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Dynamics of the Oort cloud and formation of interstellar comets

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Chapter 2

The origin of interstellar asteroidal objects like 1I/2017 U1 ’Oumuamua

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Abstract

We study the origin of the interstellar object 1I/2017 U1 'Oumuamua by juxtaposing estimates based on the observations with simulations. We speculate that objects like 'Oumuamua are formed in the debris disc as left over from the star and planet formation process, and subsequently liberated. The liberation process is mediated either by interaction with other stars in the parental star-cluster, by resonant interactions within the planetesimal disc or by the relatively sudden mass loss when the host star becomes a compact object. Integrating 'Oumuamua backward in time in the Galactic potential together with stars from the Gaia-TGAS catalogue we find that about 1.3 Myr ago 'Oumuamua passed the nearby star HIP 17288 within a mean distance of 1.3 pc. By comparing nearby observed L-dwarfs with simulations of the Galaxy we conclude that the kinematics of 'Oumuamua is consistent with relatively young objects of 1.1–1.7 Gyr. We just met 'Oumuamua by chance, and with a derived mean Galactic density of $\sim 3 \times 10^5$ similarly sized objects within 100 au from the Sun or $\sim 10^{14}$ per cubic parsec we expect about 2 to 12 such visitors per year within 1 au from the Sun.

Section 2.1

Introduction

1I/2017 U1 'Oumuamua (hereafter 'Oumuamua), a genuine interstellar object that was discovered on 19 October 2017 in the Pan-STARRS survey (Bacci et al. 2017; Meech et al. 2017a,b), was initially identified as a comet but quickly reclassified as an *unusual minor planet*. Most notable orbital parameters are the distance at pericentre, $q = 0.25534 \pm 0.00007$ au, the eccentricity, $e = 1.1995 \pm 0.0002$ and the relative velocity at infinity $v \simeq 26.32 \pm 0.01$ km/s with respect to the Sun (Bacci et al. 2017; Meech et al. 2017a; Mamajek 2017). This makes the object unambiguously unbound on an en-passant orbit through the Solar system (de la Fuente Marcos & de la Fuente Marcos 2017; Bannister et al. 2017), not unlike the prediction by Moro-Martín, Turner, & Loeb (2009). The absence of a tail indicates that the object is probably rock-like (Meech 2018), which, together with its unusual elongated shape (~ 35 by 230 m reported by Meech et al. 2017, and explained by Fitzsimmons et al. (2018) and Domokos et al. (2017)) and rapid spin (with an 8.10 ± 0.02 hour period, see Jewitt et al. 2017; Bolin et al. 2018), has been hosted by a star for an extensive period of time (Katz 2018; Hoang et al. 2018). In this period it may have lost most of its volatiles and ice by sputtering (Meech 2018; Fitzsimmons et al. 2018). By the lack of other terminology for this class of objects and for convenience, we refer in this work to *sōlus lapis*, which is Latin for "lonely stone".

Spectra taken by several instruments indicate that its colour ($g - r = 0.2 \pm 0.4$ and $r - i = 0.3 \pm 0.3$ (Masiero 2017), $g - r = 0.41 \pm 0.24$ and $r - i = 0.23 \pm 0.25$ (Bolin et al. 2018), and $g' - r' = 0.60 \pm 0.23$ (Ye et al. 2017)) matches that of objects in the Kuiper belt (Kuiper 1951) but that it is somewhat red compared to the main belt asteroids and trojans (see also Bannister et al. 2017; Jewitt 2018). However, it cannot be excluded that 'Oumuamua is the left over nucleus of a comet from another star (Ferrin & Zuluaga 2017; Meech 2018; Raymond et al. 2018b).

Based on its velocity, 'Oumuamua is unlikely to have originated from a nearby star (Mamajek 2017; de la Fuente Marcos & de la Fuente Marcos 2017), although Gaidos, Williams, & Kraus (2017) argue that it could have been ejected with a low velocity (of 1–2 km/s) from the nearby young stellar associations Carina or Columba or from the Pleiades moving group (Feng & Jones 2018). Tracing back the trajectory of 'Oumuamua through the local neighbourhood is hindered by the magnification of small uncertainties in

its orbit and in the positions and velocities of nearby stars (Zhang 2018). Even with the high accuracy achieved by Gaia and TGAS, backtracing its orbit can only be done reliably for some 10 Myr or over a distance of about 30 pc (Mamajek 2017).

