Interstellar Now!

Missions to and Sample Returns from Nearby Interstellar Objects

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1. Introduction

We live in a special epoch in which, after centuries of speculation, the first exoplanets have been detected. Detecting and characterizing these worlds holds the potential to revolutionize our understanding of astrophysics and planetary science as well as exobiology if they harbor "alien" life (e.g., [1], [2]). Terrestrial telescopes and even very large interferometers like the Labeyrie Hypertelescope will be insufficient to properly characterize and understand local geology, chemistry and possibly biology of extrasolar objects [3], [4]. These properties can only be investigated *in situ*. Miniscule gram-scale probes, even if laser-launched from Earth to relativistic speeds, are unlikely to return science data from other stellar systems much sooner than 2070 (e.g., [3]–[5]).

But there is another opportunity. Extrasolar objects have passed through our home system twice now in just the last three years: 1I/Oumuamua, 2I/Borisov (e.g., [6], [7]). Such interstellar objects (ISOs) provide a previously unforeseen chance to directly sample physical material from other stellar systems much sooner. By analyzing these interlopers, we can acquire data and deduce information about their planetary system of origin, planetary formation, galactic evolution and possibly even molecular biosignatures or even clues about *panspermia* [8], [9].

In this White Paper, we show that missions to ISOs can be performed with existing or near-term technology, demonstrating that different categories of missions to different types of ISOs are feasible within the next decade. We present three categories of missions: fast flybys, ideally combined with an impactor to sample the surface, rendezvous missions with orbiter or lander, and a fast flyby returning samples generated by high-velocity impactor(s).

An overview of various ISO types, based on their orbital dynamics, is presented in Table 1. To date, two different classes of ISOs are already known to exist: hyperbolic interstellar asteroids (1I/Oumuamua) and interstellar comets (2I/Borisov). Hyperbolic visitors that will not return can be classified in terms of their composition and excess velocity at infinity (v_∞), and furthermore these parameters may be correlated [10], [11]. We can reasonably expect other ambassadors in the coming years, especially as astronomical surveys improve [12]–[15]. In addition, there may already be captured ISOs in our solar system [16]–[18], some with very low original v_∞ that facilitated capture [8], [19], although [20] have challenged this origin for Centaurs. In order to truly determine whether they are ISOs or not, visiting them is paramount.

Type 2 ISOs in Table 1, with $v_\infty < 1$ km/s, are separated out because the problem is not just finding, but in distinguishing them from long-period Oort Cloud comets (see, e.g., [8], [19], [21]). Ultimately, this requires compositional and isotopic analysis, which can be performed in fast flybys sampling the coma directly, or collecting ejecta from impactors (see [22]).

Measurements, instruments, and mission categories described in more detail in following sections.

Table 1: Types of ISO and associated science and possible near term mission categories.

ID	Type	Examples	Mission Type
1	Clearly hyperbolic objects, $v_{\infty} \gg 1$ km/s	1I/'Oumuamua & 2I/Borisov. Currently detection limited.	Flyby/impactor
2	Similar to 1I & 2I but $v_{\infty} \sim 1$ km/s or less.	C/2007 W1 Boattini. Confusion limited.	Sample return
3	Galactic Stellar Halo objects, low spatial density, of order $\leq 1\%$ of Galactic Disk ISOs.	None known so far. Unlikely to be found with current surveys.	Not feasible even if found in next decade
4	Comets captured in the Oort cloud at the formation of solar system.	Population unknown, possibly a significant fraction of the long period comets.	Impact sampling or sample return, isotope analysis needed for confirmation.
5	Material 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.
6	Captured objects in retrograde and other unusual orbits ([20], [23], [24])	Some Centaurs; retrograde objects such as (514107) Ka'epaoka'awela	Rendezvous dep. on incl. All captured orbit objects could be ISOs or long period comets; work needed to find orbits most likely to contain ISOs.
7	Sednoids, three body traded objects, special case of case 4 or case 6.	Sedna, 2014 UZ224, 2012 VP113, 2014 SR349, 2013 FT28	Large distances, but low velocities would facilitate rendezvous or sample return.

2. Science interest

The scientific potential of the three mission categories is described in more detail. Unless noted otherwise, it can be assumed that all scientific objectives possible for a simple mission can also be addressed in 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 using an impactor(s). Assuming a hypervelocity impact, radiation from the ionized plume can be analyzed using a high resolution UV spectrometer or mass spectrometer [22]. Recommended strike velocities are in the range of 3-6 km/s; higher velocities could lead to over-fragmentation of biomolecular building blocks, whereas lower velocities render the method ineffective [25]. Collected samples can be analyzed in flight with an onboard mass spectrometer, yielding information about composition and isotope ratios. For more massive ISOs, detailed radio measurements of the target's influence on the probe trajectory could yield further clues on the object's mass, density and distribution, composition and potentially even its route and origin.

An *ISO rendezvous* would provide scientists with significantly more time for up close study, with a suite of instruments on board the orbiter or lander (e.g. DAWN mission). Besides the object's mass, density, mass distribution and composition, such a mission could perform seismologic experiments elucidating the deep structure of the ISO. Mass, density and crystalline structure (via microscopy) could potentially be 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, spectrophotometric, magnetometric, and radio measurements could be executed. Additionally, advances in miniaturizing diagnostic equipment (e.g. lab-on-a-chip), would 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.

