‘Oumuamua: An Unexpected Solar System Visitor

Abstract

I discuss the observed properties for the first detected interstellar object 1I/2017 U1 ‘Oumuamua, focusing on the properties which are unusual such as its tumbling motion and high eccentricity compared to our solar system, and their implications for the objects past. I look at possible ejection mechanisms that could’ve liberated ‘Oumuamua from its parent system; given its large size and tumbling motion, I conclude the ‘Oumuamua most likely was ejected from a debris field around another star outside of the solar neighbourhood, by an encounter with a giant planet or another star. By using Gaia data, the orbit of ‘Oumuamua and other stars are integrated backwards in time to find progenitor candidates. Close encounters with four stars are found, but these have not been observed to be binary systems or to have giant planets, and so no clear parent system is concluded.

1 Introduction

1I/2017 U1 ‘Oumuamua (‘Oumuamua hereafter), is the first confirmed object that originated from outside our solar system, after it was recently detected by the Pan-STARRS team on 19th October 2017 (1). Observations of ‘Oumuamua are extremely useful in their capacity to tell us about the composition of rocks in other systems and give clues as to the abundance of material that is ejected from other stellar systems. The most interesting properties of ‘Oumuamua are firstly, its eccentricity e=1.20113 ± 0.00002 and its relative velocity of $v_{\square}$=26.32 ± 0.01 km s^{-1} (2), and its non-repeating light curve implies tumbling motion with possible frequencies of 0.26, 0.23, 0.16, 0.14, 0.12, 0.10 and 0.009 h^{-1} (3) and an elongated shape with a ratio of more than 5:1 (4). It has shown no clear cometary activity (5), and its spectrum is similar to that of D-type or L-type asteroids found in our own solar system (6). To investigate the possible origins of Oumuamua, the expected properties and densities of interstellar objects (ISOs) for different ejection mechanisms will be compared to the observations of Oumuamua to determine the likelihood of each. I will explore research into finding a parent star for Oumuamua, in which the linear motion approximation is used to model the orbits of ‘Oumuamua as well as stars backwards in time to find previous encounters.

2 Properties

2.1 Interstellar Object

The orbit of Oumuamua has a large inclination at 122.7° (4), and an eccentricity of 1.20113 ± 0.00002 (Figure 1) (2); it has the highest eccentricity found for an asteroid. This eccentricity is at 100σ for asteroids in our solar system (7), and so it’s very likely to have originated outside of our solar system. The object was found to be moving 6.2° per day (1), and the heliocentric velocity was calculated as $v_{\square}$=(-11.2, -22.4, -7.6) km s^{-1} in right-handed galactic coordinates (1), which is very close to the average motion of stars in the solar neighbourhood (8). This is further evidence of ‘Oumuamua’s interstellar origins.

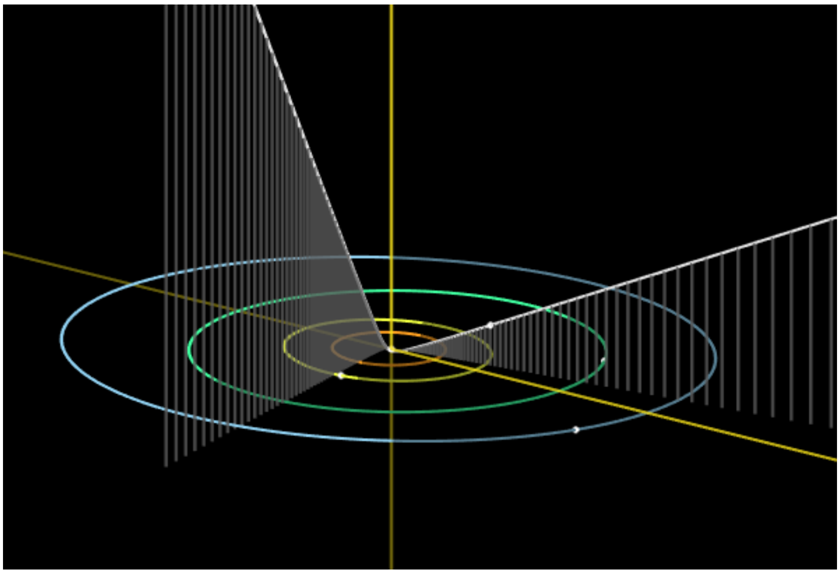

Figure 1-‘Oumuamua's trajectory through the solar system

2.2 Colour

The colour of ‘Oumuamua was determined by measuring its magnitude through various filters to construct a photometry, from which we can calculate its spectral slope which tells us how efficiently the object reflects different wavelengths. For example, ‘Oumuamua was observed from the Gemini North telescope using three filters: r’ with λ=6300 Å ($\delta\lambda$=1360 Å), g’ with λ=4750 Å ($\delta\lambda$=1540 Å), and J with λ=12500 Å (Coverage of λ=11500-13300 Å). The results are given in Figure 2 (4); this corresponds to a spectral slope of 22 ± 15%. This is consistent with other results that include 23 ± 3% (1). This means the object reflects longer wavelengths more efficiently, and so ‘Oumuamua appears a red colour. As ‘Oumuamua is tumbling on a timescale similar to the exposure time, there will be some variability in its brightness as its effective area changes, in turn impacting the measured magnitude. Using the techniques designed for the Colours of the Outer Solar System Origins Survey, repeated measurements are made in each wavelength band to determine if the brightness variations are due to albedo changes or due to the light curve. A correction can then be made to the measurements to get the true magnitudes.

