Could 1I/2017 U1 'Oumuamua be a Solar Sail Hybrid?

Todd F. Sheerin[a] and Abraham Loeb[b]

[a] *Vehicle Design and Innovation Department, The Aerospace Corporation, El Segundo, CA, USA 90245 (corresponding author, todd.f.sheerin@aero.org)*
[b] *Department of Astronomy, Harvard University, Cambridge, MA, USA 02138*

Abstract

Motivated by shortcomings of natural explanations for the first interstellar object, 'Oumuamua, this study considers implications of an artificial origin hypothesis inspired and constrained by available data. This includes an investigation of the possibility that the excess acceleration exhibited by 'Oumuamua was produced through heating of hydrogen fuel by sunlight collected with a solar sail, as proposed in human concepts for space exploration. The envisioned hybrid design is more efficient in converting sunlight to momentum as compared to a bare solar sail for non-relativistic propulsion by orders of magnitude, but it requires the use of propellant. Given the limit obtained by the Spitzer Space Telescope on the infrared radiation emitted by 'Oumuamua, upper limits are derived on the size and temperature of any putative exhaust engine, constraining its diameter to be smaller than one meter for temperatures above 800 K.

Key words: interstellar object, 'Oumuamua, solar sail, hybrid propulsion, solar thermal propulsion, solar electric propulsion

I. Introduction

The first known interstellar object detected in our Solar System, 1I/2017 U1 'Oumuamua, exhibited anomalous properties. 'Oumuamua was discovered on October 19, 2017 by the Pan-STARRS survey [1-2]. Photometry conducted over Oct. 25-30 and Nov. 21-23, 2017 [1,3-4] revealed two mysteries that have yet to be adequately addressed. The first mystery is 'Oumuamua's lack of detectable outgassing despite its comet-like acceleration [4]. The second mystery concerns 'Oumuamua's extreme geometry, which is most likely that of a flat "pancake" shape as recent studies of its lightcurves indicate [5].

Thus far, natural explanations have been physically unrealistic or insufficient to explain these observations. For example, one class of models postulates that sunlight provided the observed, excess acceleration, requiring a highly porous material to achieve the needed surface to mass ratio [6-9]. However, since the required fractal material must have a mean density that is orders of magnitude lower than air [9], it is unclear how such material can form naturally, how it might have attained the extreme geometry observed, and whether it can survive the bombardment by cosmic rays, high-energy photons, dust and gas particles through interstellar space [10-11]. Natural outgassing models have also been considered, for instance in [2], but despite 'Oumuamua's close approach to the Sun (0.25 AU), neither a dust nor water vapor tail, nor gas emission or absorption lines whatsoever were observed [1,12-15].

Recently, Seligman and Laughlin [16] proposed a molecular hydrogen ice composition for 'Oumuamua to explain its excess acceleration without visible carbon-based gases. The hydrogen ice is restricted to originate from a giant molecular cloud near our Solar System, or else it might not survive the journey. Unfortunately, there is no known nearby cloud that could have produced the vast amounts of hydrogen ice needed to explain 'Oumuamua as a member of a population of large hydrogen objects on random trajectories [17]. Furthermore, recent analysis of destruction processes for hydrogen objects through their journey from giant molecular clouds to the interstellar medium and to our Solar System indicates that starlight and collisional heating likely preclude the formation and survival of 'Oumuamua-sized objects [18]. In addition, the Oort cloud includes interstellar objects that were trapped in the Solar System, but none of the long-period comets originating from it have exhibited pure hydrogen composition thus far. Here, the alternative possibility is explored that molecular hydrogen served as fuel in an artificially-made spacecraft.

Previously, an artificial explanation was postulated in [19], wherein 'Oumuamua's acceleration is derived from sunlight reflecting off a solar sail-like structure akin to those used on current spacecraft including JAXA's IKAROS [20] or the Planetary Society's Lightsail 2 [21]. The extreme, "pancake" like shape of 'Oumuamua is also readily explained by such a hypothesis. In this work, this line of inquiry is expanded by considering spacecraft designs that include the use of hydrogen fuel.