Since we doubt that ʼOumuamua formed as an isolated object, it seems most plausible that it formed around another star, from which it was liberated. This could be the result of copious mass loss resulting from the end phase of the nuclear burning of a star (Veras et al. 2011; Hansen & Zuckerman 2017; Rafikov 2018), by a close encounter in a young star cluster (Jílková et al. 2016), or by internal scattering of planetary systems (Brasser & Morbidelli 2013; Raymond, Armitage, & Veras 2018a) or in a binary star (Jackson et al. 2018; Ćuk 2018). It is even possible that one of the Sun's own Oort cloud objects was scattered by a yet unknown planet (Wright 2017; de la Fuente Marcos, de la Fuente Marcos, & Aarseth 2018).

Here we discuss the possible origin of ʼOumuamua (see § 2.2). We analyse its orbital properties and compare those with our expectations for a random population of free-floating debris in the solar neighbourhood (see § 2.3). Our estimates of the occurrence of objects similar to ʼOumuamua is juxtaposed with several alternative scenarios. In the near future when the Large Synoptic Telescope comes online many more *sōlī lapidēs* are expected to be found at a rate of 2 to 12 per year.

Section 2.2

ʼOumuamua as a rare object

2.2.1 Observational constraints

A simple estimate of the number density of *sōlī lapidēs* implied by the detection of ʼOumuamua can be derived by calculating the effective volume surveyed by the Pan-STARRS telescope (A much more elaborate analysis was recently presented in Do et al. 2018). This telescope has a limiting magnitude of $m \sim 22$ (Bacci et al. 2017; Meech et al. 2017a). ʼOumuamua was observed with a magnitude $H = 20.19$ and was within a distance of about 0.16 au from Earth before being detected.[†]

[†]The quoted value for H is the absolute magnitude which is defined as the magnitude at 1 au from both the Earth and the Sun.

The volume surveyed by the Pan-STARRS telescope is approximately:

$$V \simeq Av\Delta t_{\mathrm{PAN}}. \tag{2.1}$$

Here A is the effective cross section for the object passing the Solar system:

$$A = \pi r_{\mathrm{detect}}^2 \left(1 + \left(\frac{v_{\mathrm{esc}}}{v}\right)^2\right). \tag{2.2}$$

In which $\pi r_{\mathrm{detect}}^2$ is the geometric cross section and the second term corrects for the gravitational focusing. Here v is the relative velocity of 'Oumuamua at infinity with respect to the Solar system's barycentre and $v_{\mathrm{esc}} \simeq 42\,\mathrm{km/s}$ is the escape velocity of the Sun at a distance of 1 au. The period over which Pan-STARRS has observed $\Delta t_{\mathrm{PAN}} \simeq 5\,\mathrm{yr}$ (the first data release in 2014 covers 3 years, see Engelhardt et al. 2017). When we naively assume that the telescope has a 100 % detection efficiency over these 5 years we arrive at a density of $\sim 0.08\,\mathrm{au}^{-3}$ or $\sim 7.0 \times 10^{14}\,\mathrm{pc}^{-3}$. The statistical uncertainty implied by a single detection means that a wide range of values (0.004–$0.24\,\mathrm{au}^{-3}$ or 3.5×10^{13}–$2.1 \times 10^{15}\,\mathrm{pc}^{-3}$) is consistent with the observations at the 95% level.

This simple estimate ignores the modeling of the detection efficiency. In spite of this, we obtain a value higher than the upper limits for finding *sōlī lapidēs* derived from the absence of detections using the Pan-STARSS1 survey up to that time by Engelhardt et al. (2017). Their estimates lead to a lower density because they considered larger objects with a cometary tail that could have been detected to a much larger distance from the Earth. We will now discuss the possible origin of *sōlī lapidēs* and their relation to 'Oumuamua .

