Exobodies in Our Back Yard: Science from Missions to Nearby Interstellar Objects

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Abstract

The recent discovery of the first confirmed Interstellar Objects (ISOs) passing through the Solar System on clearly hyperbolic objects opens the potential for near term ISO missions, either to the two known objects, or to similar objects found in the future. Such ISOs are the only exobodies we have a chance of accessing directly in the near future. This White Paper focuses on the science possible from *in situ* spacecraft exploration of nearby ISOs. Such spacecraft missions are technically possible now and are a suitable potential missions in the period covered by the 2023-2032 Decadal Survey. Spacecraft missions can determine the structure and the chemical and isotopic composition of ISO in a close flyby coupled with a small sub-probe impactor and either a mass spectrometer or a high resolution UV spectrometer; this technology will also be useful for fast missions to TransNeptune Objects (TNOs) and long period comets. ISO exploration holds the potential of providing considerable improvements in our knowledge of galactic evolution, of planetary formation, and of the cycling of astrobiologically important materials through the galaxy.

1 Introduction

The existence of Interstellar Objects (ISOs) visiting the Solar System has been predicted for many years (e.g. Sekanina [1976], Stern [1990]). We live in an interesting epoch where two of them have been found (1I/Oumuamua) and (2I/Borisov) and signs of other visitors have been proposed [Siraj and Loeb, 2019, Froncisz et al., 2020]. In addition, there are prospects to detect one or several of them per year with the Vera Rubin Observatory (or LSST) starting in 2022 [Trilling et al., 2017]. Ground-based telescopes will not be able to give reliable answers to questions about the origin, chemical composition, mineral structure, size, shape of these interstellar visitors - that will require *in situ* exploration.

During its history the solar system must have ejected vast numbers of planetesimals, comets and asteroids into interstellar space. Recent discoveries have shown that exoplanetary systems are common; if they have similar histories, there should thus be a sizable population of small protoplanetary ISO Engelhardt et al. [2017]. In addition, stars can eject dust and gas and planetary debris *after* their time on the main sequence, and it is even possible that small bodies form directly in interstellar space. Although spacecraft, radar and visual detection arrays definitely observe streams of dust-sized interstellar micrometeorites Strub et al. [2015], Baggaley [2000], and although there appears to be a population of nomadic interstellar planets Sumi et al. [2011], Strigari et al. [2012], Clanton and Gaudi [2017], until recently there was no firm evidence for even a single galactic asteroid or comet coming into the solar system from interstellar space Engelhardt et al. [2017].

In October 2017, the first known interstellar object (ISO), named 1I/Oumuamua, was detected by the *Pan-STARRS* survey, and then observed and tracked as it was moving through the solar system at a heliocentric velocity of 50 km/s. 1I/Oumuamua was detected after ~ 3.5 years of *Pan-STARRS* observing in its current survey mode. Do et al. [2018] used this to calculate an upper limit to the space density, n , of similar sized ISOs of

$$n \lesssim 0.2 \text{ AU}^{-3} . \quad (1)$$

indicating these objects may pass through the inner solar system more or less continuously and that targeted searches [Eubanks, 2019b] or more sensitive survey instruments such as the VRT [Trilling et al., 2017] may be able to find numerous targets for future missions.

The discovery of the interstellar comet 2I/Borisov on August 30, 2019 (originally C/2019 Q4 (Borisov)) [Guzik et al., 2019] provides a second InterStellar Object (ISO) available for study in its passage through our solar system. 2I was rapidly recognized to be on a hyperbolic orbit (see Figure 1). 2I/Borisov is an active object superficially similar to a small solar system comet [Jewitt and Luu, 2019] with an estimated nucleus diameter of order 1 km [Jewitt et al., 2019]. 2I/Borisov was discovered at an R magnitude of 17.8 in the Northern sky, and reached a peak apparent magnitude of about 15 near perihelion. Based on data from the IAU Minor Planet Center database, long period comets have been discovered at similar magnitudes since at least Comet Kohoutek (C/1973 E1) in 1973, 48 years before 2I/Borisov was discovered. This strongly suggests that interstellar comets as large and active as 2I/Borisov are actually rare enough that it may be decades before another such target is found.

Figure 1: The trajectory of 2I/Borisov, discovered by the amateur astronomer Gennadiy Borisov on August 30 2019 (M.P.E.C. 2019-R106). Its minimum heliocentric distance was 1.96 ± 0.04 AU with an orbital eccentricity $e = 3.155$. As of July 15 2020 its distance to the Earth is 4.74 AU and in mid-2030 it will be ~ 74 AU. Recent observations suggest that it is now fragmented [Jewitt et al., 2020].

