

RESEARCH ARTICLE

Research programmes arising from ‘Oumuamua considered as an alien craft

Martin Elvis 

Center for Astrophysics, Harvard & Smithsonian, Cambridge, MA, USA

Author for correspondence: Martin Elvis, E-mail: melvis@cfa.harvard.edu

Received: 29 April 2021; **Revised:** 24 September 2021; **Accepted:** 19 October 2021; **First published online:** 01 April 2022

Keywords: Oumuamua, Technosignatures, reliability engineering, METI

Abstract

The controversial hypothesis that ‘Oumuamua (1I/2017 U1) was an alien craft dominated by a solar sail is considered using known physics for the two possible cases: controlled and uncontrolled flight. The reliability engineering challenges for an artefact designed to operate for $\sim 10^5$ – 10^6 year are also considerable. All three areas generate research programmes going forward. The uncontrolled case could be either ‘anonymous METI’ (messaging extraterrestrial intelligence) or ‘inadvertent METI’. In the controlled case the nature of the origin star, trajectory guidance from the origin star to the Sun, and the identity of a destination star are all undecided. The ‘controlled’ case has more strikes against it than the ‘uncontrolled’ case, but neither suffers a knock-out blow, as yet. Some of the issues turn out not to be major obstacles to the alien craft hypothesis, but others weaken the case for it. Most, however, imply new studies. Some of these, e.g. intercept missions for new interstellar objects, are concepts being developed, and will be of value whatever these objects turn out to be. Overall, these considerations show that a many-pronged, targeted, research programme can be built around the hypothesis that ‘Oumuamua is an alien craft. The considerations presented here can also be applied to other interstellar visitors, as well as to general discussions of interstellar travel.

Contents

Introduction	63
Un-Guided or derelict	65
Anonymous METI	65
Inadvertent METI	65
Population implications	66
Under control	66
Where did it come from?	67
Course navigation	69
Where is it going?	72
Reliability engineering considerations	72
Lifetime	72
Repair	73
Discussion and conclusions	75

Introduction

‘Oumuamua (1I/2017 U1) was the first unambiguously interstellar object to be discovered in the solar system (Meech *et al.*, 2017). Controversially, it has been suggested to be an alien spacecraft (Bialy and Loeb,

2018; Loeb, 2021). Alien activity as an explanation for astronomical phenomena is often hard to follow up as these suggestions tend not to produce testable predictions. If researchers cannot see what research programme an idea points to, then they have no incentive to change from their present research to this new field (Lakatos, 1980). This paper points out that a well-defined research programme does arise for an alien craft interpretation of 'Oumuamua, leading to tests of this hypothesis that have various degrees of difficulty. This approach in no way rejects a natural explanation for 'Oumuamua, but simply aims at an impartial examination of the alien craft hypothesis by following the questions arising a few more steps. Though some estimates are made here, properly quantifying all the tests will require engaging a wide range of expertise.

The implications for the limited number of possible scenarios that flow from the assumption that 'Oumuamua is an alien craft are explored below. Katz (2021) has made some similar points, albeit in a less open-ended fashion. The same general considerations will apply to any future objects for which this hypothesis is raised.

The argument in favour of the alien craft hypothesis can be readily summarized. 'Oumuamua clearly accelerated on its way out of the solar system, a measurement made at high confidence (Micheli *et al.*, 2018, but see Rafikov, 2018; Katz, 2019). The acceleration was small, $\sim 5 \times 10^{-6} \text{ m s}^{-2}$, but highly statistically significant (30σ , Micheli *et al.*, 2018). The acceleration was not constant but dropped off with a heliocentric distance close to a r^{-2} law. No cometary dust (Meech *et al.*, 2017) or gas (for CO and CO₂, Trilling *et al.*, 2018) ejection was observed that could cause the observed non-gravitational radial acceleration. If no mass was lost, then the remaining possibility is that 'Oumuamua was accelerated by solar radiation pressure and the solar wind. This is *prima facie* plausible as the large (1.5 mag, a factor ~ 4) amplitude of the 'Oumuamua light curve implies a highly elongated or highly flattened geometry, a cigar or a pancake with a large, but not unprecedented, 6:1 axial ratio (Meech *et al.*, 2017; Trilling *et al.*, 2018; Mashchenko, 2019). A large area for intercepting solar radiation may then be available. This alone does not imply a non-natural explanation. However, to achieve the observed acceleration using these weak forces 'Oumuamua would have to have a huge area/mass ratio $\sim 0.1 \text{ g cm}^{-2}$, due to either low density, $\sim 10^{-5} \text{ g cm}^{-3}$, or extreme thinness, $\sim 0.3\text{--}0.9 \text{ mm}$, giving a resultant mass of only $\sim 750 \text{ kg}$ for this $\sim 100 \text{ m}$ scale object (Bialy and Loeb, 2018). An extremely thin shape is suggestive of an artefact to some researchers.

Natural explanations are not at all ruled out. Several astrophysical suggestions have been made to explain the unusual shape, high area/mass ratio, and acceleration of 'Oumuamua. e.g. a fractal icy aggregate with a density of $\sim 10^{-5} \text{ g cm}^{-3}$ (Moro-Martin, 2019; Luu *et al.*, 2020); a comet fragment (Sekanina, 2019); molecular hydrogen ice (Seligman and Laughlin, 2020); molecular nitrogen ice (Jackson and Desch, 2021); a fragment from a planetoid destroyed in a tidal disruption event around a white dwarf (Rafikov, 2018); and some have been critiqued (Levine *et al.*, 2021; Hoang and Loeb, 2020; Phan *et al.*, 2021; Loeb, 2021; Siraj and Loeb, 2021).

While most scholars find the astrophysical options plausible, for some researchers the evidence against the proposed astrophysical explanations is compelling. For these researchers, the only remaining possibility is that 'Oumuamua is dominated by a thin, large area, 'solar sail' constructed by an alien civilization (Loeb, 2021). This proposal has itself been highly criticized (e.g., Katz, 2021).

The approach taken here is to investigate the consequences of an alien spacecraft explanation so that these consequences can be studied further to either reinforce or reduce the likelihood of this option. The number of possibilities for this option appears to be quite limited, allowing the analytic approach used here.

Unknown technologies or physics for the alien craft are not invoked here, as that approach is unconstrained. Instead, the assumption is that the putative alien designers worked with the same physics we have, the same fundamental constraints on materials that we have, and design constraints that are familiar to us. The result is that, for any of the cases explored, their craft must perform to some demanding and sometimes well-constrained capabilities.

In the alien spacecraft hypothesis either 'Oumuamua is piloted (not necessarily by alien life directly but by their computers) and so is under control, or it is derelict, i.e. not under control. The long operational lifetime of 'Oumuamua in this hypothesis raises further issues. All three areas have consequences that are explored here.