2.2.2 Dynamical ejection from the Sun's Oort cloud

Considering the orbital parameters of 'Oumuamua , it seems unlikely to have been launched from the Kuiper belt or Oort cloud (Oort 1950). Asteroids and comets are frequently launched from the Kuiper belt and the Oort cloud but they rarely penetrate the inner Solar system (de la Fuente Marcos et al. 2018). Objects in the Oort cloud, however, could possibly launch into the inner Solar system after a strong interaction with a passing star (Rickman et al. 2008) or a planet (Fouchard et al. 2014).

The highest velocity, in this case, is obtained when the object would have been the member of a close binary with another, more massive, rocky

object; much in the same way in which hypervelocity stars are ejected from the supermassive black hole in the Galactic centre (Hills 1988). Binaries are known to be common in the outer regions in the Solar system, and possibly the majority of planetesimals in the Kuiper belt formed as pairs (Fraser et al. 2017). The mean orbital separation of 13 trans-Neptunian objects is 13900 ± 14000 km (Noll et al. 2008) with a minimum of 1830 km for the pair Ceto/Phorcys (object #65489), but there is no particular reason why Oort cloud or Kuiper-belt binaries could not have tighter orbits (Fraser et al. 2017), such as is suspected of 2001 QG298 (Sheppard & Jewitt 2004). An interaction of an object much like the binary (136108) 2003 EL61 (Brown 2005) with a planet with ten times the mass of Jupiter could result in a runaway velocity of the least massive member of ~ 1 km/s, but with the parameters for Ceto/Phorcys the mean kick velocity of ~ 0.13 km/s. This would be sufficient to change a circular orbit at a distance of 1000–10^4 au around the Sun into an unbound orbit with the eccentricity observed for 'Oumuamua.

We perform Monte Carlo experiments in which we distribute Oort cloud objects around the Sun using the parameters adopted in Hanse et al. (2016). We introduce a velocity kick $v_{\rm kick}$, taken randomly from a Gaussian distribution with dispersion of 0.13 km/s in each of the Cartesian directions, which results in a wide distribution in semi-major axis and eccentricity. More than 85% of the objects remain bound and the remaining 15% unbound objects tend to have high eccentricities with a median of ~ 1.2, but only a very small fraction of $\lesssim 10^{-3}$ objects pass the Sun within 100 au on their unbound orbit (see also de la Fuente Marcos et al. 2017). We subsequently performed several direct N-body simulations to verify this result. For these we adopted the connected-component symplectic integrator Huayno (Jänes, Pelupessy, & Portegies Zwart 2014) within the AMUSE (Portegies Zwart & McMillan 2018) framework. The mild kicks expected due to an interaction with an Oort cloud binary and a massive planet, either passing through or bound to the Oort cloud, are insufficient to explain the observed velocity of 'Oumuamua. We, therefore, conclude that 'Oumuamua is unlikely to have originated from either the Kuiper belt or the Oort cloud (see also de la Fuente Marcos et al. 2018).

2.2.3 Origin from the Oort cloud of another star

Naive estimates of the density of interstellar comets can be derived from the stellar density and assuming that each star has a rich Oort cloud with

$N_{\text{comets}} \sim 10^{11}$ comets per star (Kaib & Quinn 2009)