The transit of ISOs through the solar system offers the opportunity to discover and study ISOs at close range directly by *in situ* spacecraft exploration [Hein et al., 2019b, Hibberd et al., 2019]. ISOs likely form very far from the solar system in both space and time, possibly in a completely different part of the Milky Way Galaxy. Exploration of ISOs holds the promise of determining the creation mechanisms of small planetesimals during the formation of solar-type stellar systems, during the formation of other types of stellar systems (such as M-dwarf systems), and also of observing objects formed in the demise of main sequence stellar systems and ejected during the creation of white dwarf and neutron star systems.

2 Dynamical Streams as Proxies for ISO Birth Systems

Stellar perturbations make it hard to predict the detailed galactic trajectories of ISOs over intervals much longer than a few million years [Zhang, 2018], $< 10^{-3}$ of the history of the galaxy, and no firm association with a nearby star has been claimed for either 1I or 2I [Bailer-Jones et al., 2019, Hallatt and Wiegert, 2019]. Although it seems unlikely that we will find the natal star system of any passing ISO; association with a stellar dynamic stream can serve as a proxy to provide at least some bounds on the age, metallicity, and chemical composition of the source stellar system.

The Milky Way’s velocity fields are highly non-uniform [Ramos et al., 2018], with a substantial fraction of the stars in the solar neighborhood being concentrated in dynamical streams (also known as associations or moving groups) moving in the galaxy (see, e.g., [Kushniruk et al., 2017, Gaia Collaboration et al., 2018]). Figure 2 shows that the incoming 2I velocity vector “at infinity” ($\mathbf{v}_\infty$) is close to the motion of the Wolf 630 dynamical stream in all three velocity components, suggesting that 2I was (before its interaction with the solar system) a member of that stream [Eubanks, 2019c], just as 1I appears to have been a member of the Pleiades dynamical stream [Feng and Jones, 2018, Eubanks, 2019a,b].

Connecting an ISO to a dynamical stream allows the stars in the stream to be used as proxies for natal stellar system of the ISO. Data from a spectroscopic survey of stars with distances < 250 pc [Quillen et al., 2018] reveals that the Wolf 630 possesses a slightly higher than solar metallicity ($[\text{Fe}/\text{H}] > 0.2$ dex). Antoja *et al* [Antoja et al., 2008] determined the kinematics of over 16,000 nearby stars with known ages, the Wolf 630 stream (their moving group 17) has in their data almost no stars younger than 0.5 Gyr, and are mostly 2 - 8 Gyr old. The lower bound of this range agrees well with an earlier estimate for the stellar age of the Wolf 630 stream of 2.7 ± 0.5 Gyr [Bubar and King, 2010]. By contrast, the Pleiades stream consists of at least two stellar components, roughly 10^7 and 10^9 years old

Chereul et al. [1998], Famaey et al. [2008], Bovy and Hogg [2010], suggesting that 1I/'Oumuamua is a relatively young object.

Figure 2: The galactocentric U and V components of velocity for 1I, 2I, the Local Standard of Rest (LSR) and five local dynamical streams, from [Eubanks, 2019c]. The 1I and 2I incoming velocities are near the centroids of the determinations of the velocities of the Pleiades and Wolf 630 streams, respectively, and these objects presumably were members of these streams before their encounter with the solar system. The stream velocity estimates are from [Kushniruk et al., 2017], supplemented by [Chereul et al., 1998, Liang et al., 2017, Gaia Collaboration et al., 2018]. The 1I and LSR velocities are as shown in [Eubanks, 2019b], and the 2I velocity estimate is from the ephemeris of Bill Grey / Project Pluto.

3 ISOs and the Chemical Evolution of the Galaxy

The chemical evolution of the galaxy is dominated by elements created by slow neutron capture (the s-process) in Asymptotic Giant Branch (AGB) stars, [Busso et al., 1999], and by the rapid processes present in explosive nucleosynthesis in Supernova (SN) [Yoshida, 2007]. ISOs will contain these materials in different concentration than for solar system material, and determining the isotopic and elemental composition of ISOs will provide direct information. The composition of presolar grains in primitive meteorites shows that they predominately come from these two sources [Davis, 2011]; half of all the elements heavier than iron are thought to result from the s-process [Herwig, 2005]. AGB material is thus very important in the chemical evolution of the galaxy, and its presence in stardust seems to permeate the galactic disk [Gail et al., 2009]. Eubanks [2019c] described how ISOs created in the demise of stellar systems (i.e., Post Main Sequence Objects) could thus be very common in the galaxy, and could form a substantial part of the ISO flux passing through the solar system.

