



# 1I/‘Oumuamua as a Tidal Disruption Fragment from a Binary Star System

Matija Ćuk

SETI Institute 189 N. Bernardo Avenue, Suite 200 Mountain View, CA 94043, USA; [mcuk@seti.org](mailto:mcuk@seti.org)

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## Abstract

1I/‘Oumuamua is the first known interstellar small body, probably being only about 100 m in size. Against expectations based on comets, ‘Oumuamua does not show any activity and has a very elongated figure, and it also exhibits undamped rotational tumbling. In contrast, ‘Oumuamua’s trajectory indicates that it was moving with the local stars, as expected from a low-velocity ejection from a relatively nearby system. Here, I assume that ‘Oumuamua is typical of 100 m interstellar objects and speculate on its origins. I find that giant planets are relatively inefficient at ejecting small bodies from inner solar systems of main-sequence stars, and that binary systems offer a much better opportunity for ejections of non-volatile bodies. I also conclude that ‘Oumuamua is not a member of a collisional population, which could explain its dramatic difference from small asteroids. I observe that 100 m small bodies are expected to carry little mass in realistic collisional populations and that occasional events, when whole planets are disrupted in catastrophic encounters, may dominate the interstellar population of 100 m fragments. Unlike the Sun or Jupiter, red dwarf stars are very dense and are capable of thoroughly tidally disrupting terrestrial planets. I conclude that ‘Oumuamua may have originated as a fragment from a planet that was tidally disrupted and then ejected by a dense member of a binary system, which could explain its peculiarities.

**Key words:** binaries: general – minor planets, asteroids: individual (1I/‘Oumuamua) – planet–star interactions – planets and satellites: formation

## 1. Introduction

1I/‘Oumuamua is the first known interstellar object, discovered in 2017 October after it had already passed perihelion (Bacci et al. 2017; Meech et al. 2017). ‘Oumuamua is clearly extrasolar in origin, having a velocity at infinity of  $26 \text{ km s}^{-1}$  and an eccentricity of 1.2. Much of Oumuamua’s velocity relative to the solar system is a reflection of the Sun’s own velocity relative to the local standard of rest (Mamajek 2017), making ‘Oumuamua’s trajectory close to our expectations for an interstellar interloper. However, ‘Oumuamua’s physical characteristics were unexpected, starting with a complete lack of cometary activity (Knight et al. 2017; Meech et al. 2017) or associated meteoroids (Ye et al. 2017). The observed spectrum of ‘Oumuamua is featureless and somewhat red (Bannister et al. 2017; Masiero 2017), similar to a number of outer solar system objects. However, ‘Oumuamua’s solar system spectral analogs are expected to be volatile rich and should exhibit cometary activity after passing within 0.25 au from the Sun, as ‘Oumuamua did. Therefore, one cannot say if ‘Oumuamua’s spectral similarity to certain outer solar system bodies is meaningful or a coincidence. The most puzzling feature of ‘Oumuamua is its very elongated shape, with an aspect ratio of 5:1 to 10:1 (Bolin et al. 2018; Meech et al. 2017). This is an extreme value for solar system bodies of similar size, and may indicate that ‘Oumuamua has internal strength (Fraser et al. 2017). While ‘Oumuamua’s rotation period was reported to be 7–8 h, it has been suggested that the observations are not consistent with a single period, probably indicating a non-principal axis rotation, i.e., tumbling (Drahus et al. 2017; Fraser et al. 2017). Non-damped tumbling would indicate that the interior of ‘Oumuamua is not particularly dissipative, and is consistent with ‘Oumuamua being a rigid body (Fraser et al. 2017). Monolithic 100 m bodies are known in the solar system, but are less common than “rubble piles,” tend to have less elongated shapes, and, not being at risk from

rotational disruption, often have very short spin periods (as the radiational YORP effect distributes their rotation rates throughout the large allowed phase space; Pravec et al. 2002).

Therefore, while the trajectory and rotational physics of ‘Oumuamua appear to be consistent with our prior understanding, its shape and composition are surprising. In this paper, I will make an assumption of the Copernican principle with respect to ‘Oumuamua, i.e., that it is typical of bodies of its size that are populating the local interstellar space. This assumption is far from secure, as it is based on only one object, but it is also testable because we expect to detect more interstellar bodies as more and larger automated surveys become operational.

