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LETTER TO THE EDITOR

Investigating the dynamical history of the interstellar object 'Oumuamua

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ABSTRACT

Here we try to find the origin of 1I/2017 U1 'Oumuamua, the first interstellar object recorded inside the solar system. To this aim, we searched for close encounters between 'Oumuamua and all nearby stars with known kinematic data during their past motion. We had checked over 200 thousand stars and found just a handful of candidates. If we limit our investigation to within a 60 pc sphere surrounding the Sun, then the most probable candidate for the 'Oumuamua parent stellar habitat is the star UCAC4 535-065571. However GJ 876 is also a favourable candidate. However, the origin of 'Oumuamua from a much more distant source is still an open question. Additionally, we found that the quality of the original orbit of 'Oumuamua is accurate enough for such a study and that none of the checked stars had perturbed its motion significantly. All numerical results of this research are available in the appendix.

Key words. methods: numerical – celestial mechanics – comets: general – interplanetary medium

1. Introduction

The problem of the lack of evident interstellar visitors in our solar system has been discussed for decades. Recently, Engelhardt et al. (2017) considered the implications of not observing such interstellar visitors. Now, the situation has changed.

The first interstellar small body penetrating our solar system was discovered on Pan-STARRS1 images taken on 2017 Oct. 18.5 UT at mag 19.8 (MPC CBET 4450). Initially, it was designated as a comet (C/2017 U1) due to its near-parabolic orbit. Later on, due to the lack of any cometary activity it was renamed as A/2017 U1 (M.P.E.C. 2017-U183, issued on 2017 Oct. 25, 22:22 UT). Ten days later, in M.P.E.C. 2017-V17, issued on Nov. 6, 21:00 UT, a new concept for naming such unusual objects was announced and accordingly, A/2017 U1 was renamed as 1I/2017 U1 ('Oumuamua).

The unique dynamical nature of this object was first noted by Bill Gray in his Oct. 25 posting to the Minor Planet Mailing list (MPML)[1]. He obtained a preliminary orbit based on a six-day arc and noticed an atypically high eccentricity of approximately 1.2. 'Oumuamua travels at a relatively high velocity with respect to the Sun (on the order of 25 km s^{-1}). Several preprints on the kinematics of this extraordinary object have recently appeared. Mamajek (2017) analysed the stars nearest the Sun for similar spatial velocity while Gaidos et al. (2017) suggested the origin of 'Oumuamua in a nearby young stellar cluster.

'Oumuamua seems to be unique for its physical characteristics as well. Meech et al. (2017) estimated its shape to be extremely elongated while Fraser et al. (2017) and Drahus et al. (2017) determined it to be a tumbling body. An interesting paper on the determination of physical parameters for 'Oumuamua has also been presented recently by Jewitt et al. (2017).

Since the nature of this object is still unknown, it might be desirable to study its dynamical history before entering the solar system interior.

This paper is organized as follows: the following section describes the model of solar vicinity dynamics which we use to track 'Oumuamua's past motion. The main task was to collect data on potential stellar perturbers. Section 3 presents the results of our numerical experiments. In the last section, we interpret these results and discuss their importance. In appendices we present complete numerical results, all stellar parameters used in this work with their references, and several examples of the geometry of the Qumuamua – star encounters.

2. Approach to the problem

To analyze the interstellar path of 'Oumuamua in the solar neighbourhood it is necessary to numerically integrate its equations of motion, taking into account both the overall Galactic potential and all important individual stellar perturbations from the known nearby stars.

To work with contemporary stellar data, we searched the whole SIMBAD astronomical objects database[2] for all stars with known positions, proper motions, parallaxes and radial velocities. To make sure we were working only with reliable data, we ensured that parallaxes were positive and radial velocities were ≦500 km s^{-1} in modulus. The result of this search, performed on 2017 Nov. 5, consists of 201 763 individual objects. Such a great number is the result of large observational projects, mainly *Gaia* (Gaia Collaboration 2016b) and RAVE (Kunder et al. 2017). As

[1] https://groups.yahoo.com/neo/groups/mpml/info

[2] http://simbad.u-strasbg.fr/simbad/

Table 1. Osculating heliocentric orbit of 'Oumuamua, based on 118 positional observations spanning the interval from 2017 Oct. 14 to 2017 Nov. 10, available at MPC on 2017 Nov. 12.

