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

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ABSTRACT

With the recently discovered interstellar object 1I/2017 U1 (1I/'Oumuamua) we have to realize that the Solar System is not isolated, but part of a larger environment with which we interact. We compare the kinematics of 1I/2017 U1 with simulations of the Milky Way Galaxy and Gaia TGAS data to estimates the local density of objects similar to 1I/2017 U1 and to investigate its possible origin. We find that about 1.3 Myr ago 1I/2017 U1 has passed within a distance of 0.16 pc from the nearby star TYC4742-1027-1. It seems unlikely that 1I/2017 U1 originated from a possible Oort cloud around this star, but it simply trespassed on its way through.

Based on our calculations we conclude that the population of *sola lapis* (unbound non-cometary asteroidal objects) is much larger than that of cometary objects. The number of objects with characteristics similar to 1I/2017 U1 must be very common, we estimate a population density of $\approx 3 \times 10^5$ similarly sized objects within 100 au from the Sun or $\sim 10^{14}$ per cubic parsec in the Solar neighborhood. By comparing the results of simulations of the Milky Way Galaxy with the Gaia DR1 TGAS we conclude that the kinematics of 1I/2017 U1 is consistent with that expected from interstellar distribution of isolated objects that are part of the local Galactic potential. It is then hard to predict how long 1I/2017 U1 has been roaming the Galaxy before it visited the Solar System.

We subsequently argue that the Galaxy is rich in solae lapides such as 1I/2017 U1 . We speculate that such an object is formed in a debris disk as left over from the star and planet formation process. Upon interaction with other stars in the parental star cluster or due to resonant interactions within the planetary disk these objects are liberated from their parental star and float freely in the interstellar space. We just met 1I/2017 U1 by chance, and with the derived mean Galactic density we expect such visitors to be very common.

Key words: galaxies: kinematics and dynamics evolution — methods: numerical

1 INTRODUCTION

1I/'Oumuamua (1I/2017 U1) is a genuine interstellar object that was discovered on 19 October 2017 in the Pan-STARRS survey (MPC 2017a,b). The object was first classified as a comet due to its peculiar orbit but later reclassified as a *unusual minor planets*. Most notable orbital parameters are the distance at pericenter, $q = 0.254 \pm 0.002$, the eccentricity, $e = 1.1971 \pm 0.0013$ and the relative velocity at infinity $v \simeq 26$ km/s (MPC 2017a,b). This makes the object unbound from the Sun on an en-passant orbit through the Solar System. The absence of a tail indicates that the object is probably a rubble pile or rock-like for convenience we give identify it as a lonely rock or sola lapis (*mob nagh* in Klingon Okrand 1992).

A spectrum, taken on 25 October 2017 using the optical double spectrograph on the Hale telescope indicates that its color matches that of the Kuiper Belt objects but that it is somewhat too red for the main asteroid belt (Masiero 2017). A first analysis on its orbital properties indicates that 1I/2017 U1 is a genuinely interstellar object that happens to pass through the Solar System (de la Fuente Marcos & de la Fuente Marcos 2017).

Based on its Galactocentric velocity it is unlikely to have originated from a nearby star (Mamajek 2017; de la Fuente Marcos & de la Fuente Marcos 2017), but a potential candidate could be the nearby planetary system Luhman 16 (Luhman 2013) with a 0.059 $M_\odot$ star (Mamajek 2013). Alternatively, it was ejected with a velocity of 1–2 km/s from the nearby young stellar associations Carina or Columba (Gaidos et al. 2017).

Here we discuss the possible origin of 1I/2017 U1 . We analyze it's orbital properties and compare those with our expectations for a random population of free-floating debris in the Solar neighborhood and with the hypothesis that the object was recently ejected from orbit around a relatively nearby star or from our own Oort cloud.

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2 1I/2017 U1 AS A RARE OBJECT

A simple estimate of the number density of interstellar objects implied by the detection of 1I/2017 U1 can be derived by estimating the effective volume surveyed by the Pan-STARRS telescope that resulted in a present single detection. The Pan-STARRS telescope has a limiting magnitude of $m \sim 22$ (MPC 2017a,b). The object was observed with magnitude $H_{1I/2017\,U1} = 20.19$ and had a close distance of about 0.16 au before being detected [1]. It is not clear why the object was discovered only after is passed the Earth but it's speed, shape and uneven albedo may be tribute to this.