## 2. Dynamical Considerations

Ejection of planetesimals from our solar system is a natural consequence of planetary formation and migration (Fernandez & Ip 1984; Duncan et al. 1987; Kaib & Quinn 2008). Young giant planets scattered the remaining small bodies, with the resulting exchange of angular momentum enabling expansion of the orbits of Neptune, Uranus, and Saturn, which on average were passing small bodies from the trans-Neptunian belt to Jupiter. Jupiter, due to its large mass, was highly efficient at ejecting bodies from the system, resulting in the planet’s inward migration. Some of the bodies that narrowly escaped ejection ended up on very large orbits torqued by passing stars and Galactic tide, forming the Oort Cloud. The existence of the Oort Cloud, inferred from the continuous influx of long-period comets, is a direct indication that a large number of comets must have been ejected from our solar system when the Oort Cloud formed.

The ejection of volatile-free asteroids is also possible, but they are thought to have been a relatively small fraction of planetesimals that were ejected or placed into the Oort cloud. One reason for this is the much greater supply of icy

planetesimals in our system, which may not apply elsewhere. Another is that our giants planets all orbit beyond the “snowline,” the distance beyond which planetesimals incorporate large fractions of water ice. Rocky planetesimals are thus less likely to make it to Jupiter-crossing orbits, and the majority of bodies with  $a < 2.5$  au that become unstable end up colliding with the Sun (Gladman et al. 1997; Minton & Malhotra 2010).

Many known giant exoplanets are well within the relevant “snowline” for their solar system, and some of them are certainly capable of ejecting small bodies into interstellar space (Ford & Rasio 2008). In general, two major processes are competing for the elimination of planetesimals: scattering and collisions. Collisions become more likely if the planet is brought closer to the star (as size of the planet increases relative to the size of the orbit), but scattering becomes less efficient closer to the star, as the orbital velocities are higher while the planet’s escape velocity is the same. Using expressions from Tremaine (1993) and Wyatt et al. (2017), I find that the ratio of ejection and collision rates is (assuming constant density for the planet):

$$\frac{R_{ej}}{R_{col}} \propto \frac{M_p^{4/3} a^2}{M_*^2}, \quad (1)$$

where  $M_p$  and  $M_*$  are masses of the star and the planet, and  $a$  is the planet’s semimajor axis. This implies that Jupiter at 1 au would be a more than an order of magnitude weaker ejector than at its present distance. Since, for most of the main sequence,  $\log(L_*/L_{\text{Sun}}) = k \log(M_*/M_{\text{Sun}})$ , with  $3.5 < k < 4$  (Duric 2004), it is clear from Equation (1) that Jupiter mass planets at habitable zone distances from their parent stars ( $(a/1 \text{ au})^2 = L_*/L_{\text{Sun}}$ ) would be less efficient scatterers for smaller stars, but more efficient for more massive stars. Also, planets more massive than Jupiter could be efficient at ejecting rocky planetesimals even around solar-mass and smaller stars.

However, here I am making the assumption that ‘Oumuamua is typical among interstellar objects, which implies that volatile-free ejected bodies are more common than comets. Even in situations in which planets can efficiently eject rocky planetesimals (massive planets, high-mass stars), it appears unlikely that they could dominate the galactic population of scattered bodies. Even relatively low-mass planets can eject comets at large heliocentric distances (Neptune being an example), while low-mass main-sequence stars have an order of magnitude closer-in snowlines, implying less space available for purely rocky planetesimals. Additionally, the large mass available in volatiles should, in general, make the mass of solids beyond the snowline larger than that available in the inner system, where only refractories are stable. Therefore, I come to the conclusion that, on the basis of our present knowledge, we would expect most interstellar small bodies to be cometary, i.e., to be formed beyond the snowline of their solar systems and to contain significant amounts of volatiles. Lack of any cometary activity from ‘Oumuamua is therefore unexpected and should make us rethink the dominant mechanisms for formation of 100 m fragments on interstellar trajectories. This is independent of any issues related to the shape of ‘Oumuamua, which will be discussed in the next section.

At this point, I note that binary and multiple stars are very common in the Galaxy, and that they are likely to be major

sources of ejected orbits (Smullen et al. 2016; Wyatt et al. 2017). Binary star and planetary populations are quite distinct, as they are separated by the “brown dwarf desert,” at least as companions to main-sequence stars. Therefore, the populations of bodies ejected by binary companions and planets may turn out to be quite distinct. Binary separations cover a wide range of values, with some companions being closer than 1 au (Duchêne & Kraus 2013). Of course, availability of material for ejection is still an issue for binary companions, and one may still expect icy material to predominate among small bodies in binary systems. However, if ‘Oumuamua is an indication that the events leading to ejections of most numerous interstellar bodies are very different from those that operate in our solar system, it is a very good guess that stellar companions may be implicated, as they are both very common and more efficient scatterers than planets.<sup>1</sup> Interestingly, most likely candidates for the origin of ‘Oumuamua identified by Zuluaga et al. (2017) are binary systems, but the probability of any individual system being the ultimate source of ‘Oumuamua is rather small.