Un-Guided or derelict

The simpler of the two possibilities is that ‘Oumuamua is un-guided. ‘Oumuamua was found to have a rotation period of ~ 7 h, though the light curve did not repeat precisely indicating a tumbling motion (i.e. non-principal axis rotation, Meech *et al.*, 2017; Drahus *et al.*, 2018; Fraser *et al.*, 2018). This rotation state suggests that it is not under control, or not wholly under control. The object was then behaving like a derelict vessel. ‘Oumuamua entered the solar system with a velocity very close to that of the Local Standard of Rest (LSR, Mamajek, 2017). As ‘Oumuamua is in the LSR it is more correct to say that the Sun travels at this speed in the LSR. Any option requiring ‘Oumuamua to be under control is weakened, given this drifting trajectory.

Anonymous METI

‘Oumuamua may not be truly derelict but may instead be a passive ‘message in a bottle’ (Loeb, 2018). In this hypothesis ‘Oumuamua was designed to let technological life (because telescopes were needed to detect ‘Oumuamua) around another star realize the existence (at least at one time) of another civilization. The solar sail, in this case, may have been intended not for realistic propulsion but to give a small but tell-tale acceleration. That would require that the sail orient itself at times perpendicular to the radial direction from the Sun. A tumbling motion will reduce the amount of time the sail is oriented correctly to achieve a significant acceleration. If the sail were always oriented radially then ‘Oumuamua would have decelerated on approaching the Sun. That possibility would affect the apparent incoming direction which could modestly affect the arguments in Sec.3.1 below.

An additional possible motivation to situate a spacecraft in the LSR would be to deliberately hide its origin. The message in the bottle would then be ‘You are not alone, but we are not telling you where we are.’ Such a design may have been motivated as being a safe version of messaging extraterrestrial intelligence (‘Anonymous METI’¹) In this case we would expect that a mission to ‘Oumuamua, or another suspiciously behaving interstellar object (e.g. Hibberd and Hein, 2021), would find clear evidence of these bodies being a deliberate construct, but would have no identifying marks equivalent to the plaques mapping out Earth’s location with respect to nearby pulsars on Pioneers 10 and 11 and Voyagers 1 and 2².

Inadvertent METI

The upper stages of the launchers that put our space probes onto their final trajectories also reach a similar trajectory. There are numerous upper stages in heliocentric orbits and a small number on solar system escape trajectories, e.g. the New Horizons upper stage. These are inadvertent interstellar spacecraft, and so a form of unintended METI from the sender’s perspective. From our perspective, they are another example of a technosignature.

Similarly, the putative builders of ‘Oumuamua may have manufactured these craft as upper stages, presumably accelerated by directed energy (e.g. lasers), given their light-sail like design. This form of acceleration is a good way to overcome the limits imposed by the rocket equation. In this case, there must have been a highly active stellar system economy around the origin star $\sim 10^5$ year ago. Possibly this activity would leave other tracers, for example from the mining of asteroids for the raw material from which to build the craft (Forgan and Elvis, 2011). These ‘craft’ may even be just tailings from mining in the stellar system’s Oort cloud. These tailings would have been given a small velocity to expel them into interstellar space, perhaps in order to reduce threats to their infrastructure in their Oort cloud. Very approximately, comets at 10^4 AU will be moving at ~ 30 m s⁻¹, sufficient to damage loosely bound objects (including spacecraft). The space density of Oort cloud comets from 10^4 – 10^5 AU is only ~ 1 per 4000 AU³ making collisions rare, but if say 10% of the comets were cut into ~ 1 t slices there would be $\sim 10^{21}$ of them (Weissman, 1983) for a space density of $\sim 10^5$ AU⁻³ a separation of

¹Anonymous messaging of extraterrestrial intelligence.

²JPL: <https://voyager.jpl.nasa.gov/golden-record/golden-record-cover/> (Accessed 5 March 5, 2021).

$\sim 5 \times 10^6$ km, that they would traverse in ~ 5 years. Though their cross-section is ~ 0.01 km², and their probability of collision $\sim 2 \times 10^{-15}$ there would still be $\sim 10^7$ collisions/year. For a civilization with large amounts of infrastructure in their Oort cloud, this could be sufficient motivation to eject the comet slices. A true runaway ‘Kessler Syndrome’ (Kessler and Cour-Palais, 1978) may not develop.

The ‘message’ from inadvertent METI would be simply ‘we exist’ with any other information gleaned from a close inspection being also inadvertent.

Population implications

As ‘Oumuamua has a $\sim 10^5$ – 10^6 year travel time (see Sec.3.1), it was constructed before any detectable human technology was created, possibly even before homo sapiens evolved. This implies that the ‘message in a bottle’ strategy must have been implemented without knowing which stars would have technological societies capable of detecting ‘Oumuamua. There must then be at least a moderately large number of copies in order to swing through the nearby solar systems at a rate that makes their detection likely given distribution of onset times and lifetimes for this capability. The LSR velocity argues against efficient targeting, keeping the total number large.

If ‘Oumuamua came into the solar system entirely by chance, without even the ‘message in a bottle’ plan behind it, then the population density of such objects, at least locally, would be the same as if it were a naturally occurring object, and interstellar asteroid. On this basis Do *et al.* (2018) estimate the space density of ‘Oumuamua-like objects to be 0.2 AU⁻³ or 2×10^{15} pc⁻³. Loeb (2018) says that ‘This would require the unreasonable rate of a launch every five minutes from a planetary system even if all civilizations live as long as the full lifetime of the Milky Way galaxy.’ This high rate has been taken as arguing for a natural origin.

The maximum total mass of all copies of ‘Oumuamua in this scenario would be $\sim 10^{14}$ t (metric tonnes, for a density $\sim 10^{-4}$ g cm⁻³). While far larger than the Earth’s proven iron reserves³ (2.3×10^{11} t), this mass is small compared with, e.g. the $\sim 10^{18}$ t of iron in the Main Belt asteroids (Elvis and Milligan, 2019), and deployment could well have taken place over 1% of the planned 10^5 year lifetime, or $\sim 10^3$ year, as this implies a launch rate of ~ 3000 s⁻¹. For an Earth-scale economy, this is an unattainable number, but for a solar system scale economy, where the Main Belt asteroids are fully exploitable, many thousands of ‘Oumuamua factories and launchers are within the range of plausibility.

The putative designers may well have known which planets harboured, or could harbour, complex life. As roughly a quarter of all M-dwarfs have rocky planets in their habitable zones (Dressing and Charbonneau, 2015), this knowledge may not reduce the number of alien craft required by a large factor. As we learn more about the habitability of exoplanets the fraction may go down. For example, stellar activity may remove the atmospheres of all Earth-sized planets in the habitable zones of M stars (Van Eylen *et al.*, 2018) The total numbers and the required launch rate may then be reduced by some orders of magnitude if the putative builders had this knowledge.

Ongoing and expanded surveys (e.g. VRO/LSST⁴, Moro-Martín *et al.*, 2009) for more interstellar asteroids will determine the population density of interstellar objects of whatever kind and so put constraints on this case.