Unlike solar sails, which are propelled by momentum transferred from reflected sunlight, this study considers spacecraft that collect sunlight energy for conversion into the kinetic energy of ejected fuel in a traditional rocket architecture. The simplest of these systems would use collected sunlight either to thermalize liquid or solid hydrogen fuel in a solar thermal propulsion architecture, as described, for instance, by [22], or to ionize and accelerate the fuel with electric and magnetic fields in a solar electric propulsion architecture, as described for example by [23]. These hybrid approaches are more efficient than reflective solar sails, as measured by the momentum imparted to the spacecraft as a function of incident sunlight power, by a factor of a thousand or more. For instance, if sunlight is directly converted to kinetic energy in ejected fuel, the resulting momentum is greater than momentum gained from perfect reflection of sunlight with a solar sail by a factor of the speed of light to the exhaust speed of ejected fuel particles.

For both solar thermal propulsion and solar electric propulsion architectures, the required hydrogen jets could be of sufficiently low density to escape detection by our telescopes, which are mostly sensitive to either water or carbon-based molecules and dust [4]. This paper describes a set of solar sail hybrid vehicle designs that include concentrated solar thermal propulsion and concentrated solar electric propulsion that may more adequately describe 'Oumuamua's observed behavior than either natural explanations or a solar sail description could alone.

Of course, without additional observations, it is not currently possible to distinguish the relative merits of exotic, natural explanations as they compare with artificial explanations. Unless it will soon be possible to chase 'Oumuamua and collect additional information, available evidence must be relied upon for feasibility assessments. Currently, natural explanations are unsatisfactory, and so this study considers the alternative to provide a more complete perspective of possible explanations for 'Oumuamua's puzzling behavior.

II. 'Oumuamua's Excess Acceleration and the Hybrid Spacecraft Concept

The mysterious behavior of 'Oumuamua was first recognized with the non-gravitational characterization and irregular shape of the interstellar visitor as described in [2]. Among the natural explanations considered by [2], cometary outgassing was proposed to be the best explanation. However, this explanation is far from satisfactory. Even though 'Oumuamua passed close to the Sun (0.25 AU), neither molecular spectra, nor dust or water vapor tail were observed [1,12-15]. Additionally, no carbon-based molecules were detected by the Spitzer Space Telescope, to exceptionally tight levels: [4] calculated a 3σ upper limit on the CO_2 rate as 9×10^{22} molecules s^{-1}, which may be scaled into a 3σ upper limit for the production of CO (~9×10^{21} molecules s^{-1}) based on the ratio of the CO_2 and CO fluorescence efficiencies [24]. This calculation for CO production rates by [4] is much lower than the value of 4.5 x 10^{25} molecules s^{-1} calculated by [2], the next most sensitive study. This result effectively eliminates the natural outgassing explanation proposed by [2], since unacceptable albedo and thermal characteristics would be required to produce the observed motion with this limit [4]. And while it may be postulated that the lack of carbon-based molecules might be explained by an uncommonly pure water source, observations did not show the temporal break in non-gravitational force that would be expected in this case, since water is not able to evaporate beyond some predictable distance from the sun [25]. Instead, the observations indicate the extra force to be smooth in time, inversely declining with the square of the distance from the Sun. Other possible explanations considered by [2] were deemed to be not viable. These include the Yarkovsky effect, friction-like effects aligned with the velocity vector, an impulsive change in velocity, a binary system or a fragmented object, a photocenter offset, and a magnetized object.

Beyond these concerns regarding the observed trajectory of 'Oumuamua, variations of apparent magnitude and non-trivial periodicity in the observed lightcurve indicate that 'Oumuamua features a geometry akin to either a “cigar” or a “pancake” shape. Recent analyses by [5] indicate that the most likely model for 'Oumuamua is a thin disc experiencing moderate torque from outgassing. In models explored in [5], a thin disc shape exhibited a 91% likelihood to produce the lightcurve minima of the required depth, as compared with only 16% probability for the best-fitting cigar-shaped models. Of course, the hypothesis for the origin of this rotation is questionable, since the moderate torque input in [5] assumes 'Oumuamua exhibited outgassing, which, as just described, is challenging to explain with natural phenomena.

Given 'Oumuamua's uncommon shape and the conspicuous lack of evidence for comet-like behavior, it is not surprising that astronomers encountered difficulties in explaining the available data. Exotic scenarios are required to describe the observed phenomena with natural explanations, none of which have been known to exist in our own Solar System, and none of which match our understanding of stellar and solar system formation. Of course, there are objects that are known to us that could explain the observed phenomena, but these objects are artificial in origin. Such explanations are commonly eschewed when applied to astronomical observations as a force of habit, and in most cases, with good reason. In the mysterious case of 'Oumuamua, though, such a description may be the simplest explanation, and so should at least be considered.