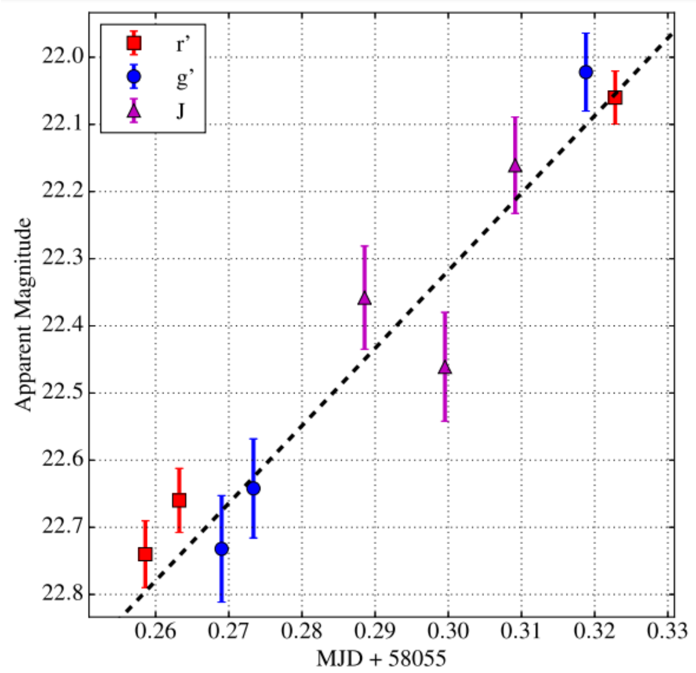

Figure 2-Photometry of ‘Oumuamua captured using the Gemini North Telescope, using r', g' and J filters

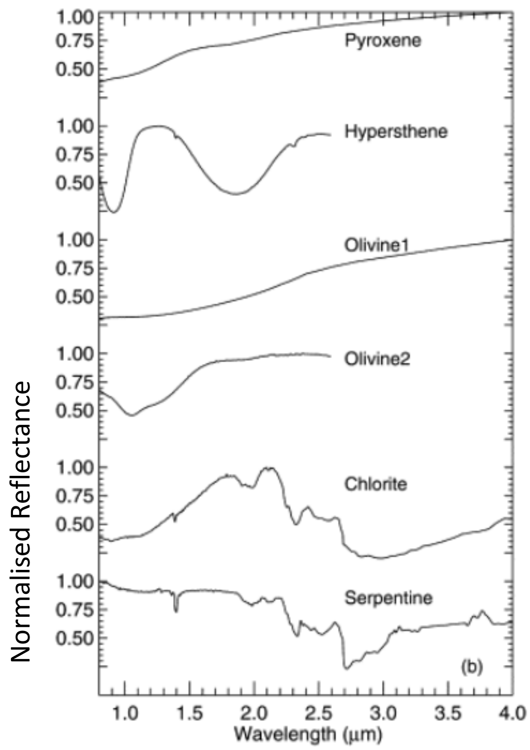

Figure 3-Normalised reflectance of different silicates at various wavelengths

The red colour of ‘Oumuamua is similar to that of D-type asteroids observed in our own solar system. Analysis of the spectra of nearby asteroids suggests a large amount of organics such as tholins (9), formed by the dissociation of molecular nitrogen and methane in the interstellar medium due to solar radiation (10), are a potential cause of the characteristic red colour which the asteroids exhibit. Another theory is the presence of hydrous and anhydrous silicates like olivine in the surface of the asteroid, as these show a higher reflectance at larger wavelengths (Figure 3) (9). These would’ve been present during the formation of ‘Oumuamua’s parent system, by analogy with our own solar system (11), and so these could be present on ‘Oumuamua. These are likely origins for ‘Oumuamua’s red colour, if it’s parent system is assumed to be similar to our system, which is a justifiable assumption given that extra-solar system circumstellar discs are similar to ours (12).

2.3 Shape and Size

’Oumuamua has a measured absolute magnitude of M=22.08 ± 0.45 mag (2), which gives a rough size < 200 m if one assumes it has a reflectivity similar to that of carbonaceous asteroids in our solar system, which have albedos in the range 0.06-0.08 (4). During observations, the brightness varies systematically on the timescale of the observations (4), which can either be due to albedo changes across the surface, or because of a unique shape. The measured magnitude changes are consistent between different filters (4), which imply the changes are due to a unique shape, for albedo changes would affect different wavelengths of light to different degrees (13). There have been multiple light curves generated for ‘Oumuamua, one of which is shown in Figure 4 (1). Using the difference between the maximum magnitude to minimum magnitude we can get an estimate of the ratio of the lengths of ‘Oumuamua. Using the example below, the variation in magnitude is Δm=2.5 mag, which gives a ratio of 10:1, so ‘Oumuamua is extremely elongated. Other light curves have been generated which give different values for the ratio, including 5.3:1 (4) and 3:1 (14). If one takes a rotation period of 8.1 hr and a length ratio of 5.3:1, the internal density required to prevent the outer layers being shed is 5.9 g cm^{-3} (4), which is much higher than the density expected for an comet with ice and silicates (15), suggesting ‘Oumuamua is rocky. ‘Oumuamua could also be contact or quasi-contact body, consisting of two smaller connected bodies with their long axes aligned (16) to give the elongated shape. However, if we take a larger ratio between the lengths, a contact binary becomes less likely as the densities required become unreasonable (1).

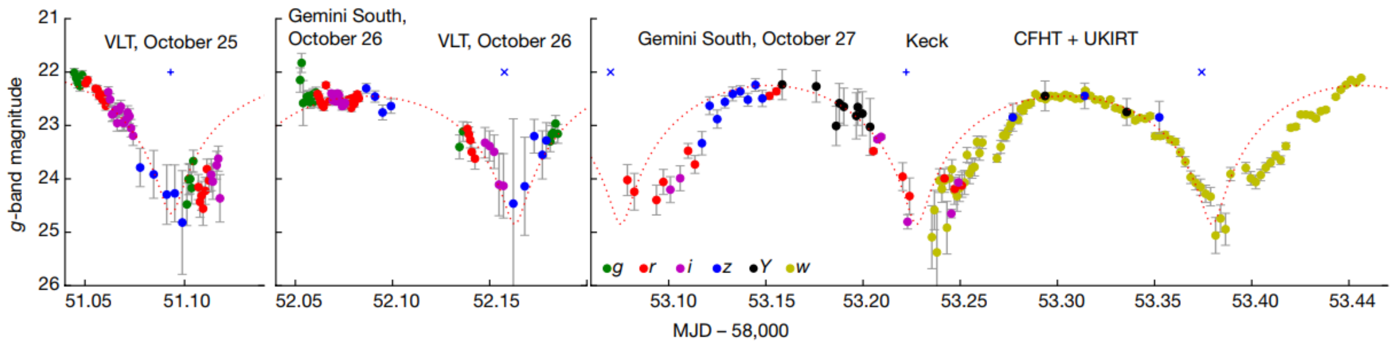

Figure 4-The light curve of ‘Oumuamua in the g band captured using different telescopes. The red line is a fitted light curve assuming a 7.34 hr period and 10:1:1 length ratio

However, there are potential errors in these measurements. The lightcurve can appear brighter if the object is observed at non-zero phase angles, for carbonaceous asteroids (which ‘Oumuamua is assumed to be), the lightcurve can appear 0.018 mag/degree brighter (17). For the above data, ‘Oumuamua was observed at a phase angle α=20° (3), and so the lightcurves was brightened by roughly 0.36 mag, which means the true ratio may be closer to 5:1. The brightening effect is dependent upon the albedo and surface topography, and so without a better understanding of ‘Oumuamua’s surface properties, it is not possible to conclusively determine how large an effect this is, and to correct for it.