Under control

If ‘Oumuamua was under control during the solar system transit, then all the properties of ‘Oumuamua are deliberate and require investigation. The first question is why is it in the LSR if the Sun is its destination? Additional questions immediately arise about (1) the origin and (2) the destination of ‘Oumuamua, and (3) the achievable accuracy of the inbound trajectory. As the design is dominated,

³https://minerals.usgs.gov/minerals/pubs/commodity/iron_ore/mcs-2017-feore.pdf (Accessed 22 March, 2021).

⁴Vera C. Rubin Observatory: <https://www.lsst.org/scientists>

in this hypothesis, by a solar sail, the craft was surely using that solar sail to navigate when near a radiation source.

Where did it come from?

‘Oumuamua must be coming from some other star if it uses the light pressure from that star to accelerate. As the light sail dominates the system mass then to be justify that mass, the origin star ought to be nearby, so that ‘Oumuamua does not spend most of its time in the isotropic illumination of interstellar space, where the solar sail is of no use. Active reflectivity control of the sail could continue to generate a modest acceleration. Otherwise, the use of a light sail would be a poor engineering choice. In addition, the challenge of lifetimes $>10^6$ years are significant, especially for large thin structures (see section 4) arguing for a local origin. There are several possibilities for the origin star.

‘Oumuamua had a hyperbolic orbit⁵ ($e = 1.20$), arriving from (RA, dec) = (18 h 42 m, +34.3°, $\pm 5'$), with an asymptotic velocity of 26 km s^{-1} (Meech *et al.*, 2017; Bailer-Jones *et al.*, 2018). At this speed ‘Oumuamua travels 2.5 pc in 10^5 years.

Main sequence stars

No catalogued stars lying within 60 pc of the Sun come within one parsec of the trajectory, and only four stars come within 4 pc in SIMBAD (Dybczyński and Królikowska, 2018), and only 6 stars have come within 2 pc in the deeper Gaia DR2 catalogue over the past 10^6 year (Bailer-Jones *et al.*, 2018). These papers assume no manoeuvres before the detection of ‘Oumuamua. The minimum course corrections needed to create a rendezvous with another star in the past would be useful to calculate.

Only stars with main-sequence lifetimes of ~ 1 Gyr or more are likely to have developed complex life. By terrestrial standards, 1 Gyr is barely enough time to harbour multi-cellular life. The oldest certain fossils found so far on Earth come from a time when the Earth was ~ 1 Gyr old (Schopf *et al.*, 2017). There are suggestions of single-cell life as early as 0.3 Gyr (Dodd *et al.*, 2017). Complex life, however, seems to have taken much longer, ~ 4 Gyr, although the Cambrian explosion that happened then was rapid (Parry *et al.*, 2017). Hence, stars with masses $>2.5 M_{\text{sol}}$ that have Main Sequence lifetimes <1 Gyr, are unlikely origin stars (spectral type A2 or earlier). This concern, though, assumes that Earth is a typical example, which it may not be as we do not know what triggered the Cambrian explosion.

Brown dwarfs

Could ‘Oumuamua have come from an undetected star within ~ 10 light-years? The obvious, and quite numerous, population of quite hard to detect stars would be brown dwarfs, i.e. T and L stars. T and L stars are long-lived enough to potentially develop life in their systems.

These stars have been searched for in infrared surveys with UKIDSS and WISE, and in deep optical imaging for high parallax and proper motion (Best *et al.*, 2021). None presently lie within 1° of the origin point of ‘Oumuamua.

Brown dwarfs have surface temperatures, $T \sim 1000 \text{ K}$, versus 6000 K for the Sun. As the emitted black body power goes as σT^4 , a brown dwarf will produce just $\sim 10^{-3}$ of the acceleration that the Sun provides. The launching process would then have to be by other means. An electric sail in one option (Lingam and Loeb, 2019). A laser that reflects off the sail would be an efficient design choice, as for the Breakthrough Starshot⁶ project. The energy required to accelerate the mass of ‘Oumuamua

⁵JPL Small Body Database: <https://ssd.jpl.nasa.gov/sbdb.cgi#top> (Accessed 26 March 2021).

⁶<https://breakthroughinitiatives.org/initiative/3> (Accessed 26 March 2021).

($\sim 1 t$) to $\sim 20 \text{ km s}^{-1}$ is $2 \times 10^{11} \text{ J}$, so a 1 GW laser would have to operate for 200 s to achieve this effect. This is not far from the Breakthrough Starshot power and duration requirements.

Origin star went supernova

Could the star of origin have gone supernova since ‘Oumuamua departed $\sim 10^5$ years ago and so no longer be present?

Supernova remnants are detectable up to $\sim 10^5$ years after the event (e.g. Cygnus Loop at 2×10^4 year, and a radius of 18.5 pc, Fesen *et al.*, 2018) and so may still be visible, depending on how soon after the departure of ‘Oumuamua the supernova happened. If a neutron star was created in the supernova then that object should still be visible as a thermal source at $\sim 10^6 \text{ K}$ (Bignami, 1996), though it may have moved significantly in that time ($\sim 250 \text{ pc}$ for a typical ejection speed of 250 km s^{-1} , Faucher-Giguère and Kaspi, 2006), in an unknown direction. Old supernova ejecta shells travel an order of magnitude faster than ‘Oumuamua ($\sim 200 \text{ km s}^{-1}$, Fesen *et al.*, 2018) and so would have travelled well past the Sun and would now lie in the opposite direction to the ‘Oumuamua origin point and would have a large angular size.

Detection of large diameter supernova remnants via radio and UV emission has been improving. Fesen *et al.* (2021) report three strong candidates at distances of $\sim 100 \text{ pc}$. Finding convincing evidence of a $\sim 10 \text{ pc}$ distant supernova remnant will be challenging but could be attempted. Abundance measurements of the surfaces of asteroids might show recent enhancements of ^{26}Al and other short-lived radioactive nuclei (with half-lives of $10^5\text{--}10^7$ year) characteristic of Type II supernova (Adams, 2010). The samples returned by Hayabusa 2 and OSIRIS-REx should be able to test this scenario. Massive stars tend to form in groups and there are only two plausible groups within 25 pc, B Pic and AB Dor (Mamajek, 2015); neither is close to the origin direction of ‘Oumuamua.

A high mass star is unlikely to have been the location where the craft was built. The massive ($8 < M < 40 M_{\text{sol}}$) stars that create core-collapse type II supernovae are short-lived ($< 3 \times 10^7$ year, Woosley *et al.*, 2002). The Earth was mostly molten for the first $\sim 10^7$ year after the Moon-creating impact, the Hadean Eon (Sleep *et al.*, 2014). It is hard to imagine life, let alone a technological civilization, growing under such conditions and so is highly unlikely within the lifetime of the star. In that case, the supernova star would have been only a way station for ‘Oumuamua.

This option raises other questions beyond the scope of this paper: how much would the supernova light and ejecta accelerate ‘Oumuamua given the sail area (see Sec. 4 of Do *et al.*, 2018)? How far from the supernova would ‘Oumuamua have to be for the sail to survive the ejecta passage at velocities of 1000 km s^{-1} or more.

