Interstellar Object Interceptor Missions: Opportunities and Challenges. James J. Wray[1], Julie C. Castillo-Rogez[2], Benjamin P. S. Donitz[2], and Gongjie Li[1], [1]Georgia Institute of Technology, Atlanta, GA (jwray@gatech.edu), [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

Introduction: Two of the most exciting recent events in the exploration of our solar system were the identification of the first two interstellar objects. 1I/‘Oumuamua was first discovered in late 2017 after its perihelion closer to the Sun than Mercury; it is now back out beyond the orbit of Neptune. 2I/Borisov was spotted in mid-2019 and passed ~2 AU from the Sun in December of that year. Both were heavily observed with Earth-based telescopes: Borisov showed comet-like activity (Figure 1) with a CO-rich composition atypical of solar system comets [1], whereas ‘Oumuamua exhibited no such activity, a highly elongated or flattened shape, and non-gravitational forces influencing its trajectory that remain difficult to explain [e.g., 2]. A third interstellar object (ISO) is now confirmed to have hit Earth as a meteor in 2014 [3]. These mysterious and varied objects represent the first known macroscopic samples of exoplanetary material available in our neighborhood for detailed analysis.

No spacecraft from Earth will now likely reach ‘Oumuamua or Borisov, but more ISOs are likely to be discovered in the near term. The Vera Rubin Observatory’s Legacy Survey of Space and Time, due to commence in 2023-4, is anticipated to detect ~1-2 new ISOs/year [4]. Each one would (presumably) be from a different stellar system and represent a unique addition to sampling the diversity of planet formation and composition. Valuable follow-up observations with other ground- and space-based telescopes will help to characterize this population. But ‘Oumuamua illustrated the limitations of such remote observations, with peer-reviewed publications variably suggesting it was a planetesimal organic-rich asteroid [5] or comet with a thin insulating mantle [6,7], an ice-dust aggregate 10,000 times more porous than aerogel [8], an H_2 ice mass formed outside any planetary system [9], an N_2 ice fragment ejected from a differentiated exo-Pluto [10], or even alien technology [11]. A space mission to intercept one of these objects, image its nucleus and collect basic chemical data, would readily resolve between these or other possibilities, and would be truly transformative for both planetary and exoplanetary science.

Science Goals and Objectives: The primary goal of interstellar object exploration is to understand the range of materials and processes by which planets are formed throughout the galaxy. Toward this end, key objectives of a mission to rendezvous with an ISO would be to determine the composition of planetary building blocks, and to characterize the physical processes of planet formation and fragmentation, in the environment where the ISO formed. A secondary objective would be to characterize the processes that ejected [e.g., 12] and altered the shape or surface of the ISO since its formation. Such information is valuable even if it is impossible to pinpoint the ISO’s galactic birth zone and trajectory to our system, just as meteorites from Mars yield profound insights into that planet’s history even without knowing their source regions. ESA’s upcoming Comet Interceptor mission [13] aims to address analogous science questions, but at a body bound to our Sun, with recent estimates suggesting a <0.1% chance that it could reach an ISO [4]. It has been argued that Oort cloud comets, one of which Comet Interceptor hopes to target, could in many cases be captured interstellar bodies [14]; but for any given object this will be unknown. By contrast, we would target a body clearly exceeding solar escape velocity and therefore definitively formed elsewhere.

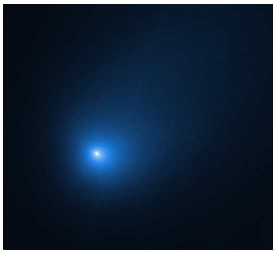

Figure 1. *Hubble Space Telescope image of 2I/Borisov taken shortly after its closest approach to the Sun, providing unprecedented insights into the composition of planet-forming materials from beyond our solar system. Credit: NASA/ESA/D. Jewitt (UCLA).*

Target Destination: Although the proposed mission’s precise target is inherently not yet known, we can presume it will be a small cometary or asteroid-like body; masses of ‘Oumuamua and Borisov are not precisely known but their inferred sizes (effective radii) were ~10^2 m and ~10^3 m, respectively [15]. But Borisov additionally had a visible dust and gas coma and tail extending ~10^5 km from the nucleus [16], with sub-millimeter and larger dust particles carrying ~10^2 kg/s of mass away from the comet during its passage through the inner solar system [15], and at least one “outburst” likely caused by ejection of ~meter-scale boulder(s) [17].