2.4 Tumbling Motion

Through observations of its light curve (Figure 5) (3), ‘Oumuamua was found to be rotating around a non-principal axis with free precession, in a tumbling motion. The light curve has extended variations in magnitude which do not have a constant, clear frequency, and so no single frequency can accurately describe its light curve, as the oscillations do not repeat exactly. The light curve varies between rotation cycles significantly, which is clear from the large variation in period estimates between academic papers, including 8.26 hr (18) and 7.34 hr (1). Using a model for light curves (19), a two dimensional, second-order Fourier transform was used to model the light curve, and then various frequencies were scanned through in order to find ones which matched the data from ‘Oumuamua. Unfortunately, there are missing areas in the light curve as ‘Oumuamua is difficult to observe, meaning there are multiple frequencies of tumbling which can fit the data, including 0.26, 0.23, 0.16, 0.14, 0.12, 0.10 and 0.009 h^{-1} (3). The gaps in the data are from the Asian and Australian longitudes, so if future telescopes capable of observing planetesimals are built here, it will be possible to further constrain the frequency. Also, there are relatively few data points, which means it is only possible to use a second-order Fourier transform when modelling the light curve. With more observations using available telescopes, it would be possible to use a third-order Fourier transform, which would improve how well the model fits the data in the areas where it under or over estimates the magnitude.

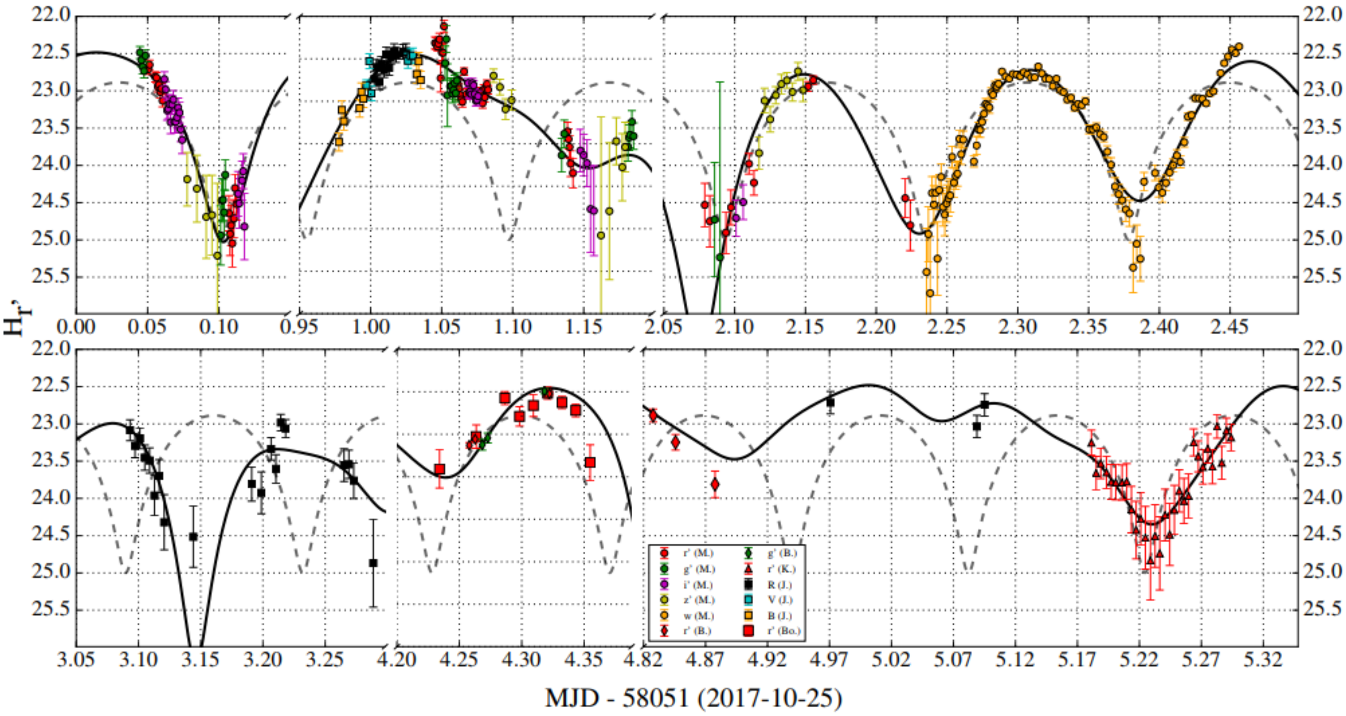

Figure 5-A light curve of ‘Oumuamua in the r band. The dashed line is the light curve assuming a period of 6.831 hr. The solid line is a light curve with tumbling motion

Over time we would expect to the tumbling motion to dampen, and the object to revert to spinning motion around the principal axis of motion with the highest moment of inertia. This is due to energy loss from internal friction, the bending stress due to torque, and the strain from the movement of the centrifugal bulge (20). Using the accepted values of the shape and size of ‘Oumuamua, and assuming a rigid, organic body, the characteristic damping time for the tumbling is 4×10^{11} to 4×10^{12} (3), which doesn’t constrain the possible origins as this is longer than the age of the universe (21).