### 3. Physical Characteristics

Despite passing within 0.25 au from the Sun, ‘Oumuamua did not exhibit any measurable cometary activity (Knight et al. 2017; Meech et al. 2017). Since ‘Oumuamua’s visible spectrum is similar to some moderately red outer solar system bodies, there have been suggestions (Laughlin & Batygin 2017) that the interior of ‘Oumuamua is volatile rich, but that the surface has been devolatilized by very prolonged exposure to conditions of interstellar space. However, this hypothesis is in conflict with the fact that Oort Cloud comets are experiencing an environment practically indistinguishable from interstellar space for billions of years, yet they exhibit cometary activity when approaching the Sun. The most likely explanation for ‘Oumuamua’s lack of outgassing is that it is inherently volatile-poor.

Comparison of ‘Oumuamua to asteroids of similar size also raises questions. The spectrum of ‘Oumuamua, being both moderately red and featureless, is not common in the inner solar system (Bannister et al. 2017). Also, ‘Oumuamua’s extreme elongation, between 5:1 (Fraser et al. 2017) and 10:1 (Meech et al. 2017) makes it an outlier among asteroids (Pravec et al. 2002). ‘Oumuamua’s undamped tumbling indicates that it may be a monolith, rather than a “rubble pile” (Fraser et al. 2017). Asteroidal monoliths in the 100 m range are known in the solar system, and considering a relatively long (for a monolith) 7–8 hr rotation period, undamped rotation by itself is not remarkable (for larger asteroids, tumbling is usually reserved for even slower-spinning bodies; Burns & Safronov 1973; Pravec et al. 2002; Sharma et al. 2005) and does not need any special excitation mechanism.

In the solar system, 100 m bodies are thought to be collisional fragments of larger progenitors. Current theories of planetesimal formation indicate that original planetesimals may have been much larger, in the 100 km range (Youdin & Goodman 2005; Johansen et al. 2007; Morbidelli et al. 2009). Asteroids (433) Eros (30 km long) and 25143 Itokawa (600 m long), both visited by spacecraft, are thought to be typical of

<sup>1</sup> After the first version of this Letter was submitted for review, I realized that Raymond et al. (2017) reached conclusions similar to mine on the relative abundance of icy and rocky planetesimals, as well as on the possible importance of binary stars for the ejection of small bodies.

intermediate steps of collisional evolution from 100 km bodies to 100 m fragments. Eros has a density of  $2.7 \text{ g cc}^{-1}$ , similar to ordinary chondrite meteorites Eros is likely related to, and is thought to be a fractured body, meaning that it is held together by gravity but without significant internal voids (Cheng 2004). Itokawa, in contrast, has a density of  $1.9 \text{ g cc}^{-1}$  despite a composition similar to Eros's. Itokawa is thought to be a rubble pile, with fragments of a range of sizes held together by gravity and possibly E-M surface forces, with a large porosity (Fujiwara et al. 2006). While solid blocks are present on Itokawa, they are results of many collisional events, some of which destroyed their past parent bodies, and some led only to fracturing. It is easy to see why long and thin fragments would be rare, as the orientation of stresses from multiple asteroidal collisions becomes basically random. Therefore, not only is the elongation of Oumuamua unusual (near-Earth asteroid 1865 Cerberus comes close to this, but it is over 1 km long and probably not a monolith), but one would expect such long and thin pieces to be rare on theoretical grounds. While 'Oumuamua could be an outlier from a population similar to asteroids, here I am assuming that 'Oumuamua is typical of interstellar objects, which would make them collectively quite distinct from asteroids.

The interstellar nature of 'Oumuamua has led to speculation of a possible artificial nature. However, its trajectory is that of "celestial driftwood"<sup>2</sup> as shown by Mamajek (2017). If 'Oumuamua were to be artificial, it would require artificial 100 m bodies on passive interstellar trajectories to be more common than ejected asteroids and comets of the same size. This is an extraordinary claim, and would require evidence more extraordinary than 'Oumuamua's elongated shape. More specifically, continuing tumbling of 'Oumuamua is most consistent with a single solid body with no moving parts (Fraser et al. 2017). A hollow object containing movable items would damp its non-principal axis rotation much more quickly (Burns & Safronov 1973). Therefore, an artificial origin would not explain any of 'Oumuamua's observed peculiarities.