Compact objects as way stations

‘Oumuamua may not have come to us not from the star system where it was built, but instead after making a slingshot gravity assist manoeuvre around another object that was merely a way station for the craft. Why a way station would be used to deliver ‘Oumuamua into the LSR rather than a swifter trajectory is a puzzle.

Compact objects, either an isolated neutron star or a black hole, are particularly effective gravity assist tools in order to set course for the Sun.

A neutron star is a plausible candidate as the expected space density of neutron stars local to the Sun is predicted to be $\sim 3.6 \times 10^{-4} N_9 \text{ pc}^{-3}$. N_9 is the total number of isolated neutron stars in the Galactic disc in units of 10^9 , that is the current best estimate (Sartore *et al.*, 2011). This implies that the most likely distance to the nearest neutron star is $\sim 10 \text{ pc}$ (Sartore *et al.*, 2011). With some luck then an isolated neutron star could have been well-positioned to serve as a gravity assist body for ‘Oumuamua. Isolated neutron stars often acquire a high velocity from the supernova event in which they formed, $\sim 250 \text{ km s}^{-1}$ (Sartore *et al.*, 2011). This makes them attractive as gravity assist targets (Johnson, 2003), although the LSR-like velocity of ‘Oumuamua suggests only a weak velocity boost.

Isolated black holes are estimated to be about an order of magnitude rarer than isolated neutron stars with $\sim 10^8$ in the Galactic disc and bulge (Fender *et al.*, 2013). For a uniform disc distribution (a more naïve calculation than that of Sartore *et al.*, 2011), Fender *et al.* (2013) find a density of 10^{-4} pc $^{-3}$, and a mean separation of just over 10 pc, so again it is plausible that an isolated black hole was conveniently located for ‘Oumuamua.

For both types of a compact object, the hypothetical trajectory designers need to have mapped out the local population of both types of object in position and velocity to high enough precision to ensure that the encounter was at the right impact parameter to produce an outbound trajectory that would give an impact parameter with the Sun of ~ 0.25 AU, as discussed in Sec. 3.2 below.

Both neutron stars and black holes are hard to detect when isolated. Limits can be put on both types of object in soft X-rays and in the EUV. Within ~ 100 light-years interstellar absorption is low, and a handful of unidentified EUV candidates exist (Maoz *et al.*, 1997). These may be neutron stars, but none lies near the ‘Oumuamua origin point. At a typical space velocity of 250 km s $^{-1}$ (Faucher-Giguère and Kaspi, 2006), the putative neutron star of origin for ‘Oumuamua will have travelled 25 pc in 10^5 years, or up to 2.5° on the sky at a distance of 10 pc, depending on the direction of travel. Searches using the eROSITA all-sky survey instrument on Spektr-X-gamma (Predehl, 2017), and with more targeted soft X-ray and EUV instruments can be undertaken.

Bialy and Loeb (2018) estimate the tensile stress on a body due to tidal forces, P_{tid} , will be $\sim 10^{-6} r_{\text{AU}} d_4^2 M/M_{\text{sol}} r_{\text{AU}}^{-3}$ dyne cm $^{-2}$, where r_{AU} is the distance of ‘Oumuamua from the star (the Sun in the case considered by Bialy & Loeb) in AU, d_4 is the length of ‘Oumuamua in units of 10^4 cm, and M/M_{sol} is the stellar mass in solar units. At an altitude of 300 km ($\sim 2 \times 10^{-6}$ AU) above an $M/M_{\text{sol}} = 1$ compact object, $P_{\text{tid}} \sim 1 \times 10^{11}$ dyne cm $^{-2}$. This is comparable to the tensile strengths of diamond or monocrystalline silicon (see Table 1 in Bialy and Loeb, 2018). These theoretical limits to material strengths imply that there is a closest possible approach to both a neutron star and a black hole, which will limit the gravity assist manoeuvres achievable.

Course navigation

How accurately can a spacecraft be navigated using only an initial external radiation powered phase? Is that accuracy sufficient to make a precision ‘landfall’ within a fraction of an AU at a target star ~ 10 parsecs away? An error of 1 arcsec at 10 pc is 1.5×10^9 km (10 AU), compared with the perihelion of ‘Oumuamua of 3.7×10^7 km (0.255 AU 1). To reliably put ‘Oumuamua on a solar gravity assist course the trajectory must then be accurate to the milli-arcsecond level. If instead the goal was only to get close to Earth, as a complex life-bearing planet, but avoid the Sun, then 0.01 arcsecond, or even 0.1 arcsecond, accuracy may suffice.

Solar sails employing starlight are only effective out to ~ 130 AU from a solar-type G star, after which the solar radiation field becomes $<1\%$ of the diffuse Galactic optical background light ($\sim 10^{-9}$ erg s $^{-1}$ cm $^{-2}$ sr $^{-1}$ Å $^{-1}$, 0.2–1 μm , Bernstein *et al.*, 2002) and the effective acceleration becomes negligible. Later course corrections are not possible until the radiation from the target star becomes significant, again at ~ 130 AU for a G star. A similar lack of course correction arises for the gravity assist case. Alternatively, the sail may be powered by a laser from farther back along the trajectory to enable a course correction. The feasibility of a laser system designed to work over parsec distances are demanding and should be investigated.

Achieving milliarcsecond accuracy in a gravity assist is particularly challenging, as the deflections gained from gravity assists are highly sensitive to the precise impact parameter of the incoming object from the massive object (e.g. Yefremov, 2020). The designers would have needed to know the 3D locations and space velocities of the compact object target to high accuracy in order to achieve the correct impact parameter $\sim 10^5$ years later. It would be interesting to determine whether there are fundamental limits to the achievable accuracy, given even small perturbations from other objects along the path, e.g. comets, interstellar asteroids.

Table 1. Summary of cases, issues, and test (section numbers are in parentheses)