There are multiple theories on how the tumbling motion could have started. One notable theory is the Yarkovsky-O’Keefe-Radzievskii-Paddack effect (22), where light from nearby stars is absorbed and reemitted, along with thermal radiation, causing a momentum change as photons are released, giving a torque. This scales with flux and time, and so whilst a possible contributor, it isn’t likely to be most effective process here due to the small size and time scale. Another possibility is cometary activity (23), as the release of volatiles and water changes the mass distribution within the comet, changing its rotation. ‘Oumuamua hasn’t shown any signs of cometary activity (1), so again this is unlikely to be significant. It could’ve also started tumbling due to collisions with other objects: the density of objects similar in size to ‘Oumuamua or larger is estimated at 0.1 au^{-3} (24), with an encounter velocity of 25 km s^{-1}, this gives an expected time of 10^{19} years between collisions. Therefore, the tumbling is most likely due to tidal forces from planetary encounters (25) on its journey before it reached our solar system.

2.5 Asteroid or Comet

Although the most popular interpretation of the data is that ‘Oumuamua is an asteroid, the data, however, may also be consistent with a comet that has subsurface ice. Statistically we expect ‘Oumuamua to be an icy object, as current models predict ISOs should be dominated by ice-rich bodies. Planet formation can expel a large amount of small bodies, and this takes place primarily around the snow line of an emerging solar system (26), so we would expect the ejected bodies to be primarily icy. ISOs can also be ejected from collections of objects analogous to the Oort cloud in other systems as they are perturbed by interactions with large objects or tidal forces. An estimated 10% of objects in the Oort cloud have been ejected due to interactions with passing stars (27), and dynamical models such as the Grand Tack model predict a comet/rocky asteroid ration of 500:1 to 1000:1 (28), so it’s overwhelmingly likely that ‘Oumuamua is icy. However, in response to solar heating, volatile species are released from the core of a comet, which then undergo photochemical reactions to give radicals such as OH, NH, C_2, and NH_2. Comets with active surfaces should have strong emission bands at 0.38 µm and 0.52 µm due to electronic transitions in CN and C_2 (29). These bands are not seen in the spectrum of ‘Oumuamua (Figure 6) (6), suggesting the surface is not active. We would also expect to see absorption band at 1.5µm due to the presence of water ice. This is present in some trans-Neptunian objects, but is not present in ‘Oumuamua (Figure 0) (6). As a comet moves close to the sun, the water inside sublimates due to the heat to give a coma, which we see as a trail behind the comet in any images, however this is absent in the images of ‘Oumuamua (Figure 7) (1). Using a plot of flux against distance from the centre of the image of ‘Oumuamua (Figure 8) (1), we obtain a maximum for the magnitude of the coma of g > 25.8 mag, which corresponds to a mass loss of 1.7 x 10^{-3} kg s^{-1}. This is around 6 orders of magnitude less than the mass loss measured for other similar comets at perihelion (30), so if there is any ice sublimating on the surface, it is of a negligible quantity.

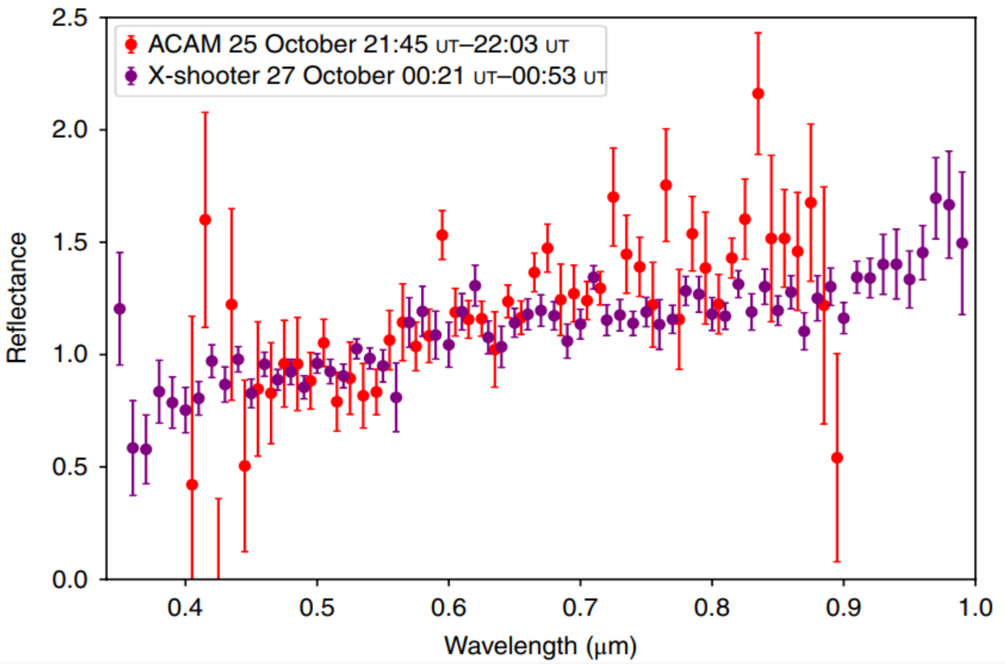

Figure 6-Optical reflectance spectrum of ‘Oumuamua, obtained using the WHT and VLT telescopes