If 'Oumuamua is not a result of collisional evolution like the one experienced by solar system asteroids, is there a way of naturally producing its shape? Collisions between the original 100–1000 km planetesimals (or planets accreted from them) would not be pre-fractured or reaccreted, so they could produce a rather different suite of first-generation collisional fragments, some of which may have unusual shapes. But the amount of mass in 100 m fragments, resulting from disruption of much larger bodies, would be modest (as most of the mass would be in larger pieces). Also, these unprocessed planetesimals would have to be on somewhat stable orbits in order to have a reasonable probability of colliding, but then their fragments would need to be ejected by a giant planet or a companion star rapidly, before a collisional cascade could obliterate non-compact shapes. This scenario is rather contradictory and unlikely to produce more interstellar bodies than ejection of more conventional collisional fragments.

Interestingly, 'Oumuamua is at or just below the size threshold at which asteroid material strength starts dominating over gravity (O'Brien & Greenberg 2003). It is tempting to speculate that if a larger body's gravity would somehow be neutralized, it may dissociate itself into fragments the size of 'Oumuamua (if other conditions are met). Gravity, of course,

cannot be "turned off," but gravitationally bound bodies can be torn apart by a variety of mechanisms, a prominent one being tidal forces. Comet Shoemaker–Levy 9 was dramatically tidally disrupted by Jupiter before its collision with the planet (Asphaug & Benz 1996). It is fully possible that some of the comets that were ejected by Jupiter may have first been tidally disrupted. However, tidal disruption in the solar system is limited by the restricted density ranges of planets and small bodies. Jupiter's density of  $1.3 \text{ g cc}^{-1}$  means that a comet must approach very closely (within a couple radii) to the planet in order to be disrupted, limiting the efficiency of the process (Jeffreys 1947; Holsapple & Michel 2008). Also, most tidal disruptions of rubble piles are marginal, with the pieces reaccreting into one or more new rubble piles afterward (Walsh & Richardson 2006).

In the previous section, I proposed that stellar companions are expected to be major producers of interstellar small bodies in the Galaxy. A solar type star has a density comparable to that of Jupiter, so tidal disruptions are unlikely to be very common during ejections. However, M-type main-sequence stars are significantly denser than the Sun, with M0V stars being 3 times, M5V stars being 20 times, and M9V stars being 150 times more dense than the Sun (Kaltenegger & Traub 2009). Such densities make it possible for these low-mass stars to tidally disrupt not only under-dense rubble piles, but also planet-sized bodies. An Earth-like planet passing close enough to an M-type dwarf would be completely torn apart, with only material cohesion on sizes comparable to that of 'Oumuamua being able to resist the star's tides. In addition, sizable planets would also suffer decompression during tidal encounters, which would help disperse the fragments during this event (Asphaug et al. 2006). Interior material would be exposed to a vacuum, which could lead to rapid solidification and other strange effects. Even if the planet was not volatile poor, atmosphere and volatile-rich layers may not survive the event, both due to tidal forces and stellar irradiation (however brief). Anisotropic forces acting to shape fragments may produce elongated bodies like 'Oumuamua, and with moderate rotation rates as observed for 'Oumuamua, in contrast to monoliths produced in collisions.