The volume surveyed by the Pan-STARRS telescope is approximately

$$V \simeq Avdt_{\rm PAN}. \tag{1}$$

Here A is the effective cross section for the object passing the Solar System

$$A = \pi r^2_{\rm detect}\left(1 + \left(\frac{v_{\rm esc}}{v}\right)^2\right). \tag{2}$$

In which $\pi r^2_{\rm detect}$ is the geometric cross section and the second term corrects for the gravitational focusing. Here v is the relative velocity of 1I/2017 U1 with respect to the Sun's local standard of rest and $v_{\rm esc} \simeq 42$ km/s is the escape velocity of the Sun at a distance of 1 au. The period over which Pan-STARRS has observed $dt_{\rm PAN} \simeq 5$ yr, assuming that the telescope has a 100 % detection efficiency and sky coverage over its 5 years of operation. We then arrive at a density of $\sim 0.08\,{\rm au}^{-3}$ or $\sim 7.0 \times 10^{14}\,{\rm pc}^{-3}$.

This simple estimate ignores the modelling of the detection efficiency (assuming here 100% efficiency), in spite of this we obtain a value higher than the upper limits of finsing *solae lapides* derived by Engelhardt et al. (2017) for the Pan-STARSS1 survey, derived from the absence of detections up to that time. The estimates by Engelhardt et al. (2017) lead to a considerably lower density because they considered larger objects with a cometary tail that could have been detected to much larger distance from Earth.

We will now discuss a few possible origins of *solae lapides* and their relation to 1I/2017 U1 .

2.1 1I/2017 U1 as a local visitor from the Kuiper belt or Oort cloud

Considering the orbital parameters of 1I/2017 U1 it seems unlikely to have been launched from the Kuiper belt or Oort cloud. Asteroids and comets are frequently launched from the Kuiper belt or the Oort cloud but for them to penetrate the inner Solar System is rare. 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 1I/2017 U1 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 center (Hills 1988). Binaries are known to be common in the outer regions in the Solar System, and the planetesimals formed near the Kuiper belt are possibly all formed as bound 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 couldn't have tighter orbits. 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 to ~ 1 km/s, but with the parameters for Ceto/Phorcys the mean kick velocity is ~ 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 1I/2017 U1 .

We perform Monte Carlo experiments in which we distribute an Oort cloud objects around the Sun using the parameters adopted in Hanse et al. (2017). We introduce a velocity kick $v_{\rm kick}$ taken randomly from a Gaussian distribution in each of the three Cartesian directions. With a random kick taken from a Gaussian distribution with dispersion of 0.13 km/s in each of the Cartesian directions 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 $\lesssim 10^{-3}$ objects pass the Sun within 100 au on their unbound orbit. We subsequently performed several direct N-body simulations to verify this result. For these we adopted the connected-component symplectic integrator `Huayno` (Jänes et al. 2014) within the `AMUSE` (Portegies Zwart & McMillan 2017) framework. With 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, is insufficient to explain the observed velocity of 1I/2017 U1 . We, therefore, conclude that 1I/2017 U1 is unlikely to have originated from either our own Kuiper belt or the Oort cloud.

2.2 1I/2017 U1 as an interstellar comet or asteroid

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 (Oort 1950) with $N_{\rm comets} \sim 10^{11}$ comets per star

$$n_{\rm comets} = \eta n_{\rm stars} N_{\rm comets}. \tag{3}$$

Here $n_{\rm stars} \simeq 0.15$–$1.0\,{\rm pc}^{-3}$ (Latyshev 1978) is the local stellar density in the Galactic disk. The efficiency at which comets are ejected for a star when it orbits the Galaxy was recently estimated to be $\eta \simeq 0.5$ (Hanse et al. 2017). We then arrive at a local comet density of $n_{\rm comets} \sim 8.5 \times 10^{-7}\,{\rm au}^{-3}$ to $7.5 \times 10^9\,{\rm pc}^{-3}$, which is consistent with the upper limits on the density of interstellar comets of $< 0.001\,{\rm au}^{-3}$ derived by Francis (2005). Here we did not correct for the intrinsic size and mass distribution of Oort cloud objects and the probable rarity of objects with a size comparable to 1I/2017 U1 .