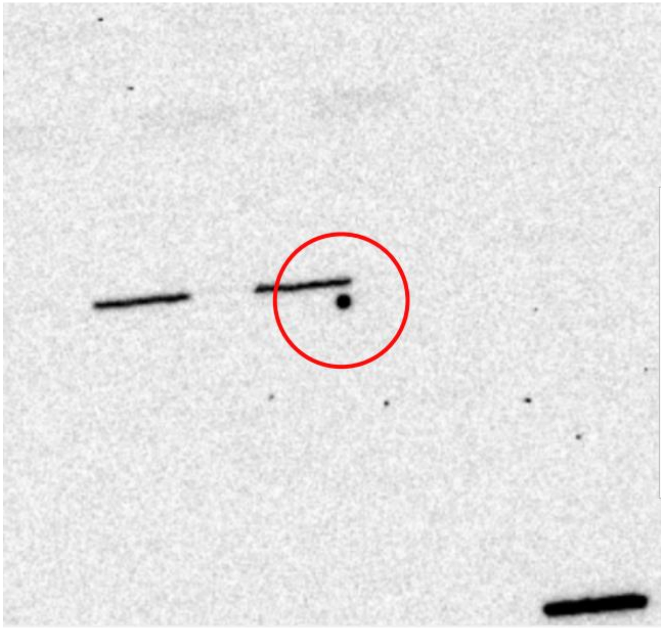

Figure 7-Image of 'Oumuamua taken with the CFHT telescope

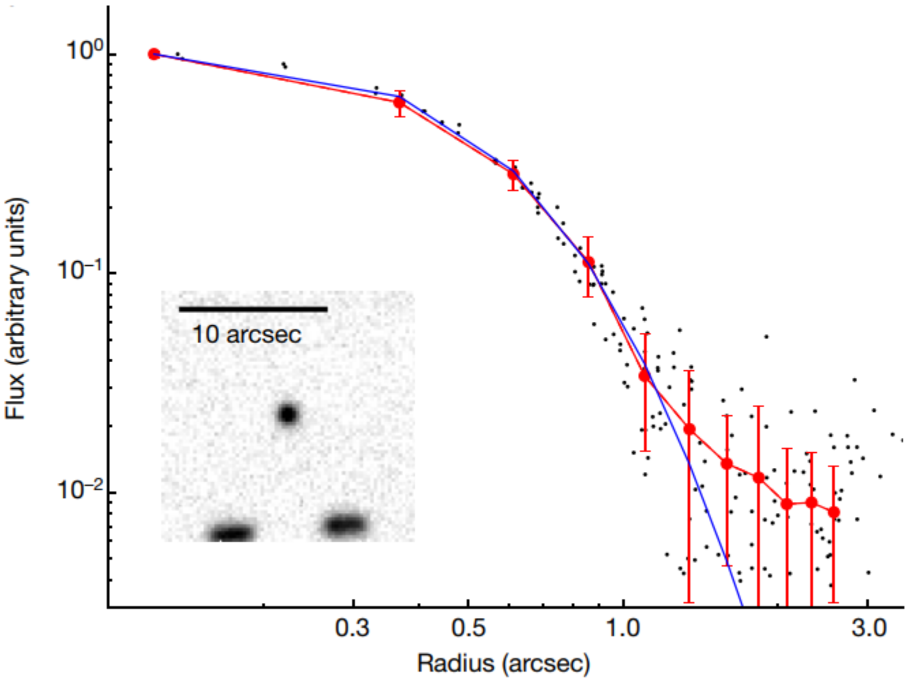

Figure 8-A plot of flux vs radius from the centre of 'Oumuamua. The red dots are the flux through an annulus at each radius, and the blue line shows a Moffat distribution with FWHM=0.87''

These omissions could be explained by subsurface ice in 'Oumuamua, underneath a devolatilised shell. Under prolonged exposure to cosmic rays, the rays can penetrate the outer layers of the comet, breaking down the chemical bonds in the volatile molecules, giving an inactive shell (31). The hydrogen molecules are small enough to escape, so the resulting mantle is carbon and oxygen rich. For an object with density 10^3 kg m^{-3}, the cosmic rays can penetrate 1m into the comet, so these comets can have a shell which is 1m thick (32). By solving the one-dimensional heat conduction equation and assuming a blackbody, the temperature and depth relationship can be modelled as 'Oumuamua approaches perihelion around the Sun (Figure 9) (6). This shows that below 40cm depth, any water in the core of 'Oumuamua would not sublimate, which could explain why we do not see a coma or any other surface activity. However, there is a significant problem with this theory: there are comets in our solar system from the Oort cloud which have had prolonged exposure to cosmic rays, yet they still show sublimation with cometary tails when they reach perihelion, so a devolatilised outer shell does not fit with our other observations. Other explanations are that 'Oumuamua underwent sublimation in the system in which it was formed, and all the water was removed before it was ejected, or due to its small size the water may have been able to escape after the object was formed. This theory can be tested using the Large Synoptic Survey Telescope when it opens in 2020, which will be able to detect smaller planetesimals in the solar system (33). We would expect the telescope to be able to detect ISOs like ‘Oumuamua, and confirmed observations of other devolatilised comets would give strong support to this theory.