An argument to this effect was first proposed by [19], where it was posited that observations of 1I/2017 U1 'Oumuamua may be most readily described if the object were a solar sail, characterized by an extremely flat shape. The object could have been accelerated by solar radiation pressure, enabled by a mass-to-area ratio of $(m/A) \sim 0.1$ g cm^{-2}. Interestingly, this figure of merit closely corresponds to current solar sail technology used for space missions propelled by solar radiation pressure. For reference, JAXA’s IKAROS solar powered, solar sail spacecraft has a mass-to-area ratio of $(m/A) = 0.16$ g cm^{-2} (total mass of 310 kg with a sail area of 196 m^2) [20]. More recently, the Planetary Society has been operating their LightSail 2 spacecraft, which has a mass-to-area ratio of $(m/A) = 0.02$ g cm^{-2} (total mass of 5 kg with a sail area of 32 m^2) [21].

But this may not be the only possible solar sail explanation. The use of solar sails in contemporary space mission concepts extends beyond the simple case of utilizing photon pressure for momentum transfer. From a kinematics perspective, momentum transfer is most efficient when the velocity of ejected (or reflected) momentum carriers matches the speed of the spacecraft. In this case, ejected particles waste no additional energy in residual speed as measured in the background rest frame. For a non-relativistic spacecraft, then, the use of sunlight energy rather than sunlight momentum increases the propulsion efficiency by a factor up to $\sim (c/u_e)$, where c is the speed of light and u_e is the exhaust particle speed. This follows from the fact that for a given unit of sunlight energy, E, the maximum momentum that can be delivered to a lightsail is $\sim (2E/c)$, whereas the momentum delivered by ejecta through the exhaust is ~

($2E/ u_e$). For typical exhaust speeds, the gain factor is (c/u_e) ~10^{3-5}, implying that a hybrid design, in which a solar sail is used to collect sunlight energy for propulsion, would be more effective than a design that relies on sunlight reflection alone for momentum transfer. The drawback of such a hybrid approach would be the need to carry fuel to be expelled, but the approach could be used to attain higher speeds than a solar sail.

Given the potential relevance to observations of 'Oumuamua, two varieties of solar sail hybrids are considered in this paper. These hybrids were succinctly described in [26] to investigate options for rapid space missions in our Solar System. In these cases, solar sails were considered as solar energy collectors for solar thermal propulsion (STP) or solar electric propulsion (SEP). In STP, sunlight is concentrated onto a thrust chamber in which a typically inert fuel is thermalized before being released at high velocities through one or more exhaust ports. This type of propulsion system is usually limited by the thermal constraints of the thrust chamber, but are capable of high thrust values. A relevant interstellar application was introduced by [27], which described the use of an STP system close to the sun to deliver a highly efficient impulse as part of an Oberth maneuver to reach relativistic speeds. It is conceivable that 'Oumuamua was initially sent beyond its birth planetary system with such a mission. The non-gravitational acceleration observed in our own Solar System may then be described by the exhaust of residual fuel left over from a mission long completed, even if the spacecraft were no longer fully operational when passing by our Sun.

The second solar sail hybrid spacecraft concept to consider is SEP, in which sunlight is converted into electricity that is then used to accelerate ionized propellant with electric and magnetic fields through one or more exhaust ports. SEP is typically constrained by power source characteristics and thruster design, as opposed to thermal material limitations. Current SEP systems are incapable of high thrust, but produce higher exhaust velocity, i.e. higher specific impulse I_{sp} (generally between 1,000 s - 10,000 s), than either STP (900 s - 1,000 s) or chemical thrusters (250 s - 450 s). Specific impulse I_{sp} is related to the exhaust particle speed u_e by the definition $I_{sp} \equiv u_e/ g_o$, where g_o = 980 cm s^{-2} is the Earth's gravitational acceleration at sea level. When operated for extended periods of time, electric propulsion thrusters with high I_{sp} allow for greater velocity changes than chemical or thermal thrusters. For this reason, while chemical and thermal thrusters are preferred today for high thrust applications, electric propulsion systems are needed to achieve the highest in-space velocity change, ΔV, as may be required for fast Solar System or interstellar missions. Given the high velocities achievable with SEP vehicle designs, it is conceivable that 'Oumuamua was just such a vehicle given that it traversed interstellar distances to reach our Solar System.