Perihelion distance [AU]	0.255234 ± 0.000062
Eccentricity	1.199236 ± 0.000164
Inverse of the semimajor axis [AU^{-1}]	−0.780603 ± 0.000618
Time of perihelion passage [TT]	2017 Sept. 09.488519 ± 0.001243
Inclination [deg]	122.677069 ± 0.005823
Argument of perihelion [deg]	241.683487 ± 0.011254
Longitude of the ascending node [deg]	24.599729 ± 0.000264
Epoch of osculation [TT]	2017 Sept. 4.0 = JD 2458000.5

Notes. Equator and ecliptic of J2000 is used. The obtained RMS is 0.35 arcsec.

Table 2. Barycentric original and future 'Oumuamua orbit elements.

Element	Original orbit	Future orbit
Perihelion distance [AU]	0.252062 ± 0.000063	0.257286 ± 0.000063
Eccentricity	1.196488 ± 0. 000164	1.200366 ± 0.000167
Time of perihelion passage [TT]	2017 Sept. 09.118037 ± 0.001262	2017 Sept. 09.310111 ± 0.001250
Inverse of the semimajor axis [AU^{-1}]	−0.779521 ± 0.000456	−0.778771 ± 0.000455
Inclination [deg]	122.725937 ± 0.005995	122.870243 ± 0.005900
Argument of perihelion [deg]	241.696866 ± 0.011361	241.842028 ± 0.011433
Longitude of the ascending node [deg]	24.251515 ± 0.000251	24.747600 ± 0.000256
Epoch of osculation [TT]	1973 Oct. 05	2061 Aug 04

it concerns a homogeneity of the data taken from the SIMBAD database we observe that 84% of astrometric measurements of these 201 763 stars were copied from the TGAS catalogue (Gaia Collaboration 2016a) and another 11% from the HIP2 catalogue (van Leeuwen 2007). The situation is slightly more complicated with radial velocity sources but still the majority of measurements (70%) were taken from RAVE data releases (Kunder et al. 2017; Kordopatis & RAVE Collaboration 2014) and another 11% from the Pulkovo compilation (Gontcharov 2006). The remaining radial velocity measurements taken by us from the SIMBAD database were copied from a large number of individual papers.

This stellar data set allowed us to perform accurate calculations, namely the numerical integration of 'Oumuamua's motion. To account for mutual stellar gravitational interactions, we had to integrate the N-body problem, consisting of 'Oumuamua, the Sun, and all individual stellar perturbers, all of which are under the influence of the overall Galactic potential. However, integrating the simultaneous motion's of over 200 000 bodies would be a waste of time – a great majority of these bodies never came close enough to 'Oumuamua to disturb its motion. Instead we first prepared a short list of perturbers; see below.

Numerical integration of motion was performed in a right-handed, non-rotating, rectangular Galactocentric frame with the OX axis directed in the opposite direction to the Sun's position at the starting time. We use the Model I variant of the Galactic gravitational potential described by Irrgang et al. (2013). As the starting position and velocity of the Sun we use vectors: $\boldsymbol{R}_{\odot} = (x_{\odot}, y_{\odot}, z_{\odot}) = (-8400, 0, 17)$ in pc and $\dot{\boldsymbol{R}}_{\odot} = (u, v, w) = (+11.352,\ +260.011,\ +7.41)$ in pc Myr^{-1}. In the former, we adopted the vertical position of the Sun given by Joshi (2007). A detailed description of the Galactic reference frame orientation and the Galactic potential form and parameters can be found in Dybczyński & Berski (2015). Here we use exactly the same dynamical model and equations of motion.

The starting position and velocities of 'Oumuamua for dynamical calculations outside a planetary zone were obtained from its original orbit. We determined this orbit elements from all positional observations available in the MPC database[3] on 2017 Nov. 12. Through careful data processing, we obtained an osculating orbit given in Table 1. Next, in order to observe the uncertainties in the motion of 'Oumuamua at every stage of our research, we cloned its orbit and built a swarm of 10 000 orbits resembling the observations, using a method described by Sitarski (1998) which fully utilises the covariance matrix obtained during the orbit determination. Then, we numerically propagated all of these orbits forward and backward up to a heliocentric distance of 250 AU (the distance at which planetary perturbations are negligible). The resulting barycentric elements of the original and future orbits of 'Oumuamua, along with their uncertainties, are presented in Table 2. We used the barycentric positions and velocities of each individual clone of 'Oumuamua at 250 au as starting data for a dynamical study of this body under the gravitational influence of stars and the full Galactic potential.