4 Missions to Interstellar Objects

The feasibility of reaching interstellar objects at close encounter with the Sun has been assessed in Seligman and Laughlin [2018], with specific missions to the interstellar objects 1I/'Oumuamua and 2I/Borisov being presented by Hein et al. [2019b] and Hibberd et al. [2019]. Such missions are feasible with more massive spacecraft (100 kg or larger) using existing rockets and technologies either if they can be initiated around the time of perihelion passage, e.g. by a Comet Interceptor type mission [Schwamb et al., 2020], or by using a combination of planetary flybys and solar Oberth maneuvers (rocket accelerations at high speed close to the Sun) to overtake the ISO as it retreats from the Sun [Hein et al., 2019b,a]. Small sailcraft could also possibly explore ISOs [Turyshchev et al., 2020], and could also act as very valuable adjuncts to larger missions, as they could serve as widely distributed precursor probes to find small and dark ISOs years or decades after their last observation from Earth. Hibberd and Hein [2020] demonstrate that a mission to 'Oumuamua would be feasible, using a GW-scale beaming infrastructure and a series of 1-100 kg probes. At 300 km/s, 'Oumuamua could be reached within 1-2 years, even when launched in 2030. Due to the faintness of some ISOs (e.g. 'Oumuamua), the capability of launching multiple spacecraft increases the likelihood that at least one of the spacecraft might obtain useful data, even if other spacecraft fly past the ISO at a too large distance. Nevertheless, the mass of the spacecraft will be 1-100 kg or even below for lower beaming power. As a consequence,

only a limited suite of instruments can be carried on an individual spacecraft, compared to a probe such as New Horizons. Launching individual spacecraft with different instruments, aggregating incoming data, and using these probes as a common spacecraft platform would effectively lead to a more efficient exploration of ISOs than via a single, monolithic spacecraft.

5 Science With Extreme Hypervelocity Impacts

No matter what technique is used to reach an passing ISO, the relative spacecraft-ISO velocities at the time of flyby will be large, probably $\gg 10 \text{ km s}^{-1}$, and there thus is little prospect of the spacecraft entering orbit or performing a soft landing on the ISO. The ISO mission science will have to be executed in a fast flyby, possibly enhanced with a sub-probe impactor.

Hypervelocity impacts have relative velocities $\gtrsim 3 - 5 \text{ km s}^{-1}$, speeds where the strength of materials is negligible compared to the impact forces. At these velocities, the impact energy / atom controls the immediate (prompt) response to the impact. As an example, it takes about 0.4 eV / molecule to vaporize water, water molecules have a binding energy of $\sim 4.4 \text{ eV}$, and the first ionization of both Hydrogen and Oxygen requires $\sim 13.6 \text{ eV}$. There is thus a profound difference between an impact at 5 km s^{-1} ($\sim 2 \text{ eV}$ / water molecule), which will produce mostly superheated steam, and an impact at 15 km s^{-1} ($\sim 18 \text{ eV}$ / water molecule), which will produce an ionized plasma.

Impacts with energies / atom $\gtrsim 20 \text{ eV}$ can thus be usefully described as extreme hypervelocity impacts, with dramatic changes in the impact physics, corresponding to temperatures $\gtrsim 2 \times 10^5 \text{ K}$ and higher. These resulting ionized prompt plumes will producing radiation at Extreme UltraViolet (EUV, 10 to 120 nm) and X-ray UV (XUV, 0.1 to 10 nm) wavelengths, depending on the collision energy, which can be used to investigate the physics of the impact and the composition of the impacted bodies.