It is conceivable that, just as in the STP case, an SEP vehicle may have residual fuel left over from the vehicle's primary mission. For either the STP or SEP cases, if such a system were not operational when passing by our Sun, it is possible that such a system would have expelled residual fuel, liberated by the sharp temperature increase during its passage through our Solar System. Given the low temperature of interstellar space (~ 3-4 K), it is conceivable that hydrogen would not boil off (boiling point ~ 10 K) until the close pass by our Sun, with the object's structure preventing cosmic rays or micrometeorites from liberating residual fuel during the interstellar journey.

III. Considerations for a Hybrid Spacecraft Hypothesis

Previously, [19] investigated the conditions necessary to elicit the observed non-gravitational acceleration for the case that 'Oumuamua was a tumbling solar sail originally designed to use solar radiation pressure to produce thrust. If 'Oumuamua were instead an STP or SEP vehicle, the non-gravitational radial acceleration measured by [2] could be explained by residual fuel escaping a non-functional (or retired) STP or SEP system when illuminated by sunlight either directly or from partial solar concentration from the large area, low mass solar sail-like reflector.

While hydrogen fuel has been considered for this study, other fuel sources are not precluded. The primary reason for this selection is hydrogen's abundance in our observable universe and its optimality for high specific impulse engines that may be useful for interplanetary spacecraft. For a fuel source of liquid or solid hydrogen, then, outgassing may be expected if any remaining fuel is heated above the evaporation threshold. Since this is merely tens of K, it would be expected that whatever fuel remained stored during 'Oumuamua's journey through interstellar space would be vaporized when passing near our Sun, assuming no functional active cooling mechanism. Furthermore, if a solar sail structure provided concentration of sunlight, then it is conceivable that the fuel was liberated at exhaust velocities greater than that which would be expected from natural outgassing. This, of course, would imply smaller mass loss fractions than natural outgassing models, and which may further help to explain non-observations of ejected particles of any kind.

'Oumuamua's trajectory in these scenarios would be modified by the release of this fuel over an extended period of time with a force that declines inversely with the square of the distance from the Sun. Assuming the fuel source is mostly pure hydrogen (which is the ideal fuel in obtaining the highest exhaust speed for an STP or SEP system, given its low atomic mass and low evaporation energy), 'Oumuamua would not exhibit a dusty or molecule-rich cometary tail, in accordance with non-detections in observations of 'Oumuamua.

A simple comparison may be conducted to assess the implications of the scenario of concentrated sunlight thermalizing a fuel source on 'Oumuamua. Based on the analysis of [2], 'Oumuamua exhibited a non-gravitational acceleration of $4.92 \pm 0.16 \times 10^{-4}$ cm s^{-2} that may be roughly estimated to occur over the transit duration, $\tau \sim 100$ days. The total change in velocity, ΔV, of this maneuver may be estimated by multiplying these figures, resulting in a $\Delta V \sim 4 \times 10^3$ cm s^{-1}. The ejected mass fraction can be derived by considering momentum conservation given the velocity shift required and is therefore independent of the actual mass and geometry of 'Oumuamua [28]. The ideal rocket equation provides a means to quantify this relationship: $m_f / m_i = exp\ [-\Delta V / u_e]$. As usual, m_f is the final mass of the object, and m_i is the initial mass of the object before outgassing. While this assumes outgassing events are directed along the observed non-gravitational acceleration vector, the relation provides a minimum for the ejected mass fraction $[m_i - m_f] / m_i$ that may be expected when taking into account the geometry and direction of outgassing. Using this relation, a comparison of the total ejected mass as predicted by a natural outgassing event may be compared with that which is predicted for the assisted outgassing as hypothesized for thermalized fuel reserves in the solar sail STP or SEP hybrids.

A range of ejection speeds for outgassing materials that are commonly found in nature was provided by [2], from $u_e \sim 1.5 \times 10^4$ cm s^{-1} to $u_e \sim 4.5 \times 10^4$ cm s^{-1}. The most probable estimate for a natural outgassing scenario for 'Oumuamua was reported as $u_e \sim 3 \times 10^4$ cm s^{-1}. Given this ejecta speed and 'Oumuamua's ΔV, the projected mass loss rate for the natural outgassing case considered in [2] is ~ 10%, as described in [28]. In order to compare this natural outgassing model to the hybrid spacecraft hypothesis, which involves collected sunlight thermalizing fuel reserves to high temperatures, the exhaust particle velocity u_e may be varied while maintaining the same overall change in velocity, i.e. ΔV, of 'Oumuamua as observed by telescopes.

