A Study of an Interstellar Object Explorer (IOE) Mission

Planetary and Space Science, Volume 241, February 2024, 105850
https://www.sciencedirect.com/science/article/pii/S003206332400014X

S. Alan Stern
Southwest Research Institute
1301 Walnut St., Suite 300
Boulder, CO 80302

Silvia Protopapa
Southwest Research Institute
1301 Walnut St., Suite 300
Boulder, CO 80302

Matthew Freeman
Southwest Research Institute
6220 Culebra Road
San Antonio, TX 78238

Joel Wm. Parker
Southwest Research Institute
1301 Walnut St., Suite 300
Boulder, CO 80302

Mark Tapley
Southwest Research Institute
6220 Culebra Road
San Antonio, TX 78238

Darryl Z. Seligman
Cornell University
122 Sciences Drive
Ithaca, NY, 14853, USA

Caden Andersson
Custom Microwave Inc.
4 Boston Court
Longmont, CO 80501

Abstract

The first discoveries of Interstellar Objects (ISOs), i.e., small bodies moving through our Solar System on high-speed hyperbolic orbits, occurred in 2017 and 2019, decades after ISOs were first predicted. The scientific value of ISOs is high, as they represent samples, most likely planetesimals, from other solar systems. A significant increase in the rate of ISO discoveries is expected in the late 2020s and in the 2030s owing to the advent of several new observing capabilities enabling more routine ISO detections. Here we investigate how a space mission to reconnoiter an ISO can be designed, including discussions of the scientific objectives and payload for such a mission, its unique mission design aspects, and some preliminary spacecraft and payload considerations, all in support of possible proposals to conduct such a mission in the 2030s.

Highlights

- Newly discovered populations of InterStellar Objects (ISOs) like comets and asteroids are valuable scientifically.
- Here we study a mission concept to ISOs.
- We describe the scientific goals and objectives of such a mission.
- We describe the mission design to accomplish an ISO mission with current technology.
- We also define a payload that accomplishes all of the stated scientific goals and objectives and also the primary spacecraft requirements for such a mission.

ISO Population Studies

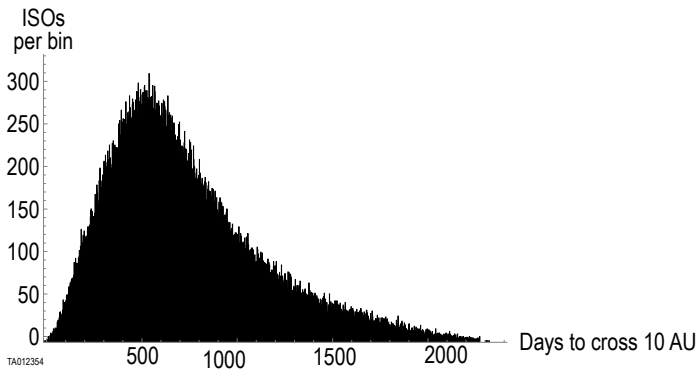
Background

- Cook et al. (2016) presented the first detailed simulation of ISOs with the objective of making predictions for the population that would be detected with the forthcoming US Large Synoptic Survey Telescope (LSST), also called the Vera Rubin Observatory (VRO). Their LSST detectability criteria required (1) that the minimum magnitude of the ISO was brighter than a specified sky survey limiting magnitude, (2) that the solar elongation was less than 18 degrees (3) that the airmass was less than 2 as observed from the observatory at Cerro Pachon, Chile.
- Seligman & Laughlin (2018; SL18) generated a synthetic population and performed a multi-dimensional Monte Carlo (MC) integration over: (1) the kinematic velocity distribution of stars, (2) impact parameter, (3) rotation angle, and (4) the location of Earth at the initialization of the simulation.
- Hoover et al. (2022) performed a more rigorous and higher-resolution simulation of the population of ISOs with more refined estimates of the observability criteria for the LSST. Their methodology was like SL18, but utilized more stringent LSST observability criteria.
- Marčeta (2023) then developed an entirely analytic method to generate synthetic populations of ISOs. They labeled this method the "probabilistic method" as opposed to the previous Monte Carlo approach labeled the "dynamic method."
- Marčeta & Seligman (2023) implemented this dynamic method with a stringent LSST survey simulation. From this, they predicted the orbital elements and physical properties that the LSST would detect for a range of populations of asteroidal inactive ISOs with varying albedo, size frequency distributions and assumed stellar kinematic distributions.