Case	Issue	Implication/test
Uncontrolled (2)		
Anonymous METI (2.1)	Tell-tale acceleration No identifying marks	Tumbling implies a lower time for useful orientation. Needs estimating. Close-up inspection. Presently not possible for ‘Oumuamua; possible for future interstellar objects. Missions are valuable whatever their nature.
Inadvertant METI (2.2)	Signs of large-scale mining 10^5 year ago, or ongoing, around origin star	Close-up inspection. Identifying marks. Unexpectedly large debris discs in older stars. IR variability in debris disc if ongoing mining.
Populations (2.3)	Large numbers, masses	A small fraction of Main Belt mass. Feasible for a stellar system-wide economy in ~ 1000 year interval (1% of journey time). Ongoing and expanded surveys (e.g. VRO/LSST) for more interstellar asteroids will determine population density.
Controlled (3)		
Where did it come from? (3.1)	Nearby stars. (3.1.1)	Large course correction is needed. Calculate the delta-v needed for each plausible star.
	T, L stars (3.1.2)	UKIDSS/WISE data appear to exclude.
	Recent supernova (3.1.3)	Search for ns remnant; search for ejecta in opposite direction to origin point; search for isotopic signatures in NEO surface material (Hayabusa-2, OSIRIS-REx).
	Neutron star (ns) way station (3.1.4)	None catalogued. New EUV, soft X-ray searches, e.g. with eROSITA, other missions.
Navigation (3.2)	Black hole way station (3.1.4)	The precision of impact parameter to achieve adequately accurate egress direction is demanding and may be not be possible. (Also for ns).
	Accuracy (3.2.1) Mid-course corrections	Requires milli-arcsecond accuracy. Are there fundamental limits? Propellant mass limits delta-v changes to a TBD amount.
Where is it going? (3.3)	Accuracy	No plausible candidates. Misses Ross 248 by $\sim 10^\circ$. Failed solar encounter? Unappealing special pleading.
Reliability Engineering (4)		
Lifetime (4.1)	$\sim 1000\times$ longer than any industrial machine	Clock of the Long Now aims for 10^4 year lifetime. Study $10\times$, $100\times$ extensions.
	Damage from radiation, dust	More sophisticated modelling using detailed material properties. Interplanetary dust?

Repair (4.2)	Stability of materials (4.1.1)	Diamond decays to graphite at high T (from dust bombardment), and from ion bombardment. Similar decay for monocrystalline Si. Need to predict/measure decay rate under interstellar conditions. Artificial magnetospheres?
	Thermal environment	Mechanisms operating at few K are challenging. Are there fundamental limits? Heating requires power.
	Power	Only long half-life radionuclides useful. Adds mass for given power. Alternative low-mass heat sources?

Course corrections could be made at a later point in the voyage, when the needed corrections could be more accurately measured. Such corrections would be correspondingly larger and would need a supplemental power source. A 1 arcsecond trajectory error can be corrected with a $\Delta v = 13 \text{ cm s}^{-1}$ for a 26 km s^{-1} velocity. For ‘Oumuamua, with a mass of $\sim 1 \text{ mt}$ (Bialy and Loeb, 2018), this would require just 16.9 J. A one degree correction of a 1 mt payload would require $6.1 \times 10^4 \text{ J}$ for a Δv of 0.49 km s^{-1} , or 100 W for 5 min. This is not a demanding requirement. For a typical chemical rocket exhaust velocity of 10^4 m s^{-1} , the rocket equation gives a fuel mass of 120 kg. A rough limit to the correction would be reached when the fuel mass is equal to the payload mass, which happens when $\Delta v = 6.9 \text{ km s}^{-1}$. Higher exhaust velocities, e.g. from ion engines, would allow larger Δv within the mass limit. A zero propellant, albeit slow, way to change course would be for the light sail to change its albedo to be high on one side and low on the other, leading to an asymmetric force even in a uniform background (e.g. Ehresmann, 2021).

Where is it going?

‘Oumuamua is departing towards (RA, dec) = (23 h 51 m 24.3 s, +24° 42′ 59.0″) (Bayler-Jones *et al.*, 2018). This exit asymptote from the solar system does not point toward any known nearby star⁷ (Best *et al.*, 2018).

‘Oumuamua will have a distant ($\sim 0.46 \text{ pc}$) encounter at $\sim 100 \text{ km s}^{-1}$ with the currently 3.1 pc distant M5 dwarf Ross 248 in 29 000 years (Bayler-Jones *et al.*, 2018). A $\sim 10^\circ$ course correction early in the flight toward Ross 248 would bring ‘Oumuamua to a close encounter with Ross 248. The acceleration of ‘Oumuamua around the Sun (Micheli *et al.*, 2018) altered the outbound direction by of order a few arcminutes compared with an extrapolation of the inbound hyperbola (Bayler-Jones *et al.*, 2018). A degree sized manoeuvre was then plausibly within the capability of ‘Oumuamua, if it is an alien craft. Unfortunately, we do not now have the means to observe such a course change. Perhaps the solar encounter was a failure? This would contradict the extreme accuracies invoked earlier.

As in the case of the incoming trajectory, ‘Oumuamua could be heading towards an undetected compact object for a gravity assist. The space density of these objects is low enough that invoking one at both ends of the trajectory seems extreme. However, they can be searched for in the same way as for the incoming trajectory.

Without a destination the large deflection of ‘Oumuamua as it rounded the Sun becomes another unexplained, low probability, event, and so argues against the under-control alien craft hypothesis.

Reliability engineering considerations

Lifetime

The reliability engineering challenges (see e.g. O’Connor and Kleyner, 2012) in designing to a 10^5 year lifetime are daunting. This lifetime is $\sim 20\times$ longer than the oldest human-built structures on Earth, most of which, though massive and built from robust materials, have suffered significant damage, albeit in a challenging environment. More relevant is that this lifetime is $\sim 1000\times$ longer than the lifetime of any industrial revolution machine, and $\sim 4000\times$ longer than the longest-lived spacecraft, Voyagers 1 and 2 launched in 1977.⁸

At 10 000 years, the ‘Clock of the Long Now’ has the longest design lifetime of any current technology⁹. The lifetime of the Clock of the Long Now is a demonstration that plausible design lifetimes ~ 100 times greater than existing machinery can be conceived of. The lifetime needed for ‘Oumuamua if it is an alien craft is $10\times$ longer still, which is however a relatively small factor. Studying the Clock of the Long Now principles may show ways that lifetimes comparable with the ‘Oumuamua journey time

⁷SIMBAD search ‘region (23.7 +24.8, 1 d) && plx >40” (Accessed 22 March 2021).

⁸NASA JPL: <https://voyager.jpl.nasa.gov/mission/> (Accessed 22 March 2021).

⁹The Long Now Foundation: <https://longnow.org/clock/> (Accessed 1 April 2021).

could be realized. If 'Oumuamua came to us from a way point, rather than from the site of its construction, then all the lifetime requirements need to be at least doubled.

The challenge of reliable operation over $\sim 10^5$ year means that the mean time to failure (MTTF), a measure often used to analyse failures in complex systems, is $\sim 5\times$ longer, 500 000 years. This time-scale arises from the result that for a non-repairable system to have a 99% probability of surviving to a given time (assuming Poisson failure distributions), engineers need to design for an MTTF five times longer). Hence the designers would need to have designed for an MTTF approaching 10^6 years for 'Oumuamua, $\sim 100\times$ longer yet than for the Clock of the Long Now. Studies made for the 100 Year Starship may be helpful starting points¹⁰. Failing to find solutions would argue against the alien craft hypothesis

Materials stability

The designers of 'Oumuamua would be constrained to the same elements that we have, although they would surely have compounds novel to us. It would be interesting to see whether we could conceive of designs that could approach these lifetimes given theoretical limits on materials properties especially for large thin structures such as light sails. For example, Bialy and Loeb (2018) show that a light sail made of diamond or silicate material, with tensile strengths of $\sim 10^{10}$ dyne cm^{-2} could lose about half of its mass due to interstellar dust bombardment. That is quite a narrow engineering margin, so the sail may well fail before any post-solar stellar encounter. If the craft used a gravity assist around another stellar body, then the time spent by the craft in interstellar space will have been of order a factor two longer, endangering the sail. In addition, the environment around the stellar gravity assist body may well have a higher density of dust. Similarly, encounters with zodiacal dust in the solar system would be relatively short-lived, but at higher speed and particle density. More sophisticated modelling using detailed material properties would be valuable.