Regarding the question of 'Oumuamua's observed velocity and associated considerations to the speed attainable with the designs considered here, there are no constraints that may be applied. The reason is that it is unknown whence 'Oumuamua came. In other words, the relative velocity of 'Oumuamua's host star or solar system with respect to our own is not known. With this in mind, it is not the intent in this study to make claims about the initial ΔVs that would be required to speed up 'Oumuamua to the observed initial velocity with respect to our Solar System. Rather, this analysis concerns only the observed acceleration and ΔV during 'Oumuamua's transit through our Solar System.

IV. Results

Fig. 1 depicts the relationship between specific impulse $I_{sp} \equiv u_e / g_o$ and the ejected mass fraction that would be required of 'Oumuamua to produce the observed acceleration profile. The most probable natural outgassing exhaust velocity assumed by [2], $u_e \sim 3 \times 10^4$ cm s^{-1}, is shown in the figure as a gray dot. Several additional gray dots are also depicted, corresponding to the most probable velocity of molecular hydrogen in a Maxwell-Boltzmann distribution at 300 K, 500 K and 1,000 K. The specific impulse upper limit for current STP systems with hydrogen fuel, I_{sp} ~ 900 s, as described in [26], is noted with a left facing gray arrow in the figure, while a common lower specific impulse limit for SEP systems, I_{sp} ~ 1,000 s, is noted with a right facing gray arrow. As can be seen from the steep slope of constant total impulse in Fig. 1, even a slight increase in the ejected material speed results in significant reductions in mass loss. Assuming even a non-functional STP or SEP system, then, partial concentration of sunlight and resulting thermalized outgassing of onboard fuel could have resulted in sufficient momentum exchange to match observed non-gravitational acceleration with only a small fraction of 'Oumuamua's total mass. This would imply that relatively little fuel (on the order of a few percent) would be needed to complete the observed maneuver in our Solar System. This might be compared with a mass loss of about 10% for a calculation involving one significant figure, which would be necessary in the case of natural outgassing.

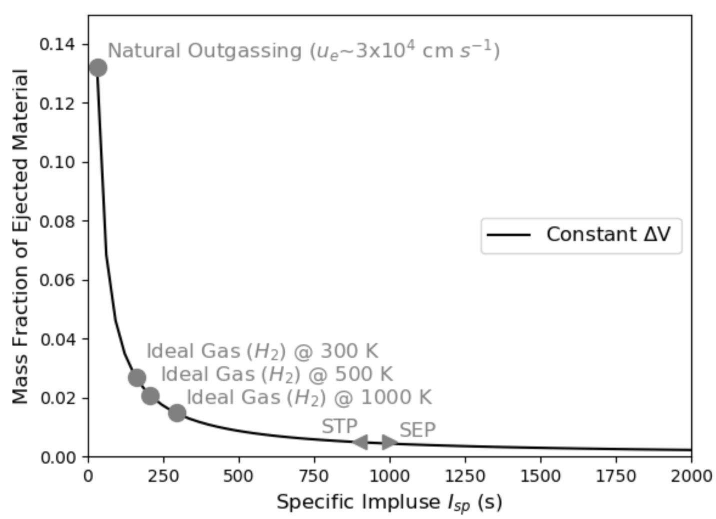

Figure 1: Minimum mass loss rate as a function of average specific impulse, i.e. ejected material particle velocity, for a fixed change of velocity ΔV of 'Oumuamua for its transit through our Solar System.

In addition to relative figures for mass loss, implications of total mass loss are also important for this discussion. The reason is that observations of 'Oumuamua yielded no trace of outgassing whatsoever. If outgassing (natural or assisted) were the source of 'Oumuamua's extra acceleration, then, a non-detection of any outgassed materials would indicate that the total mass ejected from 'Oumuamua would likely be low. The total mass loss rate and initial mass of 'Oumuamua are dependent on the albedo and geometry of the object. A range of mass loss rates is provided in [2] between $\dot{m}$ = 700 g s^{-1} and $\dot{m}$ = 1.4 x 10^5 g s^{-1}. For reference, a proposed outgassing scenario by [2] involved a spherical nucleus of radius 1.02 x 10^4 cm with a density of 0.5 g cm^{-3} and an albedo of 0.04. Such a scenario corresponds to an initial object mass of ~ 2 x 10^{12} g. With natural outgassing, such an object would have expelled at least ~ 2 x 10^{11} g, i.e. 10% of its initial mass, to achieve the observed change in velocity. Alternatively, assuming a 10:1 flat disc geometry of the same radius, a scenario that has been proposed as the more likely scenario most recently by authors including [5], the initial mass would have been an order of magnitude smaller than the scenario considered by [2]: ~ 2 x 10^{11} g, with at least ~ 2 x 10^{10} g expelled. Going further to assume the flat disc has an average thickness on the order of ~ 0.1 cm, corresponding to a geometry similar to a solar sail as considered in this paper for hybrid spacecraft designs, the estimated initial and ejected masses would be reduced by several more orders of magnitude to ~ 2 x 10^7 g and ~ 2 x 10^6 g, respectively. These mass loss fractions would be reduced further by a factor corresponding to Fig. 1 if the fuel source were illuminated by a concentrated solar source and brought to a higher mean temperature over the course of the transit.