We suppose that due to the lack of cometary activity, non-gravitational forces (we found them non-detectable from positional data) could not have changed the orbit of 'Oumuamua significantly during its close perihelion passage and that the original orbit is rather reliable, with the uncertainties presented in Table 2. To observe how these uncertainties influence the minimal distance between 'Oumuamua and all stars included in our model, we repeated our numerical integration for all 10 000 clones of 'Oumuamua. Each encounter parameters obtained from this complex calculation as well as their variation intervals are presented in Table A.3.

However, the most important source of the close passage distance uncertainty, not estimated in this paper, is the stellar data errors. This cannot simply be modelled by the simultaneous drawing of N clones for all 57 stars and 'Oumuamua because that would require N^{58} numerical integrations. In this paper,

[3] http://www.minorplanetcenter.net/db_search

Table 3. All close encounters between 'Oumuamua and a star or stellar system closer than 1 pc obtained from the 59B model.

Star name	Min. distance [pc]	Epoch [Myr]	Rel. velocity [km s^{-1}]	r_hel [pc]	Miss-distance interval [pc]
HIP 3757	0.04401	−0.1179	185.375	3.175	0.04192–0.04670
GJ 4274	0.41190	−0.0227	309.498	0.612	0.41123–0.41257
HIP 981	0.50883	−6.6740	17.660	178.558	Not tested
G 108-21	0.55083	−0.2046	64.602	5.507	0.54261–0.55933
HIP 3829	0.64437	−0.0152	240.683	0.411	0.64422–0.64460
2MASS J07200325-0846499	0.90002	−0.0953	62.902	2.567	0.89864–0.90144
HD 135226	0.92358	−0.4269	68.669	11.491	0.92010–0.92795
HIP 21553	1.01326	−0.2772	34.723	7.453	1.01326–1.03281

Notes. Only the results for HIP 981 are from a three-body calculation; see text for the explanation. The star HIP 21553 is additionally added since its minimum distance is only slightly over 1 pc and it has a small relative velocity. The nominal orbit of 'Oumuamua and nominal stellar data are used for the results presented in Cols. 2–5. In the last column we show the minimum proximity distance variation interval obtained from the 10 000 clones of 'Oumuamua.

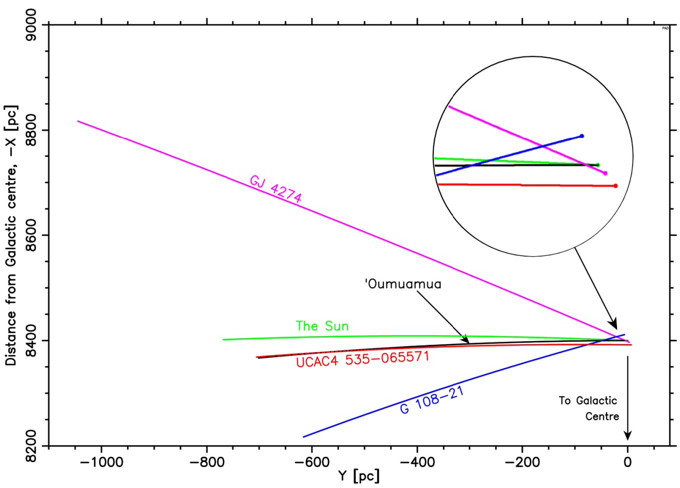

Fig. 1. Past trajectories of 'Oumuamua, the Sun, and three selected stars during the last 3 Myr. Their positions are projected onto the XY plane of the Galactocentric, non-rotating, right-handed rectangular frame. This plane coincides with the Galactic disk plane. The OX axis is directed opposite to the Galactocentric direction to the Sun at the starting epoch $t = 0$.

we restrict the error budget calculations to the influence of the 'Oumuamua orbit uncertainty.

To refine (and considerably shrink) our set of stellar perturbers, we first numerically followed the past motion of 'Oumuamua with each of the 201 763 stars individually along with the Sun, forming a three-body problem under the influence of the full Galactic potential. During this preliminary calculation, we assumed all stellar masses to be 1.0 $M_\odot$. Using these results, we selected 109 stellar objects that passed 'Oumuamua at a distance of closer than 3.5 pc. The parameters of all these encounters, derived from a nominal 'Oumuamua orbit and nominal stellar data, can be found in Table A.1.