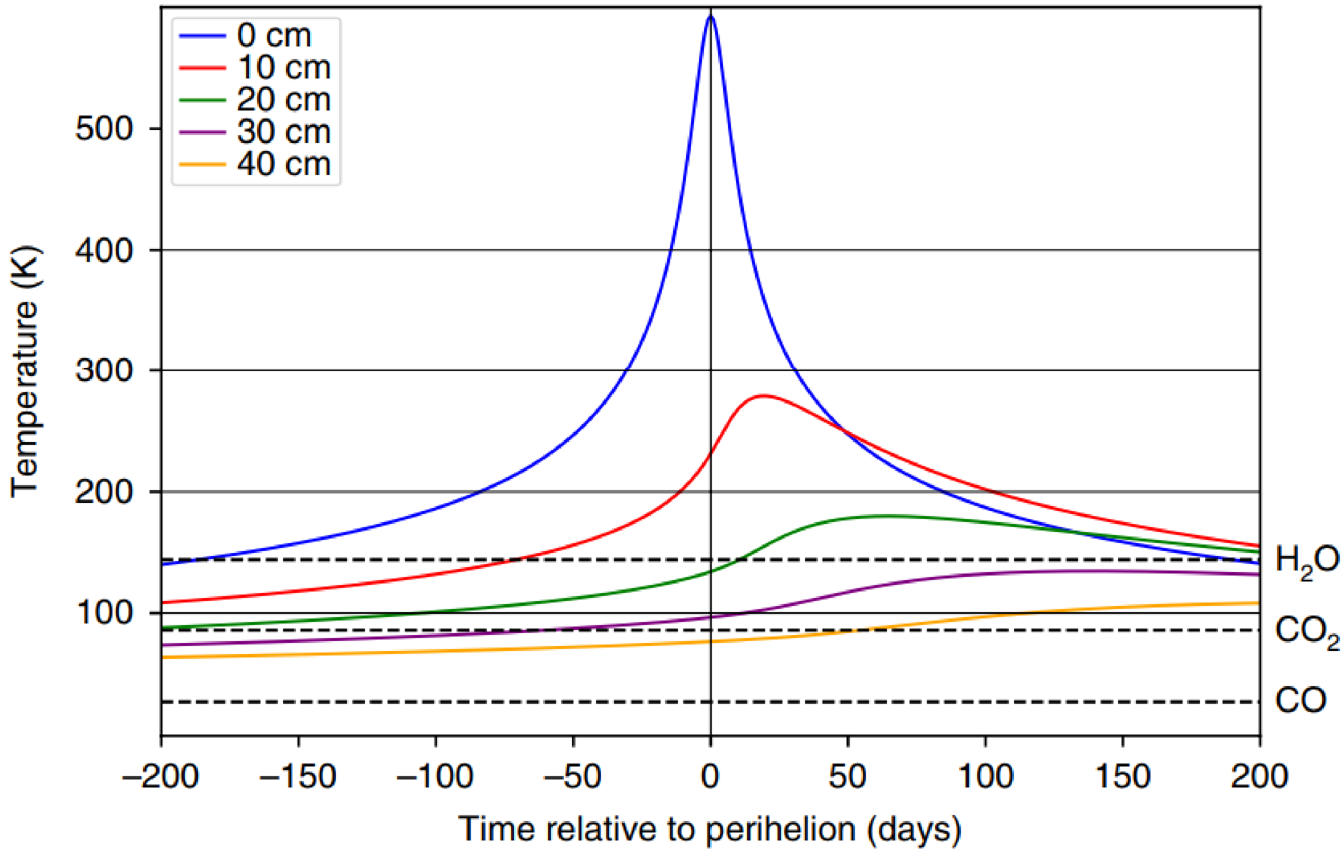

Figure 9-Model of temperature against depth inside ‘Oumuamua, relative to perihelion

Depending on the composition and mineralogy of an asteroid, we would expect some clear absorption features in the spectrum. Asteroids often contain sheet phyllosilicates like chlorite or serpentine, which give absorption bands at 0.7 µm (34), and minerals like olivine and pyroxine give a band at 0.95 µm (35). We don’t see these features in the spectrum of ‘Oumuamua, so there isn’t clear evidence in its spectrum that ‘Oumuamua is rocky. However, there is often a wide disparity between the theoretical spectral features and the measured results due to the difficulty of recreating the effects of long term exposure to the space environment, with repeated heating cycles and loss of material, in a lab (36), so these results are not inconsistent with a rocky ‘Oumuamua. These peaks can also be shallow (34), and so they may not be visible due to the noise in the data. Apart from the absence of some spectral features, the spectrum of ‘Oumuamua lines up roughly with the types of asteroid found in our solar system (Figure 10) (6). L-type asteroids only have small amounts of silicates, which may explain why we don’t see the bands for these in the ‘Oumuamua spectrum, they also have a flattened spectrum above roughly 1µm (Figure 11) (37), but the data is too noisy to see this. More accurate observations at larger wavelengths would help to identify this feature if it is present. The spectrum is also close to that of D-type asteroids, though these normally have a strong slope up to 2 µm (38). The spectrum for ‘Oumuamua appears to flatten out at 1 µm, though this is still possible for a D-type asteroid.

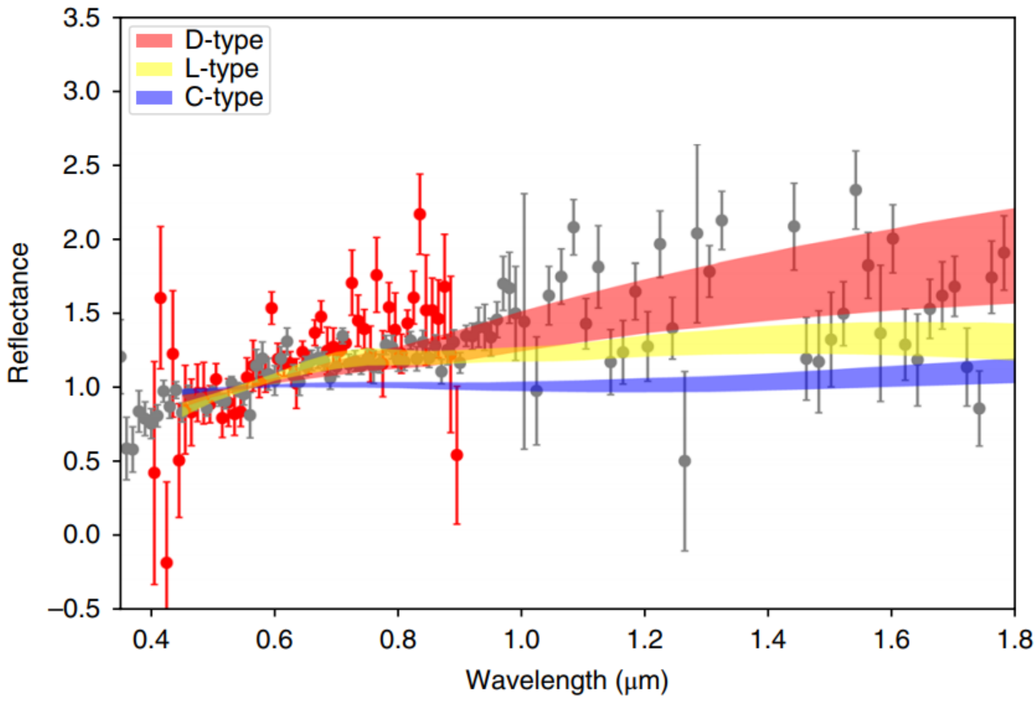

Figure 10-The reflectance of 'Oumuamua at different wavelengths compared to the types of asteroids in our solar system