$$n_{\text{comets}} = \eta n_{\text{stars}} N_{\text{comets}}. \tag{2.3}$$

With a mean mass density in the solar neighbourhood of $\rho_0 = 0.119^{+0.015}_{-0.012}\,\mathrm{M}_\odot/\mathrm{pc}^3$ (Widmark & Monari 2019) (or $0.09 \pm 0.02\,\mathrm{M}_\odot/\mathrm{pc}^3$ according to Kipper, Tempel, & Tenjes 2018) and a mean stellar mass $\sim 0.37\,\mathrm{M}_\odot$ (Chabrier 2003), we arrive at a local stellar number density in the Galactic disc of $n_{\text{stars}} \simeq 0.32\,\mathrm{pc}^{-3}$. The efficiency at which comets are ejected from a star when it orbits the Galaxy was recently estimated to be $\eta \sim 0.1/\mathrm{Gyr}$ (Hanse et al. 2016). With a mean stellar age of 6 Gyr, we arrive at a local comet density of $n_{\text{comets}} \sim 2.5 \times 10^{-6}\,\mathrm{au}^{-3}$ (or $2.2 \times 10^{10}\,\mathrm{pc}^{-3}$), which is consistent with the upper limit on the density of interstellar comets of $\lesssim 0.0007\,\mathrm{au}^{-3}$ by Stern (1990) and $< 0.001\,\mathrm{au}^{-3}$ by McGlynn & Chapman (1989) and Francis (2005). Here we did not correct for the intrinsic size and mass distribution of Oort cloud objects. The density of *sōlī lapidēs* that originate from ejected Oort-cloud objects are considerably lower than our expected density based on the observations derived in § 2.2.1, and we conclude that 'Oumuamua cannot have originated from the hypothetical exo-Oort cloud of other stars.

Copious loss of circumstellar material, however, can be initiated when a star turns into a compact remnant either on the post-asymptotic giant branch (Veras et al. 2011) or in a supernova (Boersma 1961). If each of the 2.0×10^9 white dwarfs in the Galactic disc (Napiwotzki 2009) has produced $\mathcal{O}(10^{11})$ free-floating objects, the number of *sōlī lapidēs* would be over-produced by ~ 5 orders of magnitude.

2.2.4 Origin from the debris disc of another star

A young planetary system with a circumstellar disc may be rather rich in relatively large $\gtrsim 100\,\mathrm{m}$ objects, because it is the expected equilibrium size for collisional cascade of material-strength dominated bodies (Schlichting, Fuentes, & Trilling 2013). Disruption of such a disc may inject a large number of these objects into interstellar space. This would happen in the early evolution of the star when it still was a member of its parental cluster. A similar estimate as in § 2.2.3 then reveals a total mass of ejected disc-material to be

$$m_{\text{debris}} \sim f_{\text{debris}} Z \rho_0 \tag{2.4}$$

When we adopt a disc mass $M_{\text{disc}} = 0.01 M_\odot$, and a metallicity of the disc, $Z = 0.02$, the fraction of expelled material is harder to estimate but it may

be in the range of $f_{\rm debris} \sim 0.1$. This fraction could even be higher if we argue that the Solar system may have lost a fraction $\gtrsim 10\%$ of its disc in a resonance interaction between the outer most planets (Gomes et al. 2005). The total mass of ejected metals is then of the order $\sim 2.4 \times 10^{-6}\,{\rm M}_\odot/{\rm pc}^{-3}$. The density of 'Oumuamua is estimated to be $\sim 2.0\,{\rm g/cm}^3$ (see e.g. Trilling et al. 2017), which is in the range of densities observed for the relatively ordinary Kuiper-belt object Orcus ($\rho_{\rm KBO} = 1.65^{+0.34}_{-0.24}\,{\rm g/cm}^3$, see e.g. Brown & Butler 2017) and the dense metal-rich 16 Psyche ($4.5 \pm 1.4{\rm g/cm}^3$, see e.g. Shepard et al. 2017). With the observed dimensions of a cylinder of $25 \times 230\,$m (Knight et al. 2017), we arrive at a mass of $m \simeq 1.2 \times 10^9\,$kg. A hypothetical young Solar system could then have ejected 3.3×10^{16} objects during its early evolution, leading to a mean density of $\sim 3.9 \times 10^{15}\,{\rm pc}^{-3}$, exceeding our observational estimate by a factor of ~ 6. These objects may be cometary or non-cometary in nature depending on whether these are ejected from inside or outside the snow line. The large uncertainties in this estimate, and those in § 2.2.3 make it plausible that an enormous population of expelled objects exists in the Galaxy with a density consistent with, or even exceeding our number-density estimate in § 2.2.1.

Section 2.3

Where did 'Oumuamua come from

Having compared the number of interstellar objects produced by asteroidal or cometary ejection in § 2.2 it seems plausible that 'Oumuamua was formed around another star, and was liberated upon either close planetary encounters within the young planetary system, or due to the copious mass loss when the star became a compact remnant. We now discuss the possible origin of 'Oumuamua .