Diamond sheets of this type can be made but large single-crystal sheets are well beyond our technology today (Butler and Sumant, 2008), though not theoretically ruled out. However, graphite is in a lower energy state than diamond and diamond will convert to graphite at raised temperatures or under ion bombardment (Setton et al., 2002). Dust impacts will raise temperatures locally (on a \sim mm scale), while cosmic ray bombardment is continuous. Estimates of the lifetime of diamond sheets under the conditions of interstellar space would be instructive. In principle superconducting magnets could be used to create an artificial magnetosphere¹¹ to shield the light sail from cosmic rays. To keep within the mass budget these magnets must be low density and/or thin.

Silicon monocrystals are also subject to degradation at elevated temperatures and irradiation (Sperber, 2019), but investigations so far have been in the context of photovoltaic cells. Investigation of monocrystalline silicon under interstellar conditions would also be of interest.

Repair

For repairable systems, the appropriate metric is the less demanding mean time between failures (MTBF, O'Connor and Kleyner, 2012). Repair raises its own issues. No outside materials would be available for 'Oumuamua, so the craft would require recycling. Recycling has limits; material ablated off the thin sail by collisions with interstellar dust, which could be half of the initial mass (Bialy and Loeb, 2018), would be lost. Repair would require a supply of raw material on board, and complex mechanisms to carry out the repairs, reducing available payload mass; the repair mechanisms themselves must have sufficiently long MTBFs. These mechanisms may have to operate after $\sim 10^5$ years of inaction, which presents other challenges. Repair also implies a power source during an interstellar cruise, though the amount of power may be quite small. A fault detection mechanism would seem to

¹⁰100 Year Starship: <http://www.100yss.org> (Accessed 5 March 2021).

¹¹Rutherford Appleton Lab. 2015: <http://www.minimagnetosphere.rl.ac.uk>

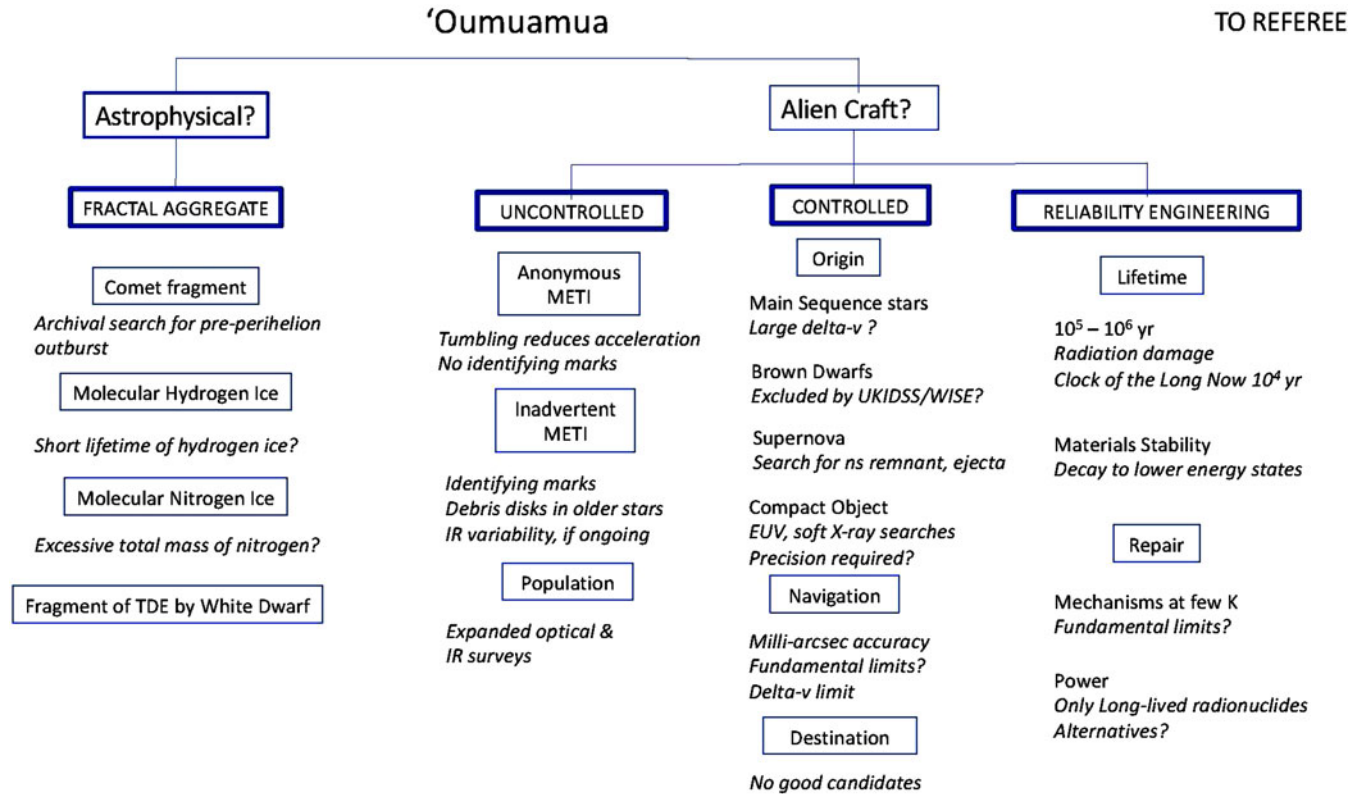


Fig. 1. Possible families of explanations for the nature of ‘Oumuamua, divided into two primary groups (astrophysical, alien craft) and sub-groups depending on properties. Possible objections and tests for each sub-group option are shown.

imply sensors and a computer that can operate for 10^5 years. As cosmic-ray hits accumulate with time the computer must have multiple redundancies for error avoidance and like thick connectors to survive. The necessary ‘super rad hard’ standards could be estimated.

Katz (2021) notes that tumbling motions will be damped out by flexing in the sail structure, and so the observed tumbling would not be expected. The sail may not flex, though, as it could have been constructed on-orbit where no deployment mechanism is required, and could then be a single (e.g. 3D printed) structure.

Keeping key elements of the craft sufficiently warm with radioisotope heating would require the use of radioactive materials with half-lives comparable to the journey time, $\sim 10^5$ year, greatly restricting the number of radionuclides available¹² and requiring larger mass to obtain the same power that more rapidly decaying materials would provide. Are there alternative low-mass long-lived heat sources? Otherwise, the temperature of the craft could be allowed to be very low. A low-temperature operation may have benefits from, e.g. superconducting components, though mechanisms operating at a few K may face fundamental limits.