The non-detections of outgassed material of any kind in observations of 'Oumuamua align well with the artificial, hybrid spacecraft model, in which only a small amount of outgassed material would have been required to generate the observed change in velocity. If the object featured a low albedo like 0.04 as considered in the analysis here, this may imply that, if the solar sail material were initially intended to be highly reflective, then it must have become highly degraded before arriving at our Solar System. Alternatively, a higher albedo, i.e., a more reflective, object would indicate an even smaller object. Assuming similar bulk densities to the analysis already considered, the higher albedo case would imply still smaller mass losses.

Further observations would be required to disambiguate these cases. While the mass and albedo of the object may not be constrained further with existing data, it is possible to derive constraints on the physical configuration and thermal properties of the object during its transit through our Solar System. Specifically, data collected from the Spitzer Space Telescope provides additional information to constrain the properties of a hybrid solar sail explanation for 'Oumuamua. A requirement derived from 'Oumuamua observations would be that the combination of the extended solar sail as well as the thermalized region (that may include exhaust ports, nozzles, or concentrated sunlight spots) would, together, feature a specific flux at or below the limit reported by [4]. For reference, [4] reports a specific flux upper limit (3σ) of 0.3 micro-Jansky at a wavelength of 4.5 microns on November 21-24, 2017. The flux per unit frequency limit corresponds to 3 x 10^{-30} erg s^{-1} cm^{-2} Hz^{-1} at a wavelength of 4.5 microns. The average distance of 'Oumuamua from Spitzer on these dates was 1.8 AU, or roughly 2.7 x 10^{13} cm. This distance may be used to convert the Spitzer observation to a limit on the surface area of a hot spot as in the case of an STP or SEP vehicle given the hot spot's temperature.

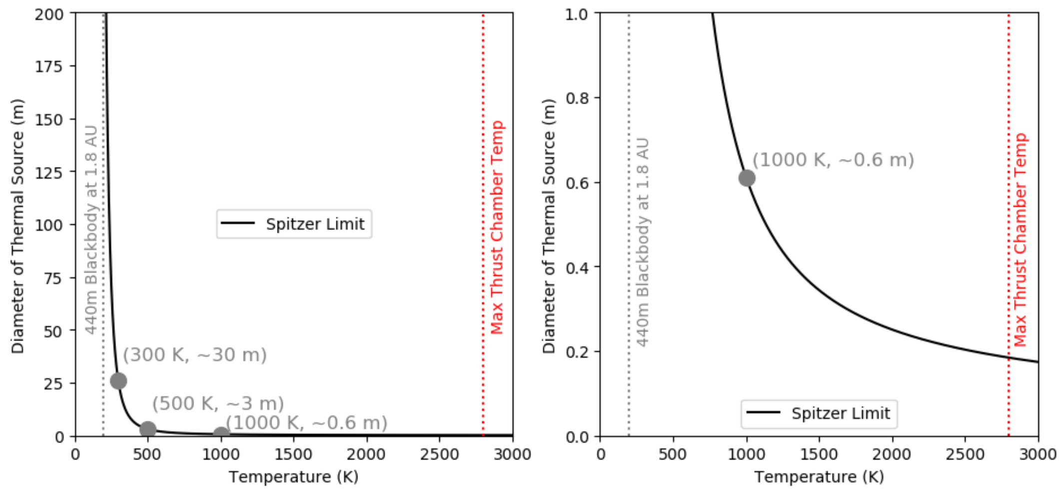

Figure 2: Thermal source size versus temperature corresponding to the spectral flux density limit from Spitzer Space Telescope data reported in [4].