Initial Conditions

- In this paper, we implement the same methodology as Hoover et al. (2022) to simulate the population of ISOs, with minor discrepancies:
    - Unlike Hoover et al. (2022), we propagate the trajectories of the initial conditions analytically.
    - We assume that the ISO kinematic distribution mirrors solar-type stars.
    - For the purposes of this work, we assume that ISOs are "detectable" if they have heliocentric distances <2 AU (i.e., the nominal solar distance where an interstellar object brighter than 'Oumuamua would be discoverable by the LSST).

Figure 1. Distribution of time in days for ISOs in this study to cross 10 AU radius sphere centered on the Sun. Vertical axis is the number of ISOs per 1-day bin. This ISO kinematic distribution matches the kinematic distribution of Sun-like stars, biased by the Sun's velocity relative to the Local Standard of Rest. Keplerian Sun-centric trajectories are assumed, i.e., with no interaction with the planets.



Science Goals

Our study set the following science goals and their specific objectives for a first mission to an interstellar object (ISO):

Science Goal 1 (SG1): Determine the composition of the ISO to provide insights into its origin and evolution.

- Characterization of the composition and physical properties of the ISO is essential for understanding:
  1. The host solar system's initial conditions.
  2. The nature and evolution of the ISO's materials.
  3. The processes responsible for planetesimal formation.

- Comparative Compositional Studies:
  Utilize insights from primitive Solar System objects (comets, asteroids, Kuiper Belt Objects) that shed light on the early history of our Solar System. These bodies serve as crucial comparatives for understanding ISOs.

Derived Science Objective (SO) for SG1:

SO1: Search for and characterize windows into the ISO's Subsurface Geology.
Focus on Subsurface Exploration: Determine the distribution of observable (a) subsurface albedo structures, and (b) exposed surface and subsurface features such as craters, scarps, and sites of past or present geological activity.

Instrument Requirements: A panchromatic visible-wavelength imager equipped with arcsecond-class angular resolution and high dynamic range.

SO2: Determine the colors, compositions, and photometric properties of the ISO's surface and subsurface.

Focus on Compositional Characterization: Assess the (a) distribution of color units at different spatial scales, (b) distribution of compositional units, including minerals, ices, salts, organics, and other materials at different spatial scales (e.g., H_2O ice, CO_2 ice, NH_x salts, aliphatic organics), and (c) disk resolved photometric properties of selected regions of interest.

Instrument Requirements: A visible-wavelength imager with a minimum of three filters, along with an infrared imaging spectrometer that spans the 1-2.5 μm wavelength range, possibly extending up to 4 μm, with a resolving power of at least 100.

SG2. Determine or constrain the nature, composition, and sources of the ISO coma activity and determine the processes responsible for observed activity.

By characterizing the composition and spatial distribution of an ISO's coma, the IOE mission can:

1. Identify the primary components of its target ISO.
2. Uncover the mechanisms driving the ISO's coma activity.
3. Enhance our understanding of the composition and processes in the ISO's protoplanetary formation disk, crucial for understanding planetesimal formation.

Derived SO for SG2:

SO3: Characterize the ISO's chemical and physical properties of the ice, dust, and gases in its coma.

Focus on Compositional Characterization: Constrain (a) the production rates for parent molecular gas species in the coma (e.g., H_2O, CO, CO_2, N_2, O_2, CH_4) (b) the abundance, path length, purity, mixing ratio of ices and refractories in the coma, and (c) the microphysical properties of the dust (ices and refractories) in the coma.