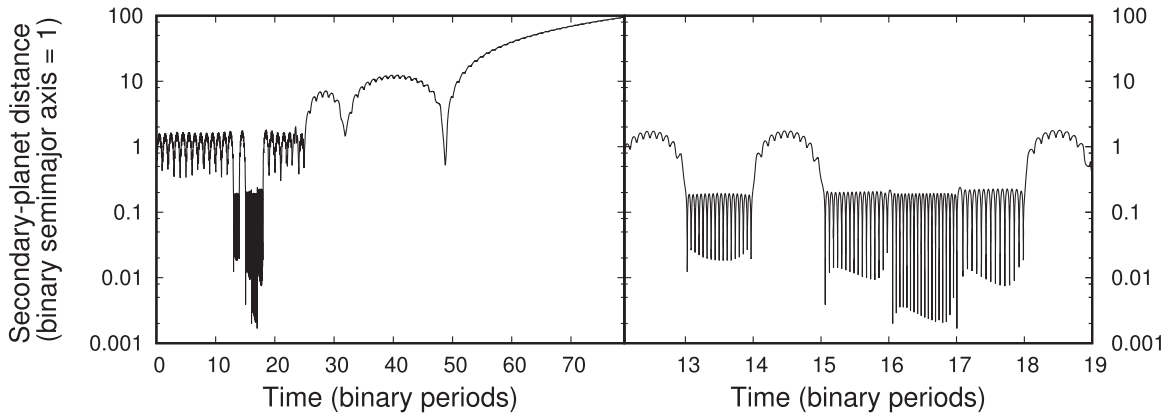
#### 4. Numerical Test

After the original manuscript of this Letter was submitted (and a preprint made public), Jackson et al. (2017) published numerical simulations of planetesimal scattering in binary systems. Jackson et al. (2017) state that their simulations did not find any cases where a planet would be tidally disrupted by a close stellar passage before being ejected, indicating that such disruptions are very rare. In this section, I will address the claims of Jackson et al. (2017) with the help of a simple numerical simulation.

Figure 1 shows a numerical simulation of a binary system, with a planet initially orbiting the more massive component. The stellar mass ratio is 2:1, the planet is treated as massless, the ratio of binary and planetary semimajor axis is 6:1, both eccentricities are 0.5, while the planet's orbit is inclined by  $10^\circ$ . Initially, both the planet and secondary are at their periastra (which are aligned), and the planet is also at its ascending node. The simulation was done using the IAS15 algorithm (Rein & Spiegel 2015) within the REBOUND integration package (Rein & Liu 2012). Figure 1 plots the distance between the planet and the smaller component. At first, the planet orbits the larger star

<sup>2</sup> Michele Bannister, 11/21/17, Twitter.





**Figure 1.** Simulation of a binary star system with a planet initially orbiting the primary, done using REBOUND’s IAS15 algorithm. The planet initially orbits the larger star, but then gets temporarily captured into orbiting around the smaller star during binary orbits 13–14 and 15–18 (enlarged in the right-hand panel). The minimum separation between the planet from the smaller star is  $1.7 \times 10^{-3}$  of the binary semimajor axis. Around the fiftieth binary period the planet is ejected from the system.

(for most of  $0 < t < 25$ ), occasionally it orbits the smaller star ( $13 < t < 14$  and  $15 < t < 18$ ), then the planet orbits both stars on a large orbit ( $25 < t < 50$ ), and finally the planet is unbound ( $t > 50$ ).

While the planet is orbiting the less massive star, mutual distance is at one point only  $1.7 \times 10^{-3}$  of the binary’s semimajor axis. A similar “temporary capture” has happened to comet Shoemaker–Levy 9 before its tidal disruption and impact on Jupiter (Kary & Dones 1996), and was likely important during the capture of Jupiter’s irregular satellites (Ćuk & Burns 2004). Temporary capture typically begins and ends when the stars are at periastron, so the less massive star’s Hill sphere is at its smallest. Figure 1 shows that the most eccentric temporary capture orbits (and the closest approaches to the smaller star) occur during entrance into and exit from temporary capture.

Our simulation results are unit-independent and can be applied to a range of binary masses and separations. If the binary semimajor axis is set to 1 au, then the closest approach of the planet to the secondary would be  $2.5 \times 10^5$  km, or  $0.36 R_{\text{Sun}}$ . This distance results in a collision for main-sequence stars of the spectral type M4 (with  $\approx 0.5 M_{\text{Sun}}$ ) and earlier. For later type M dwarfs, the collision is avoided, but the tides would totally destroy any plausible planet. The least massive main-sequence star, a  $0.075 M_{\text{Sun}}$  M9 dwarf, would be able to tidally disrupt a fluid non-rotating planet with a density of  $30 \text{ g cc}^{-1}$  (Harris 1996), and the tides from M5V–M8V stars would be even stronger.

The simulation shown in Figure 1 was literally the first simulation I attempted of an instability with a planet starting on a S-type orbit (orbiting one of the stars; nomenclature from Holman & Wiegert 1999). Jackson et al. (2017) in contrast integrated only P-type orbits, where their particles initially orbited both stars. I also did a quick test of planets initially on P-type orbits, and obtained results consistent with those of Jackson et al. (2017), as the planet never comes very close to either of the stars before being ejected. Therefore, results of Jackson et al. (2017) show that tidal disruption is unlikely only for initially P-type planetary orbits, but have no relevance for S-type orbits, which appear to hold much more potential for tidal disruption.