A young planetary system with a circumstellar disk may be rather rich in relatively large $\gtrsim 100$ m objects, because it is the expected equilibrium size for collisional cascade of material-strength dominated bodies Schlichting et al. (2013). Disruption of such a disk may inject large numbers of relatively massive 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 them reveals a total mass in disk ejected material to be

$$m_{\rm eject} \sim f_{\rm eject} Z M_{\rm disk}. \tag{4}$$

When we adopt a disk mass $M_{disk} = 0.01 M_\odot$, metalicity $Z = 0.04$ and an expelled fraction of $f_{expel} = 0.1$ we can estimate the number of 1I/2017 U1 -mass objects that can be ejected from such a disk. The density of the Kuiper belt object Orcus

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[1] 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.

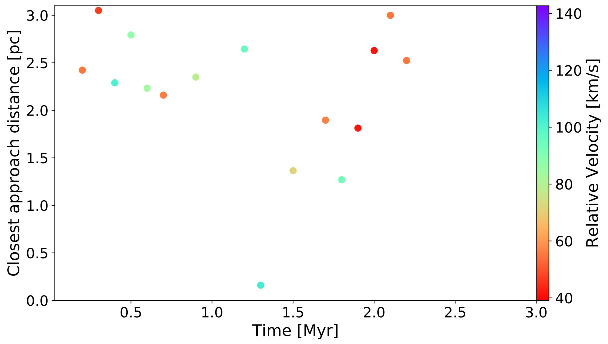

Figure 1. History of close encounters between 1I/2017 U1 and stars in the Solar neighborhood for the last 3 Myr. The color gives a measure of the relative velocity with respect to 1I/2017 U1 at the moment of closest approach. The nearest 5 stars are identified in Tab. 1.

$\rho_{\rm KBO} = 1.65^{+0.34}_{-0.24}$ g/cm^3 (Brown & Butler 2017). The magnitude of 1I/2017 U1 observed at a distance of ~ 0.16 au indicates that its size should exceed about 50 m (assuming an albedo of 1.0), but for convenience we adopt a 200 m radius (see also Knight et al. 2017).

We then arrive at a mass of $m \simeq 5.5 \times 10^{10}$ kg for 1I/2017 U1 . With our earlier estimate of the local stellar density we then arrive at a maximum total density of solae lapides of 0.24–1.6 au^{-3} or 0.2–1.4$\times 10^{16}$ pc^{-3}. This density exceeds our estimate for solae lapides by a factor of 5 to 20.

3 THE ORIGIN OF THE *SOLA LAPIS* 1I/2017 U1

3.1 Can 1I/2017 U1 have been launched from a nearby star

Gaia mission (Gaia Collaboration et al. 2016) aims to make the largest, most precise three-dimensional map of our Galaxy by surveying an unprecedented 1 billion stars over five years, allowing for about 70 observations of each star. Gaia-TGAS (Gaia Collaboration et al. 2016) provided a complete and accurate census of the distribution and motions of the stars in the Solar neighborhood. For the first data release (DR1), radial velocity components are not provided, but they can be completed using other catalogues. By matching the TGAS catalogue with the radial velocities from RAVE-DR5 (Kunder et al. 2017), Pulkovo (Gontcharov 2006), and Geneva-Copenhagen (Holmberg et al. 2009) we constructed a catalogue of 270,664 stars with complete positional and velocity information. From this sample we selected the 3,801 stars within 30 pc of the Sun. The match was performed by using Gaia Archive (`http://gea.esac.esa.int/archive/`).

We compare the observed orbital parameters of the object 1I/2017 U1 with the stars in these catalogues by integrating their orbits backwards in time. The integration was performed using the semi-analytic model for the Milky Way Galaxy (Antoja et al. 2014) called `Galaxia` which is incorporated in the `AMUSE` software framework (Portegies Zwart et al. 2013; Pelupessy et al. 2013; Portegies Zwart & McMillan 2017) using the implementation and parameters derived by Martínez-Barbosa et al. (2015). We adopted the position of the Sun of 8300 pc, with z component of 27 pc, and a velocity vector of (11.1, 232.24, 7.25) km/s.

In fig. 1 we identify the stars with which 1I/2017 U1 had a closest encounter over the last 3 Myr. At every 0.1 Myr time interval we compare the position of 1I/2017 U1 with that of the nearby stars to find the closest. In Tab. 1 we identify several of these closest stars. The quality of the velocity data of the observed stars becomes insufficient to perform an accurate calculation for integration further backwards in time. We find that 1I/2017 U1 reached a closest approach with TGAS star TYC4742-1027-1 (RAVE-DR5 #3200985387078683008) about 1.3 Myr ago at a distance of $d \simeq 0.15988$ pc and with a relative velocity of $v_{\rm rel} \sim 103$ km/s. It seems unlikely that 1I/2017 U1 was launched from TYC4742-1027-1, because of the large relative vlocity. We speculate that 1I/2017 U1 penetrated TYC4742-1027-1's Oort cloud while trespassing.