5.1 The Physics of Hypervelocity Impacts

An ISO mission with a subprobe impactor would conduct an extreme hypervelocity impact, creating a highly ionized prompt plume with energies up to $\sim 300 \text{ eV}$, or ~ 3 million K. A small impactor will not change the velocity of the impacted asteroid by more than a few mm s^{-1} , and so the ISO fixed frame can be viewed as an inertial frame, and the atomic constituents of the ISO can be viewed as initially at rest in that frame. Assume, as a first order approximation, a non-relativistic head-on elastic collision between an atom in the impactor, of mass m_i and initial velocity $v_{i_{in}}$, and an atom in the asteroid, with mass m_A and zero velocity in the asteroid rest frame. Then the post-collision velocities are given by

$$v_{i_{out}} = \frac{m_i - m_A}{m_i + m_A} v_{i_{in}} \quad (2)$$

and

$$v_{A_{out}} = \frac{2 m_i}{m_i + m_A} v_{i_{in}}; \quad (3)$$

Atoms with small atomic mass compared to those in the impactor will receive a large velocity change (up to twice the impact velocity) but a relatively small fraction of the incoming atom's Kinetic Energy (KE), while more massive atoms will have a smaller velocity change, but can absorb more of the incoming atom's KE. The energies considered in this paper are not large enough to initiated nuclear reactions, but it is reasonable to assume that cohesive and molecular bonds will be broken, and electrons removed, up to the maximum amount of energy available.

5.2 Comparison of Hypervelocity Impact Missions

Table 1 provides information about proposed and flown hypervelocity impact missions. At an impact velocity of $\sim 20 \text{ km s}^{-1}$ a hypothetical II flyby Mission with a sub-probe impacting on II/Oumuamu (henceforth called a II mission) will be more ionizing than either the Deep Impact (DI) mission, which struck the comet Tempel 1 with an impact velocity of 10.3 km s^{-1} A'Hearn et al. [2005a] or the proposed DART impact of the moon of the asteroid Didymos Cheng et al. [2015], with a planned impact velocity of $\sim 6.5 \text{ km s}^{-1}$.

Table 2 provides the collision energy imparted to some of the elements commonly found in asteroids and comets. This Table shows that, while the DART impact will not have enough energy to ionize most elements, DI should have singly ionized much of the material in its prompt plume, and the II Mission would deeply ionize the fast plume material (although only Hydrogen and Helium should be fully stripped of their electrons and thus only those elements should produce K, or Lyman alpha, spectral lines).

The DI impactor included a 178.4 kg copper mass, which, given the density of copper (8960 kg m^{-3}), would be a sphere with a radius of 168.1 mm. A prompt "hot plume" and a longer duration "ejecta plume" were observed by the main DI spacecraft, with the ejecta plume containing much more matter (a mass ratio of $\sim 3 \times 10^4$) but only $\sim 20\%$ of the prompt plume energy Groussin et al. [2010]. (The mass and energy budget totals have uncertainties of order 50%.) The prompt DI ejecta plume included a cloud of incandescent liquid droplets which dominated the optical emission from the plume for $\sim 420 \text{ msec}$. The droplet cloud, with a center of mass motion of $\sim 7.9 \text{ km s}^{-1}$ and an internal expansion rate of 1.7 km s^{-1} , are thought to have been a 4000 kg cloud of $\sim 160 \mu\text{m}$ diameter particles of cooling silica melt. Scaling this to the II impacts indicates that it would be hazardous to attempt a direct sampling of the plume by a spacecraft.

For the II Mission mission the density of the target must be regarded as very poorly observationally constrained. According to photometric data II has a rotation period of ~ 8 hours and is very elongated, the data being consistent with a prolate ellipsoid with axis

Table 1: Impact Velocities and Energies for Planned and Proposed Hypervelocity impact missions. The column marked λ is the Compton wavelength of the impact energy. For Deep Impact and DART, the composition and the Energy / Atom is for the predominant element in the Impactor. The detailed elemental breakdown of the DART impactor is not known, but the spacecraft frame will be an Aluminum alloy, and that is assumed to be the predominate element. The DI impactor mass includes 6.5 kg of unused hydrazine fuel; it is assumed that the “49% copper” listed in A’Hearn et al. [2005a] refers to the dry mass.

Mission	Impactor		V_{impact}	Energy	Energy / Atom	λ
	Mass	Composition				
DART Cheng et al. [2016]	~300 kg	mostly Al	~6.5 km s ⁻¹	6.3 GJ	5.9 eV	209.9 nm
DI A’Hearn et al. [2005b]	370.5 kg	49% Cu	10.3 km s ⁻¹	19.7 GJ	34.9 eV	35.5 nm
II-Mission	10 kg	7 kg ¹⁹⁶ Pt	~18.2 km s ⁻¹	1.65 GJ	335.7 eV	3.7 nm

Table 2: Energy changes for head-on elastic impact by the main constituent of the impactor for various missions; for elements more massive than Helium, the terrestrial isotopic distribution is assumed. The ionization refers to the energy produced in a primary impact; equipartition of energy will make more energy available to low mass elements from secondary impacts and should result in the full ionization of Hydrogen and Helium in the II Mission plume.