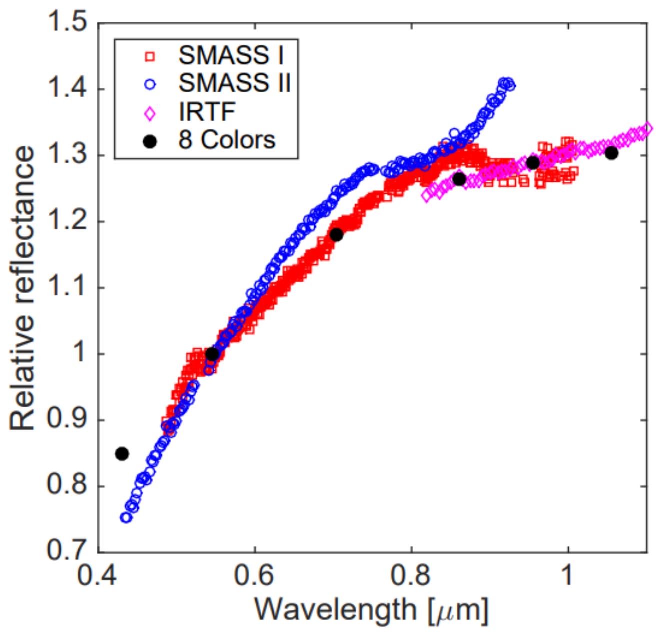

Figure 11-Spectrum of a typical L-type asteroid

3 Possible Origins of 'Oumuamua

3.1 The Oort Cloud

The Oort Cloud is a collection of mostly icy objects, located between 1,000 and 100,000 AU from the centre of the solar system, which is the source for the long period comets visible in our solar system (39). They are normally emitted after strong interactions with stars (40) or Jupiter-sized planets (41). It is possible 'Oumuamua is one of the long period comets emitted from the Oort Cloud. In order to achieve the high velocities seen for 'Oumuamua, we would expect it to be part of a binary system in the Oort cloud with another rocky object (42). Where an encounter with a planet or star causes 'Oumuamua to be ejected at a high speed. This is consistent with our Oort cloud, as an estimated 30% of objects in the Kuiper belt found in binary pairs (43). If the binary system has an encounter with a planet ten times that Jupiter, we would expect the lightest object in the binary to be ejected a velocity of 0.13 km s^{-1} (44), which would be enough to perturb the object into an unbound orbit like 'Oumuamua's, if the original circular orbit was 10^3-10^4 AU away from the Sun. Through computer simulations, Oort cloud objects can be modelled and placed in orbit around the Sun, before being given instantaneous velocity change from a Gaussian distribution with a dispersion of the expected 13 km s^{-1} in each cartesian direction. The results showed that this model was able to replicate the eccentricity of ‘Oumuamua’s orbit, with the 15% of objects which became unbound having an average eccentricity of 1.2 (44), however they were not able to replicate ‘Oumuamua’s trajectory. Less than a thousandth of these objects passed within 100 AU of the Sun, and it would be very unlikely for ‘Oumuamua to be one of these objects, as ‘Oumuamua had a closest approach of 0.25 AU (1).

Another problem with this theory is the tumbling motion of ‘Oumuamua, the cause of which was most likely a collision with another object. The number density of objects in the Oort cloud is an estimated 1.91 x 10^{-3} AU^{-3} (45), and so the odds of collision as ‘Oumuamua moves through are very low. Also, the trajectory of ‘Oumuamua is such that it missed the Kuiper belt and other areas of higher density (2), which again makes a collision less likely. The most probable solution is that the tumbling motion is due to a collision in ‘Oumuamua’s parent system.

3.2 An Exo-Oort Cloud

By analogy with our own solar system, we could expect other stars in the universe to have a collection of icy objects similar to the Oort Cloud (46), and it’s possible ‘Oumuamua was ejected from one of these clouds. The easiest way to test this theory is to model how many of these ISOs we expect to have measured and compare that with what the observation of ‘Oumuamua implies. Using the data of the Pan-STAARS telescope (47), and ‘Oumuamua (2), we get an estimate for the number density of between 3.5 x 10^{13} and 2.1 x 10^{15} pc^{-3} (44), where the large uncertainty comes from the fact ‘Oumuamua is the only confirmed observation of an ISO. This assumes objects like ‘Oumuamua are distributed isotropically, and that the detection rate of Pan-STARRS is 100%. We estimate the density of objects from other Oort clouds using: (44)

$$n_{comets} = \mu n_{stars} N_{comets}$$

We assume that every star has a cloud of objects like the Oort Cloud with $N_{comets}=10^{11}$ objects (48). We take a maximum stellar mass density of $\rho_{stars}=0.13\ M_{\odot}\ pc^{-3}$ (49), and an average stellar mass of 0.37 $M_{\odot}$ (50), we get a stellar density of $n_{stars}=0.35\ pc^{-3}$. The ejection efficiency is estimated to be 0.1 Gyr^{-1} at most (51), and an upper estimate of stellar age is 10 Gyr (52) given that the universe is 13.8 Gyr old, which gives $\mu=1$. This gives an estimate of $n_{comets}=3.5 \times 10^{10}\ pc^{-3}$, which is much less than the density inferred from the observation of ‘Oumuamua, and so this is an unlikely solution for ‘Oumuamua’s origin. A more detailed modelling of this system (53) finds that ejections from exo-Oort clouds are dominated by mass loss of stars in post-main sequence stars with masses in the range 1-8 $M_{\odot}$, and encounters with main sequence stars in the range 0.08-8 $M_{\odot}$. However, due to the inefficiencies in actually ejecting objects from these Oort Clouds, this still can’t account for the ISO density inferred from ‘Oumuamua.

The theory of an Oort Cloud or exo-Oort Cloud origin is also inconsistent with our current observations of ‘Oumuamua (53). A large majority of objects observed in the Oort are icy (54), but ‘Oumuamua shows no signs of cometary activity as it approached perihelion (1). It would be unlikely that the first ISO from an exo-Oort cloud would be rocky given that the vast majority of objects are icy. The object most likely will not have had enough exposure to cosmic rays to form the mantle described above (6), unless there is some additional drying mechanism which we have not yet discovered. This problem could be alleviated if observations of the Oort Cloud or other ISOs by the Large Synoptic Survey Telescope find rockier objects to be more common that currently thought, which could be plausible as rocky objects are harder to detect due to the lack of cometary activity. Another theory would be supernovae, which would remove volatiles from distant Oort Cloud objects without disrupting them, but these are very rare (55).

3.3 A Protoplanetary Disk

During the early stages of a solar system, discs of small dust particles and grains form around stars. These eventually begin to fall inwards as they lose angular momentum, and through collisions begin to aggregate and form the basis for planets (56). During this process large amounts of material can be ejected as smaller objects are perturbed to escape velocity, with an estimated 300 $M_{\Box}$ being ejected from our solar system during its formation (57). ‘Oumuamua could be a fragment ejected from a protoplanetary disc around another star (58). Again, we can get a rough estimate of the number density of ISOs we should see if this is the origin of ‘Oumuamua using: (44)

$$\rho_{ejection} = f_{ejected} Z \rho_{stars} M_{disc}$$

Using the approximations from before, a metallicity of Z=0.02 (59) assuming the parent system is similar to our own, a $M_{disc}=0.01\ M_{\odot}$ (60), and a fraction of mass ejected $f_{ejected}=0.1$ (61), this gives $\rho_{ejection}=2.6 \times 10^{-6}\ M_{\odot}\ pc^{-3}$. Taking the density of ‘Oumuamua as 2 g cm^{-3} (62), and the dimensions as 800 x 80 x 80 m (1), the mass of ‘Oumuamua is 1.02 x 10^{10} kg. This gives an ISO density of 5 x 10^{14} pc^{-3}, which is more in line with our estimates from ‘Oumuamua.