Table 1. Closest stars encounters whit 1I/2017 U1 within 2 pc. Columns give the Gaia identity of the star, the magnitude in G, the closest relative distance with 1I/2017 U1 , and the relative velocity.

Gaia ID	G [mag]	T [Myr]	$d_{\rm rel}$ [pc]	$v_{\rm rel}$ [km/s]
3200985387078683008	10.82	1.3	0.1599	103.09
184055875669532160	7.50	1.5	1.3648	71.18
5449397124401742976	11.32	1.7	1.8963	56.76
3179254742347006208	9.49	1.8	1.2698	93.35
4840563107644391936	10.19	1.9	1.8131	42.20

Even though 1I/2017 U1 recently passed grazed a nearby star we stil do not expect that it was ejected from such a planetary system, and in particular not from the inner most parts. The chance coincidence of launching it in our direction is small, and particularly small if the inner part of such a planetary system is as poorly populated with asteroids as the Solar System.

3.2 An origin from a homogeneous distribution of debris in the Solar neighborhood

If 1I/2017 U1 is part of the a galactic background distribution of debris objects, it is expected to follow a similar distribution function as the stellar distribution. In order to obtain a realistic distribution function from which to sample positions and velocities, we perform N-body simulations of a self-gravitating stellar disk embedded in a dark matter halo. The initial conditions for our model are based on those described in Widrow et al. (2008) and Widrow & Dubinski (2005) and the details of the simulation are described in Fujii et al. (2017).

The calculation is performed using `Bonsai` (Bédorf et al. 2012, 2014) in which the equations of motion are solved using the classical Barnes & Hut algorithm (Barnes & Hut 1986) including quadrupole expansion of the multipole moments and improved Barnes & Hut opening angle criterion (Iannuzzi & Athanassoula 2013). The calculations are performed using a shared time-step of ~ 0.6 Myr, a gravitational softening length of 10 pc and the opening angle $\theta = 0.4$.

The results to which we compare 1I/2017 U1 was performed to mimic the Mikly Way Galaxy (Fujii et al. 2017) (see their model MWv), and we adopted 10^9 particles of with 4×10^8 representing the stellar disk. We selected one snapshot at an age of 10 Gyr, which gave a satisfactory resemblance with the Milky Way Galaxy. In this snapshot, we selected all stars between 8.0 and 9.0 kpc from the center of the galaxy model. For each of these stars, we then selected all stars within 50 pc. At this distance, the structure of the disk is no longer visible and the inclination distribution is flat, indicating that we no any longer see the effect of the disk thickness in the

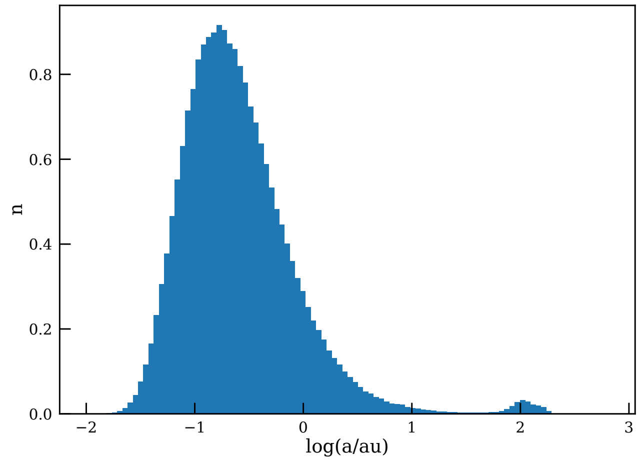

Figure 2. Probability distribution of the absolute orbital separation of 737438 stars within 50 pc of the Solar system from simulation MWv.