Fig. 2 depicts the specific flux upper limit as characterized by the Spitzer data (indicated by the solid black line, labeled "Spitzer Limit") as a function of thermal source temperature and size. The temperature of a blackbody with diameter equal to the largest spherical diameter considered by [4], 440 meters, is depicted as a vertical dotted gray line, providing a lower bound for considered temperatures. At the high extreme, temperature limitations of current solar thermal propulsion systems may be used to provide an upper bound. A limit of ~ 2800 K, or roughly ~ 0.35 kW cm^{-2} in optical light intensity, is described by [26], among others, to prevent melting the thrust chamber. A maximum thrust chamber temperature of 2800 K is indicated in Fig. 2 by a vertical dotted red line.

Assuming blackbody emission with a Planck law for the specific brightness, a hot spot approaching 2800 K would have to be smaller than 20 cm in diameter to remain below the Spitzer telescope limit as depicted in Fig. 2. Of course, both the thermal source and the reflecting solar sail would have to contribute spectral fluxes that, when combined, do not exceed the observed spectral flux density. For the case of a reflective surface alone, [4] reports effective spherical diameters of less than {98, 140, 440} meters with albedo greater than {0.2, 0.1, 0.01} under the assumption of low, middle, or high thermal beaming parameter η = {0.8, ~1, 2.5}, respectively. As described in [29], the beaming parameter η is a proxy for thermal inertia and surface roughness, representing the amount of infrared "beaming" an object has, with η = 1 corresponding to objects with zero thermal inertia and no significant topography. If the spectral flux density contributions from the sail and a thermalized region of 'Oumuamua add linearly, then constraints may be placed on the relative size of the sail material and of the thermalized area. The constraint would be that the combined spectral flux density remains at or below the observed spectral flux density in Spitzer space telescope data.

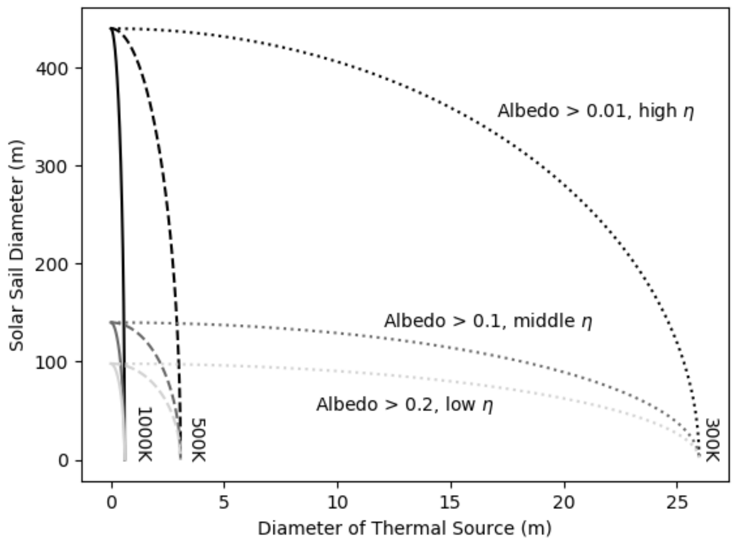

Figure 3: Sail diameter versus thermal source diameter for hybrid solar sail spacecraft concepts, constrained to a total spectral flux density of 0.3 micro-Jansky, derived by [4] as a limit from Spitzer Space Telescope data.

Fig. 3 depicts the relationship between sail diameter and thermal source diameter. The full range of allowed diameters are plotted for three sail albedos and three thermal source temperatures. Black lines correspond to a minimum albedo of 0.01 with a high thermal beaming parameter η, dark gray lines to a minimum albedo of 0.1 and a middle η, and light gray lines to a minimum albedo of 0.2 with a low η. Solid lines correspond to 1,000 K, dashed lines to 500 K, and dotted lines to 300 K. Sail albedo in all cases is assumed to be uniform.

At the limit where the diameter of the thermal source goes to zero and no sunlight is concentrated on 'Oumuamua, solar sail diameter allowances match the albedo and thermal beaming parameter as derived from predictions for a comet nucleus in [4]. By contrast, at the opposite extreme, in which the observed spectral flux density is primarily generated by a thermalized region of concentrated sunlight, the size of the thermal source is maximized to the values from Fig 2.

IV. Summary and Discussion

This investigation considered the possibility that the excess acceleration exhibited by the interstellar object, 'Oumuamua, was produced through heating of hydrogen fuel by sunlight collected with a solar sail, as envisioned in human concepts for space exploration. The hybrid design is more efficient than a bare solar sail for propulsion by orders of magnitude. A key difference is that the hybrid design requires propellant, unlike a solar sail, which uses only reflected sunlight. With even modest solar collection, expended fuel need account for only a small fraction (few percent) of the initial object's mass to explain the non-gravitational acceleration observed, which would help to explain the non-detection of any outgassing whatsoever in observations of 'Oumuamua. Given the limit obtained by the Spitzer Space Telescope on the infrared radiation emitted by 'Oumuamua, upper limits were derived on the surface area and temperature of any putative exhaust source, implying a diameter smaller than a meter above 800 K.