Element	DART		DI		II Mission	
	ΔKE	Ionization	ΔKE	Ionization	ΔKE	Ionization
¹ H	0.8 eV	-	2.1 eV	-	6.8 eV	-
² H	1.5 eV	-	4.2 eV	-	13.5 eV	-
³ He	2.1 eV	-	6.1 eV	-	20.0 eV	-
⁴ He	2.7 eV	-	7.8 eV	-	26.3 eV	I
Li	3.8 eV	-	12.4 eV	I	44.4 eV	I
C	5.0 eV	-	18.8 eV	I	73.1 eV	IV
O	5.5 eV	-	22.6 eV	I	93.7 eV	IV
Mg	5.9 eV	-	28.0 eV	II	131.8 eV	IV
Si	5.9 eV	-	30.1 eV	II	147.2 eV	IV
Fe	5.1 eV	-	35.5 eV	III	231.8 eV	VIII

ratios of 6:1:1 Jewitt et al. [2017] or 5.3:1:1 Bannister et al. [2017], with both papers estimating a minimum density $\gtrsim 6000 \text{ kg m}^{-3}$ in the absence of any cohesion. Given that this body could conceivably be largely metallic, this density does not seem impossible, although a cohesive body is certainly possible as well, in which case there is no observational constraint on ρ_A at all. The nominal II Mission impactor is a 7 kg rod, 1 m long and 1 cm in radius, of isotopically pure ¹⁹⁶Pt (this isotope was chosen as it is commercially available).

Table 2 shows the ionization of common elements in the DART, Di and II Mission impact plumes. While the II Mission impact should provide enough kinetic energy to directly ionize deuterium but not hydrogen (in this context, ¹H or protium) secondary collisions and a fast equipartition of energy should provide enough kinetic energy to ionize Hydrogen (and thus generate Lyman alpha emission between 121.6 and 91.18 nm), and Helium. Deuterium Lyman Alpha lines are shifted bluewards by $\sim 0.03 \text{ nm}$ from the protium lines; as this corresponds to a velocity shift of $\sim 80 \text{ km s}^{-1}$; these lines should be separable given adequate spectral resolution.

The EUV spectrum of the II Mission impact plume should span the range of 5 to 100 nm. The ALICE EUV instrument on the *New Horizons* spacecraft has a spectral pass band of 42 - 187 nm Stern et al. [2008]. The Alice instrument should be able to observe Hydrogen and Deuterium L α , but a redesigned UV telescope with fast optics would be required to observe the rapid EUV signatures expected from a II mission-type impact.

6 ISO Missions and Interstellar Medium

At about 100 AU, the Solar Wind becomes subsonic and beyond 120 AU it encounters the Local InterStellar Medium (LISM). While the Voyager 1 and 2 probes are currently exploring this region, several fast probes in different directions and at different distances would provide a 3D map of the heliosphere up to around 200 AU. In particular the region opposite to the direction of the solar wind with respect to the Local Interstellar Medium [Katushkina et al., 2014], i.e. at RA DEC = 20H, 28 deg (the Cygni constellation), would reveal a possible plasma magnetotail of the Solar wind in the LISM. Whether this magnetotail exists is still a matter of debate, which can likely only be resolved by direct *in situ* observation, which could be done as part of a ISO chase mission.

The IBEX Ribbon is a compelling possible target for ISO missions. The IBEX Ribbon is a unexpected feature discovered by IBEX in the flux of energetic neutral hydrogen. It covers a wide swath of the sky roughly 20° by 75° and is hypothesized to be due to interactions between the heliosphere and the Interstellar Medium (ISM) [Fichtner et al., 2014]. The parallax of the ribbon has been estimated to be $140^{+84}_{-38} \text{ AU}$ [Zirnstein et al., 2019] rendering the entire Ribbon region accessible to direct *in situ* exploration by sailcraft. Exploration of an extended region over 100 AU in length would certainly benefit from a series of probes sampling many locations; this can be done relatively inexpensively by a fleet of fast sailcraft. We recommend that ground based astronomical resources be utilized to find TNOs

in the foreground of the Ribbon [Trilling et al., 2018]; flyby exploration of such objects would be a useful complement to a Ribbon exploration campaign.

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