After a detailed inspection involving the removal of obsolete objects and replacing components of multiple stellar systems with their respective centre of mass parameters, we finally collected a list of 57 stars or stellar systems which should be taken into account when studying 'Oumuamua's past motion in the solar neighbourhood. To use these stars as perturbers it was necessary to find estimations of their masses. It appeared that a lot of them are red (or even brown) dwarfs with a very small mass. Additionally, we recognised several pairs of stars forming double systems as well as one triple system (Alpha Centauri A,B + Proxima) and calculated their centre of mass coordinates, total mass, and a systemic velocity. The most massive perturbers in our list are the Alpha Centauri and Sirius systems. A list of these perturbers with their estimated masses, starting positions and velocities is presented in Table A.2. In the last column of this table we present references for all values used by us. Some adopted mass values are rather crude estimations, but due to 'Oumuamua's large velocity it turned out that the change in a perturbers mass does not significantly influence the path of 'Oumuamua. This of course might be false for mutual interactions of perturbers.

Finally, we integrated the N-body problem, consisting of 'Oumuamua, the Sun, and all 57 individual stellar perturbers, a 59-body system under the influence of the overall Galactic potential (hereafter 59B model).

Figure 1 shows the past trajectories of 'Oumuamua (in black), the Sun (in green), and three example stars selected from Tables 3–4. Their motion is projected onto the Galactic disk plane.

3. Results

After analysing 'Oumuamua's past motion within the solar vicinity, we found seven encounters closer than 1 pc between 'Oumuamua and nearby stars. These encounters are described in Table 3 and presented in Fig. 2. The first 'Oumuamua star encounter (with HIP 3757) is a very close one, with a miss distance of only 0.04 pc but with a rather high relative velocity of over 200 km s^{-1} taking place 118 000 yr ago. The second encounter, with GJ 4274, happened only 23 000 yr ago with an even greater relative velocity of 316 km s^{-1}. The minimum distance of the third event, with HIP 981, is also very close, but due to the large heliocentric distance of this event and practically unknown radial velocity of the star (rv = 4.00 ± 6.5 km s^{-1}, Barbier-Brossat & Figon 2000) we treat this case as a "false positive". The remaining cases presented in Table 3 yield a relative velocity of over 60 km s^{-1}, which also makes them not very promising candidates for 'Oumuamua's source system.

When searching for the parent star of 'Oumuamua, one probably should look for a close passage with a much smaller relative velocity. From among the over 200 000 tested stars, we found only four such cases; see Table 4.

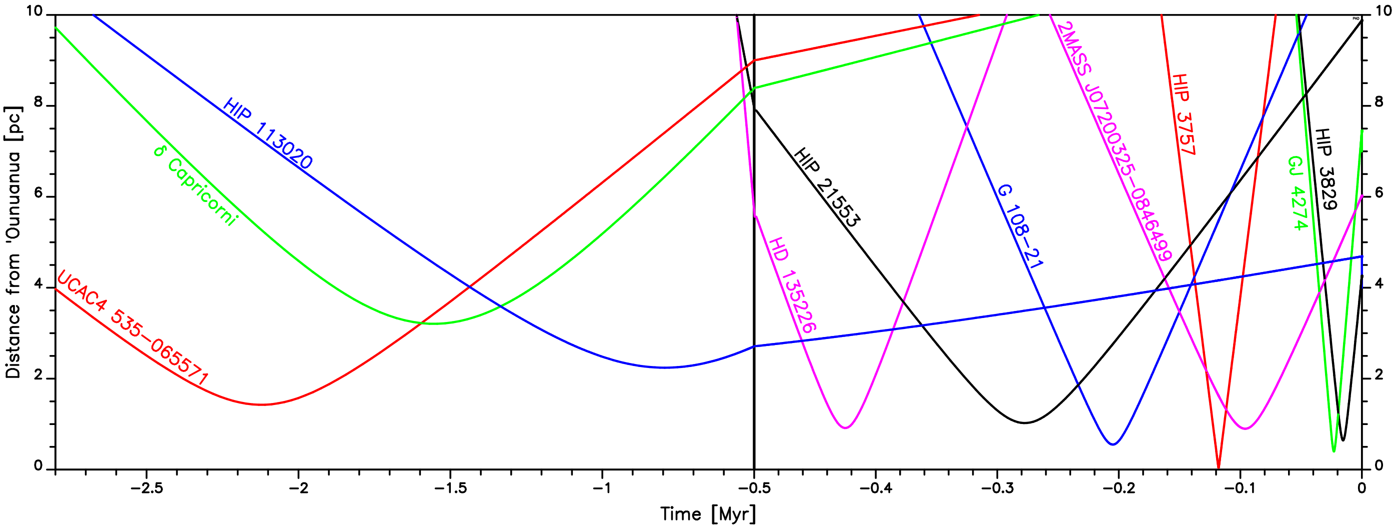

Fig. 2. Changes in the distance between 'Oumuamua and stars listed in Tables 3 and 4. Only HIP 981 and TYC 5325-1808-1 are omitted due to their unreliable kinematic data. Please note a horizontal scale change in the middle of the plot.