Discussion and conclusions

The above discussion highlights a number of challenges for the alien craft hypothesis that further analysis could examine. Table 1 summarizes all the cases, the issues they raise, and the implications and/or tests that flow from these issues. Figure 1 puts these in the context of the broader picture including astrophysical explanations.

The ‘controlled’ case has more strikes against it than the ‘uncontrolled’ case, but neither suffers a knock-out blow, as yet. Some of the issues turn out not to be major obstacles to the alien craft hypothesis, but others cast doubt on it. All of the discussion here is highly simplified. Most of the issues suggest new, more sophisticated, studies that could be carried out. Some of these, e.g. intercept missions for newly discovered interstellar objects, are concepts already being developed and will be of value whatever these objects turn out to be.

Overall, these considerations show that a broad and well-defined research programme can be built around the hypothesis that ‘Oumuamua is an alien craft. More generally, the considerations presented here can also be applied to other interstellar visitors, as well as to general discussions of interstellar travel.

Author contributions. The author acknowledges helpful contributions from, J. Arenberg, C. J. F. Elvis, G. Fabbiano, A. Lawrence, J. C. McDowell, M. Micheli, J. Wright, and an anonymous referee.

References

- Adams FC (2010) The birth environment of the solar system. *Annual Review of Astronomy and Astrophysics* **48**, 47.
- Bailer-Jones CAL, Farnocchia, D, Meech, KJ, Brassier, R, Micheli, M, Chakrabarti, S, Buie, MW and Hainaut, OR (2018) Plausible home stars of the interstellar object ‘Oumuamua found in Gaia DR2. *Astronomical Journal* **156**, 205.
- Bernstein RA, Freedman WL and Madore BF (2002) The first detections of the extragalactic background light at 3000, 5500, and 8000 Å. I. Results. *Astrophysical Journal* **571**, 56.
- Best WMJ, Liu MC, Magnier EA and Dupuy TJ (2021) A Volume-limited Sample of Ultracool Dwarfs. I. Construction, Space Density, and a Gap in the L/T Transition. *Astronomical Journal* **161**, 42.
- Best WMJ, Liu, MC, Magnier, EA and Duput, TJ (2018) Photometry and proper motions of M, L, and T dwarfs from the pan-STARRS1 3π survey. *Astrophysical Journal Supplement* **234**, 1.
- Bialy S and Loeb A (2018) Could solar radiation pressure explain ‘Oumuamua’s peculiar acceleration? *Astrophysical Journal Letters* **868**, L1.
- Bignami GF (1996) Isolated neutron stars. *Science (New York, N.Y.)* **271**, 1372.
- Butler JE and Sumant AV (2008) The CVD of nanodiamond materials. *Chemical Vapor Deposition* **14**, 145.

¹²CERN: A Table of Frequently Used Radioisotopes: https://cds.cern.ch/record/1309915/files/978-3-642-02586-0_BookBackMatter.pdf (Accessed 1 April 2021)

- Do A, Tucker MA and Tonry J (2018) Interstellar interlopers: number density and origin of 'Oumuamua-like objects. *Astrophysical Journal Letters* **855**, 10.
- Dodd MS, Papineau, D, Grenne, T, Slack, JF, Rittner, M, Pirajno, F, O'Neil, J and Little, CTS (2017) Evidence for early life in earth's oldest hydrothermal vent precipitates. *Nature* **543**, 60–64.
- Drahus M, Guzik, P, Waniak, W, Handzlik, B, Kurowski, S and Xu, S (2018) Tumbling motion of 1I/'Oumuamua and its implications for the body's distant past. *Nature Astronomy* **2**, 407.
- Dressing CD and Charbonneau D (2015) The occurrence of potentially habitable planets orbiting M dwarfs estimated from the full Kepler dataset and an empirical measurement of the detection sensitivity. *Astrophysical Journal* **807**, 45.
- Dybczyński PA and Królikowska M (2018) Investigating the dynamical history of the interstellar object 'Oumuamua. *Astronomy & Astrophysics* **610**, L11.
- Ehresmann M (2021) Asteroid control through surface restructuring. *Acta Astronautica* **178**, 672.
- Elvis M and Milligan T (2019) How much of the solar system should we leave as wilderness? *Acta Astronautica* **162**, 574.
- Faucher-Giguère C-A and Kaspi VM (2006) Birth and evolution of isolated radio pulsars. *Astrophysical Journal* **643**, 332.
- Fender RP, Maccarone TJ and Heywood I (2013) The closest black holes. *Monthly Notices of the Royal Astronomical Society* **430**, 1538.
- Fesen RA, Weil KE, Cisneros IA, Blair WP and Raymond JC (2018) The Cygnus loop's distance, properties, and environment driven morphology. *Monthly Notices of the Royal Astronomical Society* **481**, 1786.
- Fesen RA, Drechsler, M, Weil, KE, Strottner, X, Raymond, JC, Rupert, J, Milisavljevic, D, Subrayan BM, di Cicco, D, Walker, S, Mittelman, D and Ludgate, M (2021) Far UV and optical emissions from three apparent supernova remnants located at unusually high galactic latitudes. *Astrophysical Journal*, **920**, 9.
- Forgan DH and Elvis M (2011) Extrasolar asteroid mining as forensic evidence for extraterrestrial intelligence. *International Journal of Astrobiology* **10**, 307.
- Fraser WC, Pravec P, Fitzsimmons A, Lacerda P, Bannister MT, Snodgrass C and Smolić I (2018) The tumbling rotational state of 1I/'Oumuamua. *Nature Astronomy* **2**, 383.
- Hibberd A and Hein AM (2021) Project Iyra: catching 1I/'Oumuamua—using nuclear thermal rockets. *Acta Astronautica* **179**, 594.
- Hoang T and Loeb A (2020) Can planet nine be detected gravitationally by a sub-relativistic spacecraft? *Astrophysical Journal Letters* **899**, 23.
- Jackson AP and Desch SJ (2021) To see a World in a Shard of Ice: 'Oumuamua As A Fragment Of N2 Ice From An Exo-Pluto. *52nd Lunar and Planetary Science Conference 2021*, 1718.pdf.
- Johnson RC (2003) The Slingshot Effect. Available at <https://maths.dur.ac.uk/%7Edma0rcj/Psling/sling.pdf> (Accessed 27 April 2021).
- Katz JI (2019) Evidence against non-gravitational acceleration of 1I/2017 U1 'Oumuamua. *Astrophysics and Space Science* **364**, 51.
- Katz JI (2021) 'Oumuamua is not Artificial, arXiv:2102:07871.
- Kessler DJ and Cour-Palais BG (1978) Collision frequency of artificial satellites: the creation of a debris belt. *Journal of Geophysical Research* **83**, 2637.
- Lakatos I (1980) *The Methodology of Scientific Research Programmes*. Cambridge University Press. Cambridge ISBN-13: 978-0521280310.
- Levine WG, Cabot SHC, Seligman D and Laughlin G (2021) Constraints on the Occurrence of 'Oumuamua-Like Objects, ApJ, in press. arXiv:2108.11194.
- Lingam M and Loeb A (2019) Electric sails are potentially more effective than light sails near most stars. *Acta Astronautica* **168**, 146.
- Loeb A (2018) Six Strange Facts about our First Interstellar Guest, 'Oumuamua, Scientific American, November 20. Available at <https://blogs.scientificamerican.com/observations/6-strange-facts-about-the-interstellar-visitor-oumuamua/> (Accessed 27 April 2021).
- Loeb A (2021) *Extraterrestrial: The First Sign of Intelligent Life Beyond Earth*. New York, New York: Houghton Mifflin Harcourt.
- Luu JX, Flekkøy EG and Toussaint R (2020) 'Oumuamua as a cometary fractal aggregate: the 'dust bunny' model. *Astrophysical Journal Letters* **900**, L22.
- Mamajek EE (2015) A Pre-Gaia Census of Nearby Stellar Groups. In Kastner JH, Stelzer B and Metchev SA (eds), *Young Stars & Planets Near the Sun, Proceedings of IAU Symposium No. 314*, p.21.
- Mamajek EE (2017) Kinematics of the interstellar vagabond 1I/'Oumuamua (A/2017 U1). *AAS Research Notes*, **1**, 21.
- Maoz D, Ofek EO and Shemi A (1997) Evidence for a new class of extreme ultraviolet sources. *Monthly Notices of the Royal Astronomical Society* **287**, 293.
- Mashchenko S (2019) Modeling the light curve of 'Oumuamua: evidence for torque and disc-like shape. *MNRAS* **489**, 3003.
- Meech KJ, Weryk, R, Micheli, M, Kleyana, JT, Hainaut, OR, Jedicke, R, Wainscoat, RJ, Chambers, KC, Keane, JV, Petric, A, Denneau, L, Magnier, E, Berger, T, Huber, ME, Flewelling, H, Waters, C, Schunova-Lilly, E and Chastel, S (2017) A brief visit from a red and extremely elongated interstellar asteroid. *Nature* **552**, 378.
- Micheli M, Farnocchia, D, Meech, KJ, Buie, MW, Hainaut, OR, Pralnik, D, Schörghofer, N, Weaver, HA, Chodas, PW, Kleyana, JT, Weryk, R, Wainscoat, RJ, Ebeling, H, Keane, JV, Chambers, KC, Koschny, D and Petropoulos, AE (2018) Non-gravitational acceleration in the trajectory of 1I/2017 U1 ('Oumuamua). *Nature* **559**, 223.