Without further knowledge of 'Oumuamua's origin and nature, it is difficult to assign priority to any assumption regarding the ΔV requirements or design objectives associated with it as an artificial space mission. However, in the case of an artificial origin, it is likely, given that the object travels across interstellar distances, that it was designed to provide enough change in velocity to escape its own stellar neighborhood and venture into interstellar space [30]. It is therefore likely that an operational spacecraft of this kind would be designed to obtain large ΔVs, requiring a fast exhaust speed for efficient transfers.

The limit facing thermal propulsion technology is that known materials cannot withstand temperatures above ~ 3000 K. If 'Oumuamua were a solar thermal propulsion vehicle, then, the system may have been designed to operate at high temperatures. Alternatively, if 'Oumuamua were a solar electric propulsion vehicle, then the system may have been designed to achieve very high specific impulses with correspondingly high power demands to be satisfied by the large area structure collecting sunlight energy or another directed energy source. For either case, what may have been observed, then, in 'Oumuamua's passage by our Sun, was a system featuring a poorly configured concentrator capable only of delivering a small fraction of reflected light onto the thrust chamber, at a temperature-to-area ratio commensurate with the Spitzer observations. This partially-functioning system may then be expelling remaining fuel from a mission long past, but with much lower specific impulse than the fully operational system would be capable of achieving. Hydrogen may not be the only fuel source desired for such a system, but it would certainly be a prime candidate if the mission objective were to achieve the highest possible specific impulse.

A reasonable question that might be raised is: in the STP or SEP hypothesis, how is the radial direction of the observed acceleration explained? There are two possible explanations to this query. First, assuming the tumbling is random, the radial direction of the acceleration may be explained by the solar sail-like structure, hypothesized to collect sunlight. While gas may be vented in all directions during 'Oumauma's pass by our Sun, an asymmetry in the force vector in the radial direction may arise if the heating of the fuel storage unit were greatest when sunlight is concentrated by the large area collector. In most orientations, little sunlight is collected by the solar sail, providing only uniform heating to the whole structure. Indeed, the collector might shade the fuel source when facing in the wrong radial direction. When the collector is facing the sun, however, the heating may spike, strengthening the fuel boil-off. Even when assuming this boil-off is isotropic, the solar sail itself might break the symmetry by “catching” or at least getting in the way of much of the hydrogen released in its direction, resulting in net radial acceleration in the opposite direction. Alternatively, it is conceivable that the vehicle was designed to thrust away from the solar light source, e.g. as might be expected for a vehicle designed to exit a solar system. In this case, the tank and nozzles may be reasonably expected to be positioned behind other structures, away from the collector, i.e. toward the host star, resulting in the observed radial acceleration.

A second explanation follows from assuming the tumbling is not random, but intentional, for instance to produce gyroscopic stability. The radial direction of the acceleration in this case may follow from the assumption that 'Oumuamua was in a configuration to thrust in a direction facing away from its home star system, repeating the act (but with limited fuel, perhaps, or reduced solar concentration capabilities) on its pass through our Solar System. This is a weaker argument, though, since the lightcurve observed featured large variations in reflected light, indicating that the spin did not optimize surface area exposed to the sun. Even if an STP or SEP spacecraft were initially designed with a stabilizing spin, then, it is likely that this spin degraded into random tumbling before 'Oumuamua reached our Solar System.

Together, solar sailing, solar thermal propulsion, and solar electric propulsion may be considered as a family of possible explanations for 'Oumuamua in the context of an artificial origin hypothesis. The higher efficiency of the hybrid model allows the payload to be much heavier than in the pure solar sail scenario. This means that either the sail itself can be thicker than a millimeter (as derived by [19]) or it could carry a much heavier payload than allowed with the solar sail option. The results of this study do not imply that these hybrid concepts provide the only explanations for the observed anomalies, nor do the results imply that these are the most feasible explanations. Instead, this study intends to introduce a plausible alternative to the set of thus far unsatisfactory natural explanations for 'Oumaumua's mysterious behavior. More importantly, though, such considerations may inspire scientists, engineers, and thinkers of all kinds to envision optimal designs for the space aspirations of our own civilization within the Solar System and beyond.

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