Table 4. Four cases of low-velocity encounters of 'Oumuamua with stars from our list.

Star name	Miss distance [pc]	Epoch [Myr]	Rel. velocity [km s^{-1}]	r_hel [pc]	Miss-distance interval [pc]
TYC 5325-1808-1	2.93291	−10.1215	7.940	269.220	Not tested
UCAC4 535-065571	1.42718	−2.1395	5.206	57.538	1.37201–1.48409
δ Capricorni	3.21225	−1.5259	6.872	41.049	3.16832–3.25921
HIP 113020	2.24104	−0.7907	3.927	21.278	2.21875–2.26360

Notes. Columns 2–5 are from the 59B calculation. Only the results for TYC 5325-1808-1 are from the three-body integration; see text for the explanation. The last column presents the miss-distance variation interval from the 10 000 clones of 'Oumuamua.

In Fig. 2 we show how the distance of 'Oumuamua from stars listed in Table 3 and Table 4 changed in time.

Almost 820 000 yr ago, 'Oumuamua passed near the star HIP 113020 (also known as BD-15 6290, GJ 876, or Ross 780) with a relative velocity of about 5 km s^{-1} and at a heliocentric distance of 21.3 pc. For the nominal 'Oumuamua orbit, the minimal distance between these two objects was 2.24 pc. However, it should be noted that (going backwards along its track) the motion of 'Oumuamua was perturbed by six stars from Table 3 as well as 51 other stars acting from larger distances of 1–3 pc. Every close passage of 'Oumuamua near a star magnifies starting point uncertainties, additionally increased by the stellar data errors. While most of the stars included in our calculations are M dwarfs with relatively small masses, some have masses greater than the Sun. However, while the stellar kinematics data uncertainties are the most important source of the proximity distance uncertainty, these are not estimated in this paper. To observe how the uncertainties of 'Oumuamua's orbit affect our results, we repeated our calculation of the 59B model for the 10 000 clones of 'Oumuamua. We individually searched for the closest and the farthest clone at the approach epoch and recorded the encounter parameters for each star, obtaining their variation intervals. For this number of clones, these intervals are wider than 3σ and are presented in the last column of Table 3. Similar data for all the studied stars may be found in Table A.3.

Three more low-velocity encounters happened further than 30 pc from the Sun. We recognised the encounters with the high-proper-motion star UCAC4 535-065571 and the eclipsing binary δ Capricorni as the most interesting ones. TYC 5325-1808-1 cannot be reliably included in our list of perturbers since its mass and spectral type are unknown. The correct mass value is indispensable for dynamically tracing such a long trip (almost 270 pc).

UCAC4 535-065571 is a red dwarf of M6V spectral type and its mass is estimated to be 0.205 $M_\odot$ (Newton et al. 2016) We obtained an encounter relative velocity of 5.35 km s^{-1} but with a minimum distance of 3.46 pc. With such a large miss-distance, one might reject this star as a parental candidate for 'Oumuamua. However, we noticed that the kinematics of UCAC4 535-065571 is rather poorly known. In the SIMBAD database we found its parallax, plx = 85.40 ± 3.30 mas (Dittmann et al. 2014), proper motions, pma = −107.0 ± 8 mas yr^{-1} and pmd = −133.0 ± 8 mas yr^{-1} (Zacharias et al. 2012), and radial velocity rv = −19 ± 5 km s^{-1} Newton et al. (2014). By manipulating numbers within their uncertainties, we obtained a miss distance of 0.6 pc but with a relative velocity of 10 km s^{-1} (by adopting: plx = 82.1 mas, pma = −99 mas yr^{-1}, pmd = 141 mas yr^{-1} and rv = 14.0 km s^{-1}). Alternative kinematic parameters for this star can also be found in West et al. (2015), where plx = 76 mas and rv = −9.5 km s^{-1}. The discrepancy between radial-velocity measurements might be connected with the rotational velocity of 43 km s^{-1} (Newton et al. 2016) for this star. Using these kinematic data, we obtained a nominal proximity distance of 0.4 pc but with a relative velocity of 14.7 km s^{-1}.