- Moro-Martin A (2019) Could 1I/'Oumuamua be an icy fractal aggregate? *Astrophysical Journal Letters* **832**, L32.
- Moro-Martín A, Turner EL and Loeb A (2009) Will the large synoptic survey telescope detect extra-solar planetesimals entering the solar system? *Astrophysical Journal* **704**, 733.
- O'Connor P and Kleyner A (2012) *Practical Reliability Engineering*, 5th Edn. Wiley. Chichester, West Sussex, UK
- Parry LA, Boggiani PC, Condon DJ, Garwood RJ, JdeM Leme, McLroy D, Brasier MD, Trindade R, Campanha GAC, Pacheco M Laf, Diniz CQC and Liu AG (2017) Ichnological evidence for meiofaunal bilaterians from the terminal Ediacaran and earliest Cambrian of Brazil. *Nature Ecology & Evolution* **1**, 1455.
- Phan VHM, Hoang T and Loeb A (2021) Erosion of Icy Interstellar Objects by Cosmic Rays and Implications for 'Oumuamua. arXiv:2019.04494.
- Predehl P (2017) eROSITA on SRG. *Astronomische Nachrichten* **338**, 159.
- Rafikov RR (2018) Spin evolution and cometary interpretation of the interstellar minor object 1I/2017 'Oumuamua. *Astrophysical Journal Letters* **867**, L17.
- Sartore N, Ripamonti E, Treves A and Turolla R (2011) Space and velocity distributions of neutron stars in the Milky Way. *Advances in Space Research* **47**, 1294.
- Schopf JW, Kudryavtsev, AB, Osterhout, JT, Williford, KH, Kitajima, K, Valley, JW and Sugitani, K (2017) An anaerobic ~3400 Ma shallow-water microbial consortium: presumptive evidence of Earth's Paleoarchean anoxic atmosphere. *Precambrian Research* **299**, 309.
- Sekanina Z (2019) 1I/'Oumuamua as Debris of Dwarf Interstellar Comet that Disintegrated before Perihelion. arXiv:1901.08704.
- Seligman D and Laughlin G (2020) Evidence that 1I/2017 U1 ('Oumuamua) was Composed of Molecular Hydrogen Ice. *ApJ* **896**, L8.
- Setton R, Bernier P and Lefrant S (2002) *Carbon Molecules and Materials*. CRC Press, Boca Raton, Florida.
- Siraj A and Loeb A (2021) The Mass Budget Necessary to Explain 'Oumuamua as a Nitrogen Iceberg. arXiv:2103.14032.
- Sleep NH, Zahnle KJ and Lupu RE (2014) Terrestrial aftermath of the moon-forming impact. *Proceedings of the Royal Society A* **372**, 1.
- Sperber B (2019) *Bulk and Surface Related Degradation Phenomena in Monocrystalline Silicon at Elevated Temperature and Illumination* (PhD thesis). Universität Konstanz. Available at [http://nbn-resolving.de/urn:nbn:de:bsz:352-2-af03ujroa2ux1.y\[p](http://nbn-resolving.de/urn:nbn:de:bsz:352-2-af03ujroa2ux1.y[p).
- Trilling DE, Mommert, M, Hora, JL., Farnocchia, D, Chodas, P, Giorgini, J, Smith, HA, Carey, S, Lisse, CM, Werner, M, McNeill, A, Chesley, SR, Emery, JP, Fazio, G, Fernandez, YR, Harris, A, Marengo, M, Mueller, M, Roegge, AI, Smith, N, Weaver, HA, Meech, K and Micheli, M (2018) Spitzer observations of interstellar object 1I/'Oumuamua. *Astronomical Journal* **156**, 261.
- Van Eylen V, Agentoft C, Lundkvist MS, Kjeldsen H, Owen JE, Fulton BJ, Petigura E and Snellen I (2018) An asteroseismic view of the radius valley: stripped cores, not born rocky. *Monthly Notices of the Royal Astronomical Society* **479**, 4786–4795.
- Weissman PR (1983) The mass of the Oort cloud. *Astronomy & Astrophysics* **118**, 90.
- Woosley SE, Heger A and Weaver TA (2002) The evolution and explosion of massive stars. *Reviews of Modern Physics* **74**, 1015.
- Yefremov AP (2020) Sensitivity of the gravity assist to variations of the impact parameter. *Gravitation and Cosmology* **26**, 118.