Instrument Requirements: In addition to the previously mentioned instruments, an ultraviolet (UV) spectrometer spanning the wavelength range of 700 to 1970 Å with a spectral resolution of ≤20 Å.

SO4: Understand the nature of the ISO coma activity.
Focus on Dynamical and Compositional Characterization: Assessing (a) the types and distribution of coma structures (e.g., sources of vents, plumes, jets, cliff collapse, mass wasting processes) and, (b) the chemical nature of the coma structures (e.g., H_2O, CO_2, CO).
Instrument Requirements: Panchromatic visible-wavelength imager, and UV and infrared imaging spectrometers are essential.

Payloads

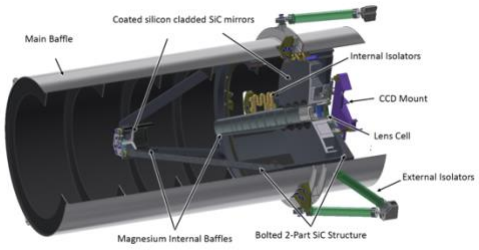
The IOE payload needs to be broad enough to enable discovery of unexpected features and properties, while still being tailored to capture the ISO's properties, likely shared with the various small body types in our Solar System. In addition, the payload needs to meet its observation requirements for the expected high encounter speeds of a relatively small target at a close approach distance.

The science objectives drive us to consider a payload suite with broad, general capabilities for imaging and spectroscopy. The strawman payload is comprised of a panchromatic visible imager, a color imager and IR spectrometer, and a UV spectrometer.

Panchromatic Visible Imager. This instrument is needed to characterize the geology and photometric properties of the ISO's surface, for measuring light curve and rotational properties, for determining the ISO's shape, mapping structures in its coma, and searching for orbiting satellites or escaping fragments.

We base the concept of this IOE instrument on the L'LORRI imager on the Lucy mission (Weaver et al. 2023), which itself is based on the LORRI instrument flown on the New Horizons mission (Cheng et al. 2008; Weaver et al. 2008). This imager is a Ritchey-Chrétien optical design, with a 20.8 cm primary mirror feeding a 1024x1024 pixel imaging CCD. The key attributes of this instrument are:

Attribute	Value
Aperture	20.8 cm
Focal Length	262 cm
FOV	0.29 deg (5.1 mrad)
Pixel Size	1.04 arcsec (5.03 µrad)
Spectral Range	420–795 nm at 50% of peak QE 380–860 nm at 10% of peak QE

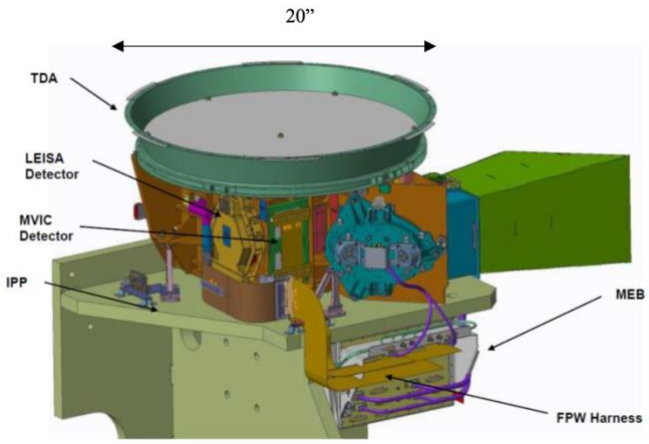


Color Imager and IR Mapping Spectrometer. This instrument is needed for IOE's color imaging and surface composition objectives, such as determining the colors, compositions, and photometric properties of the ISO's surface and its coma particles.

We base this IOE instrument on the L'Ralph instrument on the Lucy mission (Reuter et al. 2023), which itself was based on the Ralph instrument on the New Horizons mission (Reuter et al. 2008; Weaver et al. 2008). The instrument consists of a single telescope that passes light through a dichroic beam splitter to transmit light to two cameras: the Multi-spectral Visible Imaging Camera (MVIC) and the Linear Etalon Imaging Spectral Array (LEISA).