2.3.1 An origin from the solar neighbourhood

Results by the Gaia Collaboration, Brown et al. (2016) provide the most complete and accurate census of the distribution of stars in the solar neighbourhood (for which we adopt a volume centred around the Sun with a radius of 50 pc). The radial velocity components are not (yet) part of this database, but they can be completed using other catalogues. By matching the TGAS catalogue with the radial velocities from Kunder et al. (2017), Pulkovo (Gontcharov 2006), and Geneva-Copenhagen (Holmberg, Nordström, & Andersen 2009), we constructed a catalogue of 270,664 stars with

position and velocity information (Torres, Portegies Zwart, & Brown 2018), we selected those stars with relative proper motions and parallax errors $< 1\,\%$, with radial velocity $< 100\,\mathrm{km/s}$, with errors $< 10\,\mathrm{km/s}$ (see also Feng & Jones 2018).

The orbits of the selected stars as well as 'Oumuamua are integrated backwards in time for 10 Myr in the Galactic potential. The uncertainty in the Gaia database and in the orbital parameters of 'Oumuamua are too large to integrate reliably backwards in time any further (see also Mamajek 2017, who adopted similar criteria). The integration was performed using Galaxia (Antoja, Helmi, Dehnen, Bienaymé, Bland-Hawthorn, Famaey, Freeman, Gibson, Gilmore, Grebel, Kordopatis, Kunder, Minchev, Munari, Navarro, Parker, Reid, Seabroke, Siebert, Steinmetz, Watson, Wyse, & Zwitter 2014). This semi-analytic Milky Way Galaxy model is incorporated in the AMUSE software framework (Portegies Zwart, McMillan, van Elteren, Pelupessy, & de Vries 2013a; Portegies Zwart & McMillan 2018) using the parameters derived by Martínez-Barbosa, Brown, & Portegies Zwart (2015). As position for the Sun, we adopted $x = 8300\,\mathrm{pc}$, with a z component of 27 pc, and a velocity vector of (11.1, 232.24, 7.25) km/s.

We now generate one million objects within the error ellipsoid (in astrometric and radial velocity) of each of the selected stars. This results, for each star, in a probability density-distribution in time, relative distance and relative velocity of the closest approach between that particular star and 'Oumuamua . In Fig. 2.1 and Fig. 2.2 we show the various probability distributions for time of closest approach, relative distance, and relative velocity for the 4 stars within 2 pc that have a closest approach. We identify these stars in Table 2.1. About 6.8 Myr ago, 'Oumuamua passed the star HIP 17288 within a distance of $\sim 1.3\,\mathrm{pc}$ and with a relative velocity of $\sim 15\,\mathrm{km/s}$ which is consistent with the result of Feng & Jones (2018) and Dybczyński & Królikowska (2018). We find several other relatively close encounters which, despite their close proximity with 'Oumuamua , we have not included here because of the large uncertainty in the radial velocity. Based on this data, we do not expect that 'Oumuamua was launched from any of the nearby stars in the Gaia catalogue. We speculate that 'Oumuamua originates from well beyond the solar neighbourhood.

2.3.2 An origin from beyond the solar neighbourhood

If 'Oumuamua is part of the Galactic background distribution of *sōlī lapidēs*, its velocity is expected to be consistent with the distribution of low-

Table 2.1: Closest star encounters with 'Oumuamua within 2 pc. Columns 1 to 3 give the identity of the star, the following columns give the time of the encounter, the closest relative distance with 'Oumuamua, relative velocity, and the variation intervals of the samples in time, distance and velocity. Note that time is negative, indicating that the encounter happened in the past.