Mission Architecture/Platform: ‘Oumuamua and Borisov were traveling at ~88 and 45 km/s relative to the Sun at their respective perihelia, so any spacecraft on a plausible trajectory to intercept similar objects would likely approach at a relative velocity of many tens of km/s. The mission architecture would be limited to a fast flyby of the target. Attempting to enter orbit of the ISO would require a prohibitive amount of propellant with currently available technologies. The addition of a hard impactor could reveal fresh material from the object and remove any effects of space weathering; a JPL Planetary Science Summer Seminar mission study suggested such an impactor [18].

Expected Measurements: Imagery capable of resolving the ISO's solid body would be essential, to definitively measure its size, shape, morphology and potentially reveal surface processes; even small satellite-ready cameras are capable of exceeding Earth-based telescope spatial resolutions by orders of magnitude if carried within ~10^5 km of the target [19]. A measurement of the ISO's mass would helpfully reveal its bulk density, but the rapid flyby architecture may preclude measuring gravitational influences on spacecraft trajectory. The other critical measurement would be bulk chemistry, to resolve competing ISO origin hypotheses and enable direct comparison to solar system compositions; remote sensing and/or direct sampling approaches should both be considered for this [e.g., 18]. Resolving compositional heterogeneities within the ISO related to aggregation, differentiation, and/or subsequent evolution would also be valuable, but perhaps less critical. Arguably, the unique nature of any individual ISO motivates a restricted payload on a small satellite that could potentially be sent to each of several ISOs (pending suitable targets) to explore galactic diversity.

Target Solicitation: The recently published Planetary Science and Astrobiology Decadal Survey report [20] advocates strategic research areas for the upcoming decade, including to "Characterize the rotational, physical, chemical, geological, and interior properties of Interstellar Objects and comparison with small bodies in the solar system with spacecraft and/or ground-/space-based observations" (Q2.6); and to "Identify and characterize interstellar objects (e.g., size, dynamical origin, and composition) with spacecraft data, telescopic observations, theoretical and modeling studies of their formation and evolution, and laboratory studies of analogue materials" (Q12.1). The report says "These strategic research areas ... are intended to provide useful guidance and context in support of activities beyond those specifically prioritized in this report, e.g., involving Discovery-class or smaller missions...." ISO missions are thereby endorsed for consideration under upcoming Discovery or SIMPLEx mission calls. A somewhat higher cost cap than imposed for prior SIMPLEx calls (as recommended by the Decadal Survey) would likely be needed to achieve ISO rendezvous [21,22].

Technology Challenges and Opportunities: The dynamic nature of comets, especially combined with high flyby speeds, poses risk to the spacecraft. Indeed, many instruments and subsystems of ESA's Giotto spacecraft were affected by dust impacts during passage within 600 km of 1P/Halley's nucleus at 68 km/s [23]; however, the spacecraft remained operational and revolutionary measurements were returned. Giotto's impact mitigation strategies provide some guidance for how to approach ISO flybys but there is still development required for a high reliability, extremely fast flyby to an ISO, which would be similar to fast flybys of other solar system small bodies such as centaurs, KBOs, or Oort cloud comets. The greatest challenge for planning ISO missions is that the intercept trajectory and timing are unknown until the object is discovered. 'Oumuamua-like objects would be found only ~months ahead of their closest approach to Earth [4], and even more visible Borisov-like objects provide at most a few years' lead time [21]. This requires: 1) a faster mission development timeline than standard for NASA, *or* 2) building the spacecraft now, then storing on the ground until discovery, *or* 3) launching prior to discovery and waiting in space, as Comet Interceptor will do [13]. While challenging, this situation is also an opportunity, as similar challenges await if/when we must one day respond to a potentially hazardous asteroid for planetary defense [20].

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