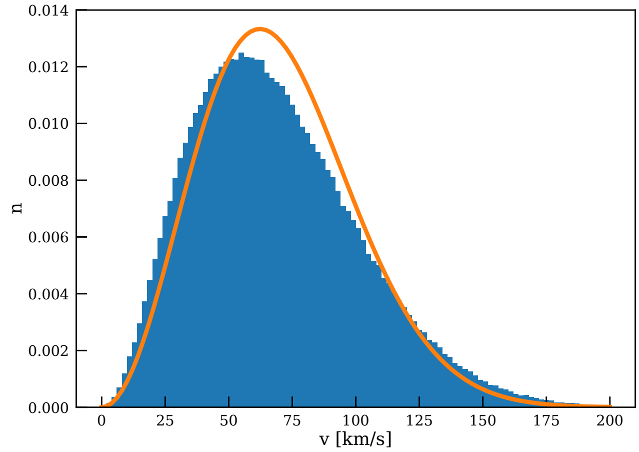

Figure 3. Relative velocity distribution of stars within 50 pc of the Solar position from simulation MWv. The blue histogram gives the binned distribution for 729713 selected objects in the simulation. The curve gives the best fit Maxwellian velocity distribution with a dispersion of $\sigma = 44.04$ kms.

data. In our simulations, a total of almost 10 million stars complied to this criterion. For each of these stars, we calculate the Kepler elements assuming that the central star in the particular volume and the selected star are isolated.

The distribution in $\log_{10}$ semi-major axis of this sub-selected sample matches a Maxwellian distribution with a median of $|a_{\rm median}| \simeq 0.213$ au and a mean of $|a_{\rm mean}| \simeq 0.255\pm$ au. The eccentricity distribution is much wider with $\langle e \rangle = 8.0 \pm 0.51$. In Fig. 2 we present a histogram of the orbital separation of stars near the Sun in the simulations. The relative velocity distribution also matches a Maxwellian probability density function with a dispersion of $\langle v \rangle \simeq 68.9 \pm 32.6$ km/s with a median of $v_{\rm median} = 64.9$ km/s but the distribution has a rather broad peak between 36 km/s and 85 km/s, which is somewhat high compared to the observed velocity at infinity for 1I/2017 U1 of $\sim$ 26 km/s. In fig. 3 we present the relative velocity distribution measured in this simulation between the Sun and another star within 50 pc.

4 DISCUSSION AND CONCLUSIONS

Based on the presence of one *sola lapis*, an isolated object unbound but in the direct neighborhood of the Sun, we derive a local density of $\sim 0.08\,{\rm au}^{-3}$ or $\sim 7 \times 10^{14}$ objects per pc^3. This is a high density, but not inconsistent with the amount of debris ejected during the star and planet formation process (see § 2). If each star contributes to the formation of *sola lapis* the entire Galaxy may indeed be swarming with such objects. Once liberated from their parent star it is not unlikely that such an object grazes any other star in an orbit comparable to the one observed for 1I/2017 U1 . In fact, the semi-major axis and relative energy of such an interaction represent the median for interstellar debris.

Earlier estimates of the interstellar asteroid density were carried out to explain the daily X-ray flares on the supermassive black hole in the Galactic center Sgr A⋆ (Hamers & Portegies Zwart 2015). They argue that the daily X-ray flares in the direction of Sgr A⋆ requires 0.2–1.1×10^8 asteroids per star. With an average density of 10^6 stars pc^{-3} within the inner parsec this leads to a local density of $\sim 10^{14}$ asteroids pc^{-3}, which is only a factor of a few smaller than the density of *sola lapis* derived for the Solar-System neighborhood.

We do not expect 1I/2017 U1 to be a left over from the Sun's birth cluster. This cluster was estimated to be composed of some 10^3 to 10^4 stars Portegies Zwart (2009). Even if each of these stars produced $\sim 10^{11}$ *solae lapides* the current galactic populaton is unlikely to exceed $\sim 10^{15}$ objects distributed over a volume of $\sim 1.7\,{\rm kpc}^{-3}$ (assuming a toroid of 100 pc radius at a distance of the Sun around the Galactic center. The density of birth cluster debris will then be $\sim 6 \times 10^5$ pc^{-3}, which is about 10^8 smaller than the contribution from the rest of the Galaxy.

We conclude that 1I/2017 U1 is the left-over of the star and planet formation process in the Galaxy. The entire Galaxy is rich in such objects, with an estimated density of $\sim 10^{14}$ objects per cubic parsec. We can estimate the probability that a *sola lapis* passes the Sun within 1 au taking the gravitational focussing corrected cross section into account, we arrive at an event rate of about 2–12 per year.

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