ID	Gaia identity	HIP	t $[Myr]$	t_{sample}	d_{rel} $[pc]$	d_{sample}	v_{rel} $[km/s]$	v_{sample}
[a]	5108377030337405952	17288	-6.793	[-7.011, -6.574]	1.342	[1.330, 1.363]	14.854	[12.917, 17.184]
[b]	4863923915804133376		-8.970	[-10.135, -8.037]	1.554	[1.526, 1.644]	22.106	[17.281, 27.255]
[c]	5140501942602437632		-6.653	[-7.755, -5.481]	1.931	[1.840, 2.447]	40.228	[32.951, 85.899]
[d]	1362592668307182592	86916	-0.455	[-2.083, 2.223]	1.783	[1.781, 1.799]	43.430	[28.745, 62.525]

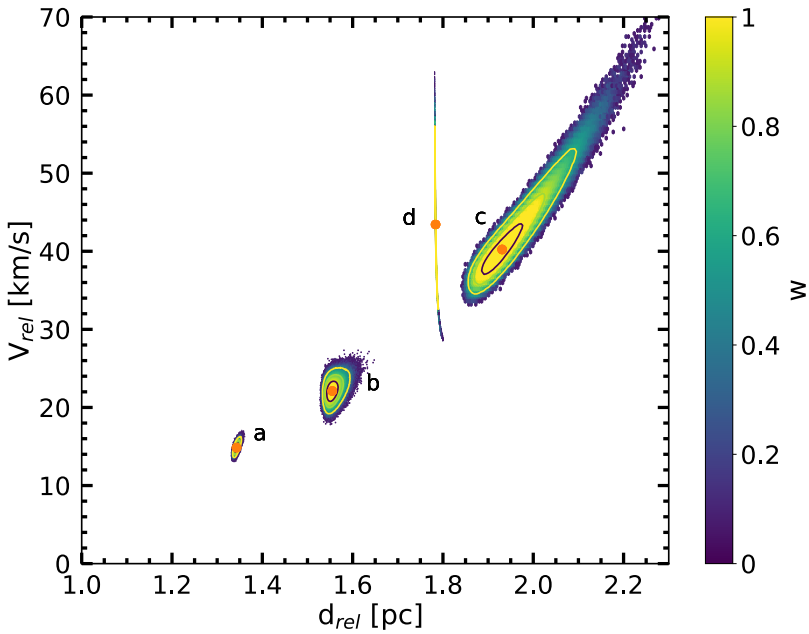

Figure 2.1: Probability density-distribution in relative distance ($d_{\rm rel}$) and relative velocity ($v_{\rm rel}$) between 'Oumuamua and the four closest stars a, b, c and d (see Table 2.1). The colour bar to the right gives a weigthing (w) with respect to the A and v from Eq. 2.1 and Eq. 2.2 with respect to the same values of 'Oumuamua .

mass objects in the Galaxy. To analyse quantitatively this hypothesis, we compare the velocity of 'Oumuamua with the distribution of the stars in Gaia-TGAS. This distribution is presented in Fig. 2.3.

Ideally, we would like to compare 'Oumuamua to a population of objects with similar characteristics. We decide to take the population of L-dwarfs, which in mass are sufficiently small that they could be considered mass-less in the Galactic potential. In addition, there is a reasonable consistent census of the population of L-dwarfs within 20 pc of the solar neighbourhood (Kirkpatrick et al. 2012). For these dwarfs, the velocity has been measured as a function of age (Burgasser et al. 2015), and this distribution follows:

$$v \simeq \frac{t}{[\mathrm{Gyr}]} \times 6 \ \mathrm{km/s} + 20 \ \mathrm{km/s}. \tag{2.5}$$