Note that the planet (or several, since an instability is required to couple the planet to the binary companion) would need to form within 20% of binary periastron distance

(Quintana et al. 2007), or 0.1 of binary semimajor axis in this case. Almost half of the red dwarfs are thought to have super-Earth’s in their habitable zones (Bonfils et al. 2013), and the habitable zone of 0.1 au corresponds to a M4V star (Kaltenegger & Traub 2009), so a binary separation of 1 au is not in conflict with planets forming close to the primary. For larger stellar separation, optimal size of the disrupting star would move to somewhat larger masses.

## 5. Discussion and Conclusions

Here I am proposing that ‘Oumuamua is a part of the dominant population of 100 m interstellar objects that were generated in tidal disruptions of solid planets by M-dwarfs in binary systems. Many of the resulting fragments should be of size when material forces become more important than gravity, that is hundreds of meters. Fragments would generally be volatile poor, and their shapes may be quite irregular, possibly elongated. Unless the original planet was a bound companion of the red dwarf, the fragments would almost certainly be ejected from the system, likely without any significant collisional evolution.

This is a somewhat exotic way of producing small bodies, quite different from our experience based on the solar system. However, ‘Oumuamua is clearly suggesting that the range of processes operating on 100 m bodies in the Galaxy extends beyond those we are familiar with. First of all, it is very likely that binary stars are very important contributors to the population of interstellar asteroids, as stars are naturally more powerful scatterers than the planets. Second, if occasional extreme events are able to produce large numbers of 100 m fragments, such bodies may overwhelm the population of collisionally produced comets and asteroids that are ejected individually by either planets of binary companions.

How common are objects like ‘Oumuamua? Published estimates of their number density based on one detection include  $10^{15} \text{ pc}^{-3}$  (Meech et al. 2017; Portegies Zwart et al. 2017) and  $10^{16} \text{ pc}^{-3}$  (Trilling et al. 2017). Since there is no more than one star per cubic parsec in the Galactic disk (Portegies Zwart et al. 2017), this would mean that there are at least  $10^{15}$  ‘Oumuamuas for each star in the disk. If we assume an albedo of 0.2 and therefore dimensions of  $180 \times 18 \times 18$  meters, equivalent volume sphere radius is about 40 meters (5:1 aspect ratio does not change that). A total of  $10^{15}$  such objects, with a density of  $3 \text{ g cc}^{-1}$  would have a mass comparable to that of

Mars ( $0.1M_{\text{Earth}}$ ). On the other hand, if the solar system ejected approximately  $10 M_{\text{Earth}}$  of 100 km icy planetesimals (Nesvorný & Vokrouhlický 2016), and the overall cumulative size distribution of TNOs below 100 km is proportional to  $D^{-2}$  (Bierhaus & Dones 2015; Greenstreet et al. 2015; Robbins et al. 2017), then I estimate that approximately  $0.01 M_{\text{Earth}}$  of 100 m bodies were ejected by the planets from our solar system. Therefore, if the Sun is typical, mass in ‘Oumuamua-like objects may be 10 times larger than in interstellar comets of the same size (the number ratio is a factor of a few closer due to lower cometary densities). Actually, the average stellar rate of cometary ejections may be below solar, as comets are easier to detect than asteroids like ‘Oumuamua (Engelhardt et al. 2017; Meech et al. 2017).

A Mars-mass of ‘Oumuamuas ejected from every system seems rather excessive, especially given that this is the low end of available estimates of the number of ‘Oumuamuas. Not every star is a binary, and not all binaries include a dense M-dwarf. Therefore, I speculate that a smaller number of larger events generates the observed population. So the kind of “typical” disruption I am envisioning is that in every hundredth solar system, a  $10M_{\text{Earth}}$  super-Earth has a close encounter with a dense late M-dwarf and is tidally disrupted into 100 m strength-dominated fragments with a relatively high efficiency, and that these fragments are then ejected from the system. M-dwarfs are the most common stars, while we have recently learned that possibly as many as half of the stars have super-Earths (Buchhave et al. 2012), so an occasional event of this type would not be extraordinary.

The present hypothesis is based on the assumption that ‘Oumuamua is not a fluke but a typical representative of interstellar asteroids. If future discoveries look more like solar system comets or small asteroids, the need for this exotic formation mechanism becomes less pressing. But if new discoveries are likewise monolithic fragments with unusual shapes, defying the expectations based on collisional evolution, this idea may warrant a closer look, with in-depth modeling of binary system dynamics and tidal disruptions being needed before we can determine if this hypothesis is tenable.

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