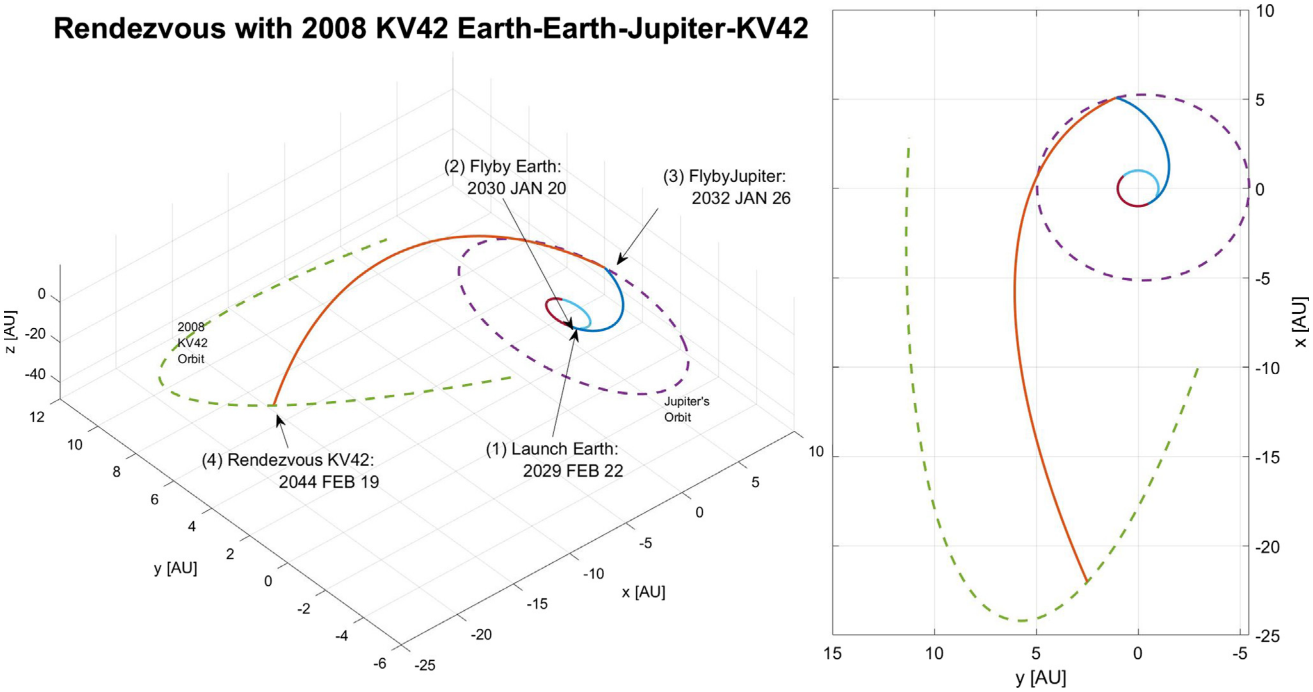

Fig. 6. Rendezvous Mission to KV42.

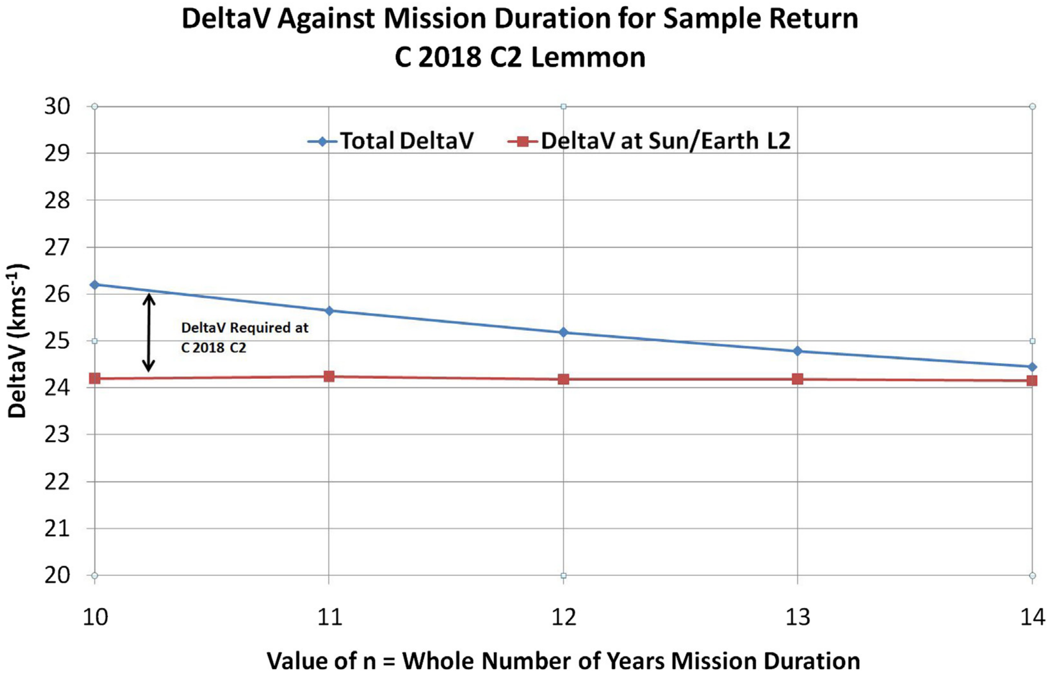

Fig. 7. Sample Return from C 2018/C2. ΔV Dependency on In-flight Time n (= Number of Years).

of planetary systems is concerned. However, we still remain in the dark when it comes to more specific questions such as the modality of planet formation, the composition and interior structure of rocky and/or icy objects, the gravitational ejection of planetesimals, and obviously the prevalence of prebiotic chemistry and life. It is apparent that a first-hand study of ISOs, along the lines proposed herein, may enable us to settle most, if not all, of these vital questions, thereby paving the way toward a more in-depth assessment of the Copernican Principle.

Hence, the goal of this paper was to explore whether missions to various categories of ISOs are realizable by utilizing existing or near-term technology. The answer is in the affirmative as illustrated by our analysis in Section 3.

Such near-term missions would generate in situ data from bona fide extrasolar objects, the scientific value of which is difficult to overstate, without actually flying to other stellar systems. We presented concrete scenarios for the actualization of the fast flyby, rendezvous, and sample return mission categories.

A combination of Falcon Heavy or SLS launch vehicles, chemical propulsion, and Parker Solar Probe-derived heatshield technology would be sufficient for fast flybys. When it comes to a rendezvous, solar electric propulsion ought also be incorporated to achieve the appropriate mission constraints. Lastly, in the case of sample return, NTP would be rendered necessary as well. In the event of sufficiently quick detection and launch of the spacecraft, we showed that all three categories could be implemented with reasonable flight durations of ~10 years. The minimal suite of onboard instruments for answering the questions posed a couple of paragraphs earlier, about the origin of these objects, is a camera and mass spectrometer; we will not delve into it further as it falls outside the scope of this paper.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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