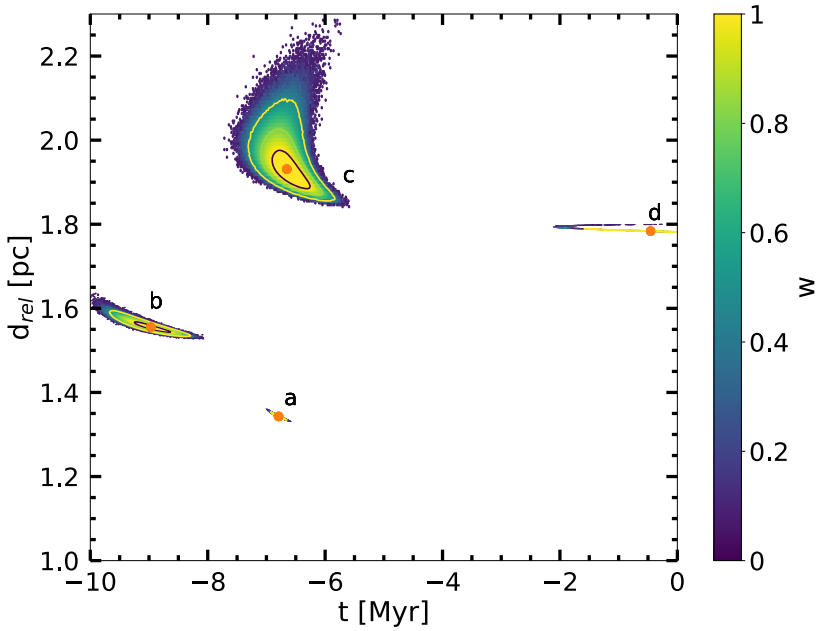

Figure 2.2: Probability density-distribution in time of closest approach (t) and relative distance ($d_{\rm rel}$) between ’Oumuamua and the four closest stars (see Table 2.1).

Inverting this relation leads to an age estimate for ’Oumuamua of ~ 1 Gyr, which is consistent with the sample of youngest (1.1–1.7 Gyr) L-dwarfs (Burgasser et al. 2015). Considering the velocity distribution of the entire population of brown dwarfs results in an average age of about 5 Gyr (see Fig. 2.3), which is consistent with the estimate of 5.2 ± 0.2 Gyr by Burgasser et al. (2015), whereas for the Gaia-TGAS data, we find 3 ± 0.5 Gyr. The difference between the brown-dwarf age-estimates and those in the Gaia-TGAS catalogue is possibly due to a selection effect caused by the magnitude-limited sample in the latter (see also Bailer-Jones 2018).

To further validate the use of the brown-dwarf velocity-distribution to constrain the age of ’Oumuamua, we compare it to the velocity distribution of objects in recent simulations of the Milky Way Galaxy by Fujii et al. (2018). This calculation, performed with the Bonsai (Bédorf et al. 2012, 2014) gravitational tree-code using a shared time-step of ~ 0.6 Myr, a gravitational softening length of 10 pc and with opening angle $\theta = 0.4$ are car-