ISO sample return using high-velocity impacts is the most complicated and audacious, similar to what was accomplished by the Genesis and Stardust missions. (In general, this mission type would utilize available ΔV not to rendezvous, but to return 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. Molecular composition and micro-crystalline structure can be deduced from vaporised ejecta and dust. Determining mineralogic, mechanical and structural properties would need one or two centimeter-sized samples, either collected in the plume/coma of the ISO or from ejecta generated by an impactor. Laboratories back on Earth can provide analysis of the isotope ratios of heavy elements, molecular chemistry, nuclear chemistry, neutron activity, and detailed crystallography. Diagnostic equipment here obviously is not subject to mass constraints of the spacecraft and can provide, among others, higher-resolution spectroscopy, spectrophotometry, extremely high electron- and atomic force microscopy. One trade-off is that a sample return mission may yield less information about basic mass, density and seismology.

In addition to scientific objectives at the ISOs themselves, interesting measurements can also be performed en-route, including but not limited to collection and analysis of interplanetary dust and ions and close-up observation of phenomena, e.g., the IBEX ribbon. One concrete example of each of the three mission categories follows. Minimum instrumentation should be a camera and mass spectrometer on each of the missions.

3. Missions to interstellar objects

3.1 Fast flyby/impactor with 1I-type $\Delta V > 15$ km/s (chem), $\Delta V < 40$ km/s (NTP)

For chemical propulsion to 1I, extensive research has been conducted [26], [27]. A sample mission shown in Figure 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, and 2-stage SRM at the SO which enables intercept at 200 AU. Using 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 of order 10s up to 1000s of kg by the target depending on launch date, mission duration, and maneuvers [26], [27]. Even as close as 6 solar radii, heatshields similar to the Parker Solar Probe can be used to protect against solar heating [27], [28]. Due to uncertainty in 1I's orbit, at 200 AU there will be a possible million-km displacement from its estimated solar escape asymptote. At an approach speed of 30 km/s, observations from the spacecraft would require a telescope. Alternatively a swarm of chipsats could be dispensed around 1I's estimated escape asymptote and travel in the vanguard of the bus, 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 spectroscopically.

For nuclear thermal propulsion (NTP) to 1I, Hibberd and Hein [29] show that a direct trajectory leaving LEO in 2030 to fly by 1I is achievable using a small nuclear rocket engine (derived from the AEC/NASA 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 NERVA "Pewee"-class NTP system can deliver 2.5 tonnes on target in a 14-year flight. The flight segment from LEO to Jupiter would take 5 months and so needs a zero-boil-off cryocooler and zero-leakage LH₂ tanks. Other existing/near-term technologies could also be applied to drastically reduce this mission's duration, e.g., solar, electric sails, and multi-grid electric thrusters [26], [28], [30]–[32].

Figure 1: Flyby mission scenario to 1I/Oumuamua with GA @ Jupiter and SO @ 6 radii

3.2 Rendezvous with 514107 Ka'epaoka'awela $\Delta V=11.5$ km/s; ΔV strong $f(i, q)$

Type (6) ISOs in elliptical orbits (as opposed to hyperbolic orbits of types (1) & (2)) follow periodic optima, and so can spacecraft, opening possibility of rendezvous missions attainable with reasonable ΔV . Retrograde object (514107), a possible captured ISO, is a candidate for type (6) and is also co-orbital with Jupiter. It can be reached by a 1-year Earth V_∞ Leveraging Maneuver starting from a 2024 launch, travel to Jupiter, a reverse GA at Jupiter (perijove=18,474 km and $\Delta V=1.1$ km/s) to bring it on a retrograde orbit to eventually rendezvous after 9 years from launch (2033). Solar electric propulsion provides high- I_{sp} braking, ΔV of 2.4 km/s, for the rendezvous.

3.3 Sample return via flyby type (1), (2) & (4) ISO, $\Delta V= 20.4$ km/s

With NTP, sample returns are feasible from type (1), (2) & (4) ISOs, beginning with a prepositioned 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 an example for a type (2) & (4) ISO, is shown in Figure 2. A future discovery of such an object would have an identical general sample return mission architecture to that shown but different values of n , 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, (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 ΔV s along this ellipse. For the chosen target, the departure ΔV is applied at the optimal launch time using NTP or SEP with arcjets. As the target is approached, an

impactor is deployed and the spacecraft travels through the plume. For hazardous plumes, a swarm of subprobes are 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.

Figure 2: Sample return mission scenario from candidate ISO C/2020 N1

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

Total velocity and mission duration for a variety of ISOs are plotted in Figure 3. Rendezvous with at least one type 6 ISO (514107) would be feasible with existing chemical propulsion.

Figure 3: Total ΔV vs. mission duration for a variety of ISOs

These sample missions we have presented demonstrate that for each mission category and ISO type, at least one feasible mission exists, which could be launched by using existing or technology that is reasonably available within the next 10 years.

4. Synthesis and broad science impact

This White Paper shows that missions to various ISOs can be launched with existing or near-term technology "before this decade is out". Such missions would generate in the near-term *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 exemplary scenarios for the fast flyby, rendezvous, and sample return mission categories. A combination of Falcon Heavy or SLS, chemical propulsion, and Parker Solar Probe-derived heatshield technology would be sufficient for fast flybys. For a rendezvous, solar electric propulsion would also be needed. For sample return, NTP would be required as well. The minimal suite of onboard instruments for answering questions about the origin of these objects is a camera and mass spectrometer.

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