The MVIC color imager has multiple 5024x64 pixel Time Delay and Integrate (TDI) arrays that meet the science requirements for broadband color and composition imaging. The Lucy MVIC has five such color TDI CCDs (violet, green, orange, phyllosilicate, and near-IR) and one panchromatic channel, which has a wider field of view to complement and serve as a backup to the visible imager. The LEISA hyperspectral imager has a 2048x2048 pixel HgCdTe array operated in push broom mode. It creates a 2-D spatial x 1-D spectral data cube. The key attributes of this instrument and its two camera systems are:

Attribute	Value
Overall	
Aperture	75 mm
Focal Length	450 mm
MVIC Imager	
FOV (TDI array)	8.25 deg x 0.105 deg
Pixel Size	29 µrad
Spectral Range	0.38-0.92 µm
Spectral Resolution	47-550 nm
LEISA Mapping Spectrometer	
FOV	2.35 deg x 3.37 deg
Pixel Size	40 µrad
Spectral Range	0.95-3.95 µm
Spectral Resolution	10 nm

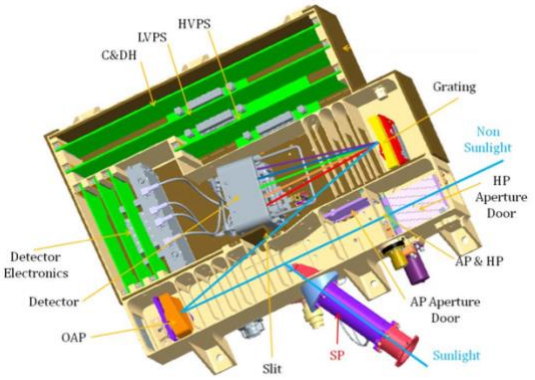


UV Spectrometer. The ultraviolet spectrometer instrument for IOE measures the UV photometric properties of the surface, measures or sets upper limits on the chemical and physical properties of dust and gas in the ISO coma, and characterizes the nature of the ISO's activity.

This IOE instrument is based on the UV spectrograph (UVS) on the ESA JUICE mission (Davis et al. 2021), which itself is based on the long line of "Alice" UV spectrographs that flew on the ESA Rosetta (Stern et al. 2007), NASA New Horizons (Stern et al. 2008), NASA Lunar Reconnaissance Orbiter (Gladstone et al. 2010), and NASA Juno missions (Gladstone et al. 2017).

The instrument's optical design is an off-axis primary in a Rowland circle mount. The detector is a 2-dimensional (2048 spectral x 512 spatial) microchannel plate, with a Caesium Iodide (CsI) photocathode, and cross-delay-line readout. The key attributes of this instrument are:

Attribute	Value
FOV	0.1 x 7.3 deg
Pixel Size (spatial)	0.0092 deg
Pixel Size (spectral)	0.106 nm
Spectral Resolution	0.5-0.8 nm (point source) < 1.2 nm (extended source)
Spectral Range	50-204 nm



Mission Design

Our model population has a velocity distribution consistent with class G stars biased by the Sun's velocity with respect to the local standard of rest. We modeled all ISOs passing within 10 AU of the Sun over a 10-year test period, and included the effect of the Sun's gravitational focusing.

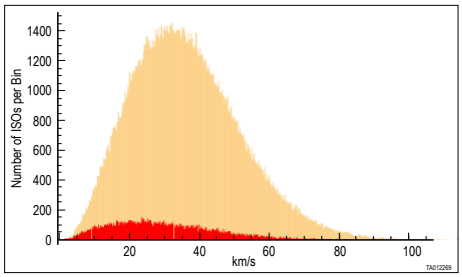


Figure 2. Velocity Distributions. Velocity distribution of our overall population in yellow, and superposed on this, the velocity distribution of the detectable subset of that population in orange. Vertical axis is number of ISOs per bin, horizontal axis is velocity in km/s.

Mean approach velocity is 32.14 km/s; average time within the 10 AU radius modeled sphere is 770.5 days. Most viable intercept trajectories result in a flyby near the middle of this arc, so time between detection of the ISO and intercept is often less than one year.