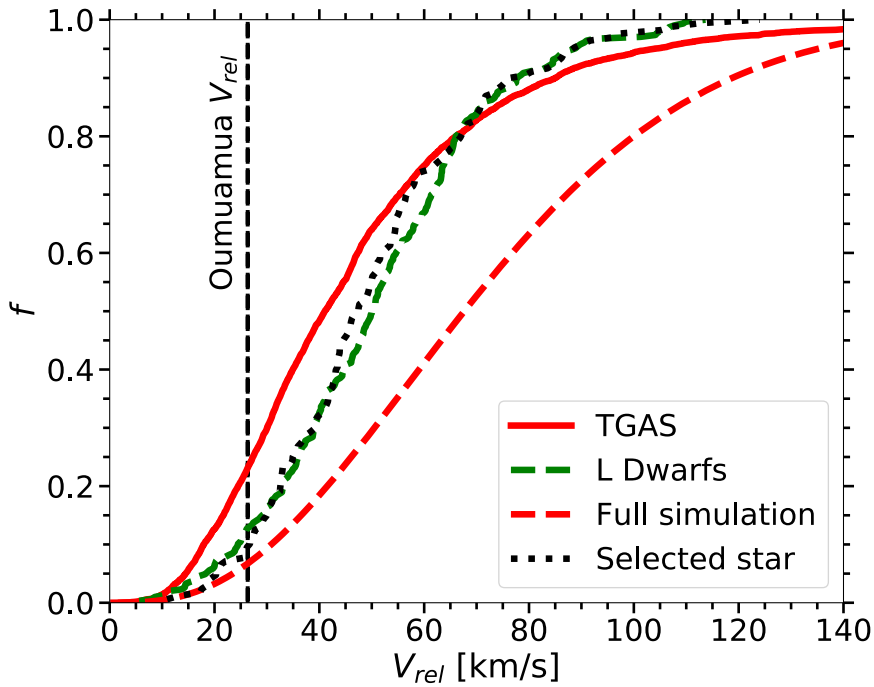

Figure 2.3: Cumulative relative velocity distributions of single objects in the solar neighbourhood. 'Oumuamua is presented as the vertical line near 26 km/s. The solid red curve gives the velocity distribution of stars within 30 pc of the Sun from the Gaia-TGAS catalogues. The green dashed curve gives the distribution of 100 L-dwarfs within $\sim$ 20 pc of the Sun (Schmidt et al. 2010). The red dashed curve gives the mean relative velocity-distribution of all stars within 7.5-8.5 kpc from the Galactic centre, whereas the black dotted curve gives the distribution between one Sun-like star (at a distance of $\sim$ 7.2 kpc from the centre with a velocity of $\sim$ 223.1 km/s and at an angle of $\sim 20^\circ$ from the tip of the bar, Holmberg et al. 2009) and its neighbours. The latter distribution is statistically consistent with that of the brown dwarfs with KS-probability of $\sim$ 0.3.

ried out with 8×10^9 particles in a stellar disc and include a live halo, bulge, and bar. In this snapshot at an age of 10 Gyr, we selected objects within 30 pc around a hypothetical star that matches the current relative location of the Sun in the Milky Way. At this distance, the structure of the disc is no longer visible and the inclination distribution is flat. The resulting relative velocity distribution of the full sample is presented as the red-dashed curve

and a sample star that matches closest to the L-dwarfs is represented by the black-dotted curve in Fig. 2.3.

The age distribution of all the objects in the simulations is consistent with an age of ~ 8.3 Gyr, but for the star representing the Sun it is comparable to the age-velocity distribution of 100 L-dwarfs in the age-range of 1.1–1.7 Gyr of Yu & Liu (2018). Instead of comparing the relative velocity-distributions directly, they should be weighted by the encounter rate and corrected for gravitational focusing (see Eq. 2.2). For the relevant velocity range ($v_{\rm rel} \lesssim 100$ km/s) however, this correction is small ($< 25\%$).

Section 2.4

Discussion and conclusions

Based on the existence of ʼOumuamua , we derive a local density of 3.5×10^{13}–2.1×10^{15} pc^{-3} (0.0040–0.24 au^{-3}). This is a high density, but in line with other estimates (Do et al. 2018). It is consistent with the amount of debris ejected during the star and planet formation process, but inconsistent with expulsion of exo Oort-cloud or asteroidal objects (see § 2.2).

If each star contributes to the formation of *sōlī lapidēs* then the entire Galaxy may be swarming with such objects, with O(10^{23}) *sōlī lapidēs* in the Milky Way. Once liberated from their parent stars, it is quite possible that such an object grazes any other star, much in the same way ʼOumuamua passed close to the Sun. The velocity of ʼOumuamua is low compared to the stars in the Gaia-TGAS catalogue, and low compared to the mean velocity distribution of L-dwarfs. Young L-dwarfs have a considerably lower velocity than their older siblings, and the velocity of ʼOumuamua is consistent with the youngest population of brown dwarfs (1.1–1.7 Gyr). Based on its velocity, we argue that ʼOumuamua has a similar age (see also Feng & Jones 2018).

Earlier estimates of the interstellar asteroid density were carried out to explain the daily X-ray flares on the super-massive black-hole in the Galactic centre Sgr A$\star$ (Hamers & Portegies Zwart 2015). They argue that the daily X-ray flares in the direction of Sgr A$\star$ can be explained with a local density of $\sim 10^{14}$ asteroids pc^{-3}, which is consistent with the density of *sōlī lapidēs* derived here.

We conclude that ʼOumuamua is part of the left-over debris of the star and planet formation process in the Galaxy. We expect that the Galaxy is

rich in such objects, with a density of $\sim 10^{14}$ or 10^{15} objects per cubic parsec. We estimate the probability that a *sōlus lapis* passes the Sun within 1 au, taking the gravitational focusing corrected cross-section into account, at an event rate of about 2–12 per year.

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