However, there are other important factors that may decrease this estimate. One such factor is that the majority of mass ejected from a protoplanetary disc is from photoevaporation (63), but for larger objects like ‘Oumuamua radiation pressure isn’t sufficient to accelerate them to escape velocity. Larger objects need to be ejected by gravitational processes, like encounters with stars or planets, or orbital resonances (64), where two objects exert a periodic gravitational force on each other, creating a unstable system. Ejections are most common in systems that include a large planet, roughly Jupiter sized, that can provide the necessary perturbation to accelerate an ‘Oumuamua sized object to escape velocity (65). The frequency of Jupiter-like planets is estimated at 3% (66), and so only a small proportion of systems have the large objects necessary to effectively eject objects like ‘Oumuamua. Systems with encounters with other stars could also emit ‘Oumuamua, but this only increases the fraction to an estimated 15% (55). The estimated number density inferred from ‘Oumuamua could also be higher than expected, as we assumed a 100% detection rate, which isn’t realistic, so there’s likely other ISOs which haven’t been detected. The Large Synoptic Survey Telescope observations will help to constrain the density of ISOs as it detects more. This means the density of ISOs predicted from protoplanetary discs may not be enough to meet our observations, but there is a large amount of uncertainty in these estimations which would be helped through further observations.

3.4 Solar Neighbourhood or Beyond

The velocity of ‘Oumuamua was found to be very close to the local standard of rest (LSR) (1), with a velocity (0.5, -5.6, -0.6) km s^{-1} relative to the LSR (67). This suggests that ‘Oumuamua was formed as part of a young system (68), which generally have lower velocities relative to the LSR, although this isn’t conclusive as older systems will still have a range of peculiar velocities. Using the data for ‘Oumuamua, and 6D information on the parallaxes, proper motion, radial velocities and positions on 7.2 million stars taken from the Gaia telescope (69), the orbits were integrated backwards to find any encounters ‘Oumuamua had with other star to find a possible origin. This was only possible for 10 Myr (44), as the errors in the Gaia and ‘Oumuamua data become amplified the further back the stars integrated. To minimise the computing power required, it was done using the linear motion approximation, where every object moves on a unaccelerated orbit (70). Stars that ‘Oumuamua approached of less than 0.5 pc were considered as possible progenitors, as that is the distance the Oort cloud would extend out to (54), but all stars with an approach less than 2 pc were considered. The results are shown in Table 1 (44).

Gaia identity	HIP	*t*	*t*sample	*d*rel	*d*sample	*v*rel	*v*sample
		(Myr)		(pc)		(km s^{-1})	
5108377030337405952	17288	−6.793	[−7.011, −6.574]	1.342	[1.330, 1.363]	14.854	[12.917, 17.184]
4863923915804133376		−8.970	[−10.135, −8.037]	1.554	[1.526, 1.644]	22.106	[17.281, 27.255]
5140501942602437632		−6.653	[−7.755, −5.481]	1.931	[1.840, 2.447]	40.228	[32.951, 85.899]
1362592668307182592	86916	−0.455	[−2.083, 2.223]	1.783	[1.781, 1.799]	43.430	[28.745, 62.525]

Table 1-The stars that Oumuamua approached within 2 pc

The closest approach in the solar neighbourhood was with HIP 17288 6.8 Myr ago, at a relative distance of 1.342 pc, which isn’t close enough to the star for ‘Oumuamua to be part of its Oort Cloud, so these encounters are unlikely candidates for the origin of ‘Oumuamua. Looking beyond the solar system, there are four potential home candidates for ‘Oumuamua (67), with the closest encounter being with Gaia 2525688198820543360 at a relative distance of 0.599 pc, which means it’s possible that ‘Oumuamua originated from this system. However, as discussed previously, in order to eject ‘Oumuamua at its measured velocity, the system would need either a Jupiter-sized planet or a stellar encounter. None of the potential candidates have been observed to have a giant planet in orbit or to be binary systems. There is one candidate star which may have had a stellar encounter which could’ve ejected ‘Oumuamua, although the encounter distance has a lot of uncertainty in it. We therefore can’t conclude if one of these is the parent system of ‘Oumuamua. These estimates could be vastly improved with more observations for different stars, as the current Gaia catalogue provides 6D information for only 7.2 million stars, and so there are many more stars for which we can't integrate backwards in time which could be home candidates. The sample from Gaia is also magnitude limited, and so it doesn't include many lower magnitude and smaller stars which are harder to detect (71).

Conclusions

Based on the predicted densities of ISOs from different ejection mechanisms, we estabilished that an origin from the Oort Cloud or exo-Oort Cloud could not reproduce the density of ISOs that we infer from the detection of Oumamua, which is between 3.5×10^{13} and 2.1×10^{15} pc^{-3} (44). The predicted density of ISOs from debris fields in protoplanetary discs is 5×10^{14} pc^{-3}, closer to our predictions, but this has some issues. The system of origin would require a giant planet or stellar encounter to eject an object the size of 'Oumuamua, which are very rare, and so this significantly limits the viable origin systems. Based on research which attempted to find previous encounters that 'Oumuamua had with other stars using the linear motion approximation, it was concluded that there were no suitable candidates in the solar neighbourhood, as the distances and relative velocities were too large for Oumuamua to have been ejected from them (44). Beyond the solar neighbourhood, four potential progenitors were found, with the best candidate, HIP 17288, having a relative distance of 1.342 pc and a relative velocity of 24.7 km s-1 with 'Oumuamua (67). However, none of these stars have been observed to be part of binary star system, or to have the giant planet necessary to eject an object the size of Oumuaua into interstellar space. The stars may have giant planets which haven't been observed due to the difficulties in detecting exoplanets, or the more likely case is that we do not have the 6D information on 'Oumuamua's parent star necessary for the orbit modelling. I therefore was unable to conclude a clear system from which 'Oumuamua originated.

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