Electric propulsion systems are not effective because they require too long to generate large ΔV, so we are limited to two intercept mission design options: storage on the Earth, with a high-energy (planetary trajectory) type launch soon after detection of the ISO, or launch to a storage on-orbit from which the intercept is commanded following discovery of a suitable target ISO.

To be most effective, Earth-based launch requires a maximum of 30 days between detection of the ISO and launch, not practical in a NASA mission proposal. We then place the IOE spacecraft into a storage orbit after launch at the Earth-Moon L1 point:

- C3=0 in its storage location
- Fall time from L1 to a near-Earth flyby is less than 4 days
- Orbit period enables any launch azimuth within ≤28 days after detection
- Orbit maintenance easy, and 400 km swingby at Earth is easy to reach

Earth maximum launch V_∞ is 8.6 km/s, based on a C3=0 (exactly escape velocity) launch vehicle supplemented by a 3.0 km/s ΔV from the IOE spacecraft itself. For Lunar L1 storage orbit with similar launch vehicle and SC parameters, final V_∞ varied from a maximum of 7.35 km/s in the ecliptic down to a minimum 6.72 km/s for a polar Earth departure inclination.

Table 1. Key Mission Parameters

Parameter	Value	Precedent Mission
Spacecraft Design ΔV Capability	3.0 km/s	Cassini (2.1 km/s)
Minimum Flyby Altitude	400 km	Galileo (303 km)
Maximum Heliocentric Radius	<3 AU	Juno (5.2 AU)
Flyby Relative Velocity	100 km/s	"Halley Armada" (70 km/s)

Minimum 3-day period between ISO detection and the maneuver departing lunar L1 storage orbit.

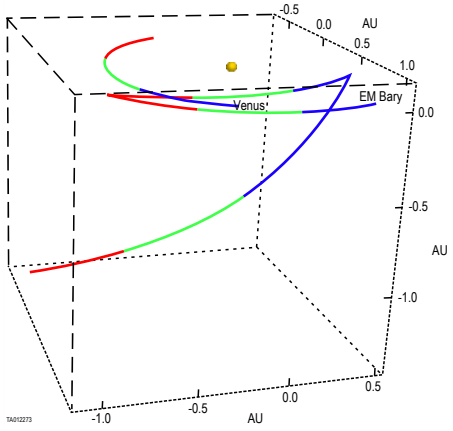


Figure 3. Sample intercept trajectory with constraints applied. Departure from Earth-Moon L1 is constrained by detection date + 3 days, and subsequently by Earth/Moon geometry being correct for departure asymptote after low Earth swing-by. Departure V_∞ from Earth is 4.529 km/s, which is easily achievable for our spacecraft. Each color band represents 30 days.

Mean time between reachable ISOs follows equation (1):

$$T_{avg} = T_{model}/(D_{int} V_{model} P_{feas}) \quad (1)$$

Here, T_{avg} is time between interceptable ISOs, V_{model} is the volume of the sphere containing all of the impact parameters, D_{int} is the expected density of ISOs in interstellar space ($0.1/AU^3$), T_{model} is the time each ISO is within V_{model} (770 days), and P_{feas} is the fractional chance that a given ISO from the original model population is interceptable. For the parameters given, chance of a viable ISO target being found within 10 years is 94.5%.

Spacecraft Requirements

- Selected payload requires 65 kg and 60 W, including 25% contingency
- Total encounter data estimated at 67 GB
    - Downlink bandwidth not a driving case as encounter data can be downlinked over a long period after the flyby
- Pointing the instrument suite during flybys will be challenging
    - Pointing capability of the spacecraft needs to be 14 deg/s at closest approach
    - LORRI drives the stability requirement of 2.5 microrad
- Chemical propulsion will be required for initial intercept burn
    - Liquid propellant is suitable for the initial burn, as well as future trajectory corrections and propulsive maneuvers
- Mission environment estimates
    - Mission lifetime 13 years (10 years loiter, 2 years flight, 1 year downlink)
    - Survival temperature range -30 C to +45 C
    - Operational temperature range -15 C to +40 C
    - Radiation
        - TID 40 krad (si), displacement Dose $6x10^{11}$ MeV/g
- Operations
    - Loiter
        - Launch and acquisition of storage orbit
        - Instruments in hibernation with only routine and infrequent health checks until discovery of interceptable ISO
        - Max planned duration 10 years
    - Approach and Flyby

        - Execution of intercept burn
        - Monitoring of spacecraft navigation and necessary course corrections
        - Instruments awakened and begin rehearsals for flyby
        - Flyby executed with a high level of autonomy, minimal real time commanding and a worst-case comet geocentric distance of 3.3 AU
    - Downlink
        - Instruments go back into hibernation
        - Spacecraft downlinks data via single 34m DSN antenna

References

Cheng, A. F., et al. 2008. Long-Range Reconnaissance Imager on New Horizons. *Space Science Reviews*, 140, 189-215. doi:10.1007/978-0-387-89518-5_9.

Cook, N. V., et al. 2016. Realistic detectability of close interstellar comets. *The Astrophysical Journal* 825, 51. doi:10.3847/0004-637X/825/1/51.

Davis, M. W., et al. 2021. The JUICE ultraviolet spectrograph: a next-generation compact UVS for ESA's JUICE mission. *International Conference on Space Optics - ICSO 2020*, 11852,1185226.

Gladstone, G. R., et al. 2010. LAMP: The LMP Project on NASA's Lunar Reconnaissance Orbiter Mission. *Space Science Reviews*, 150, 161-181. doi:10.1007/s11214-009-9578-6.

Gladstone, G. R., et al. 2017. The Ultraviolet Spectrograph on NASA's Juno Mission. *Space Science Reviews* 213, 447-473. doi:10.1007/s11214-014-0040-z.

Hoover, D. J., et al. 2022. The Population of Interstellar Objects Detectable with the LSST and Accessible for In Situ Rendezvous with Various Mission Designs. *The Planetary Science Journal* 3, 71. doi:10.3847/PSJ/ac58fe.

Marčeta, D. 2023. Synthetic population of interstellar objects in the Solar System. *Astronomy and Computing* 42, 100690. 2301.09375.

Marčeta, D. & Seligman, D. Z. 2023. Synthetic Detections of Interstellar Objects with the Rubin Observatory Legacy Survey of Space and Time. *Planet. Sci. J.* 4, 230. 2310.17575.

Reuter, D. C., et al. 2008. Ralph: A Visible/Infrared Imager for the New Horizons Pluto/Kuiper Belt Mission. *Space Science Reviews*, 140, 129-154. doi:10.1007/s11214-008-9375-7.

Reuter, D. C., et al. 2023. L'Ralph: A Visible/Infrared Spectral Imager for the Lucy Mission to the Trojans. *Space Science Reviews*, in press.

Seligman, D. & Laughlin, G. 2018. The Feasibility and Benefits of In Situ Exploration of 'Oumuamua-like Objects. *The Astronomical Journal,* 155, 217. doi:10.3847/1538-3881/aabd37.

Stern, S. A., et al. 2007. Alice: The Rosetta Ultraviolet Imaging Spectrograph. *Space Science Reviews* 128, 507-527. doi:10.1007/s11214-006-9035-8.

Stern, S. A., et al. 2008. Alice: The UV Imaging Spectrograph Aboard the New Horizons Pluto-Kuiper Belt Mission. *Space Science Reviews*, 140, 155-187. doi:10.1007/s11214-008-9407-3.

Weaver, H. A., et al. 2008. Overview of the New Horizons Science Payload. *Space Science Reviews*, 140, 75-91. doi:10.1007/s11214-008-9376-6.

Weaver, H. A., et al. 2023. The Lucy Long Range Reconnaissance Imager (L'LORRI). *Space Science Reviews,* 219, 82-135, doi: 10.1007/s11214-023-01028-z