δ Capricorni (HIP 107556, GJ 837) is also a good candidate, with high-precision kinematic parameters. It is an eclipsing binary so its mass is also accurate and it has a small relative velocity of 6.9 km s^{-1}. 'Oumuamua passed this star at a rather large distance of 3.21 pc.

4. Discussion and conclusions

No obvious parent star has been identified. The closest 'Oumuamua – star proximity found by us, an encounter with HIP 3757 almost 120 000 yr ago, does not indicate that 'Oumuamua originated from this star system; it might be true provided some mechanism of ejecting 'Oumuamua from this system with the relative velocity of 185 km s^{-1} be proposed.

It seems more reasonable to search for the parent star of 'Oumuamua in the cases of a much smaller relative velocity. Utilising such an approach would make HIP 113020 a more promising candidate. This well known star (known also as BD-15 6290, GJ 876, or Ross 780) has a rich planetary system consisting of four planets: one very small and three other massive and strongly interacting planets; see for example Rivera et al. (2010) and the references therein. Our resulting miss distance is highly sensitive to the systemic radial velocity of the HIP 113020 system. There seems to be some discrepancy between the centre of mass velocity of about 0.5 km s^{-1} obtained in the paper quoted above and the value presented in the SIMBAD database: -1.519 ± 0.157 km s^{-1} (Terrien et al. 2015). Taking into account that the motion of 'Oumuamua was perturbed by tens of stars after passing HIP 113020 and that kinematic parameters (and masses) of these perturbers are of a significantly different quality and accuracy, we cannot rule out the possibility that 'Oumuamua originated from the HIP 113020 planetary system. Definitively, we have to wait for much more precise stellar data from the *Gaia* mission (Gaia Collaboration 2016b).

In our results obtained for the vicinity of the Sun there is yet another nearby star worth mentioning. 'Oumuamua nominally passed HIP 21553 at a distance of 1.02287 pc almost 280 000 yr ago with a relative velocity of less than 35 km s^{-1}. HIP 21553 (also known as HD 232979 or GJ 172) is a M0.5V-type red dwarf according to SIMBAD (Keenan & McNeil 1989). Its astrometric data were recently highly improved by the *Gaia* mission (Gaia Collaboration 2016b).

Additionally, we found another candidate past the 30-pc heliocentric distance, the star UCAC4 535-065571. By varying this star's position and velocity within their respective uncertainty intervals, we obtained a very close encounter with 'Oumuamua at a reasonably small relative velocity of 5–15 km s^{-1}. It seems necessary to study the kinematics of this star in more detail in order to make any definitive conclusion on the putative relation between this star and 'Oumuamua. There is also a small probability that 'Oumuamua comes from δ Capricorni.

An equally interesting hypothesis is that this interstellar object came to our planetary system from a more distant source.

Over the studied period of the past few million years, the heliocentric trajectory of 'Oumuamua appears to be almost a straight line with an approximately constant velocity. This is mainly because of its great velocity, relatively large distance from perturbing stars, and their small masses (in most cases). This fact is illustrated in several figures included in Appendix B. One can also see in Fig. 1 that the deviation from the straight line motion is also very slight in the Galactocentric frame over a similar time interval.

Another important conclusion from our work is that despite the short observational interval of 'Oumuamua, its original orbit uncertainties do not influence our results in any significant way.

There recently appeared a preprint by S. Portegies Zwart and colleagues (Portegies Zwart et al. 2017) in which the authors propose five other stars as potential sources for 'Oumuamua. We carefully checked all these cases and according to our calculations 'Oumuamua did not come closer than 20 pc to any of these stars. A probable reason for this finding is that an approximate dynamical model was used in the quoted paper, where as in all five cases these stars are very distant and therefore their motion is sensitive to the dynamical model details, especially the mutual interactions between all stars involved. Such a disagreement is also noted in Feng & Jones (2018). On the contrary, these authors confirm our results for overlapping stars.

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Appendix A: Supplementary material

Table A.1. 109 individual objects selected form the SIMBAD data that fulfil the following conditions: an object must approach 'Oumuamua closer than 3.5 pc before leaving the heliocentric sphere of 300 pc radius.

Star name	Alternative name	Min. dist [pc]	Epoch [Myr]	Vrel [km s^{-1}]	r_hel [pc]
LP 646-17	HIP 3757	0.04378	−0.117935	207.96	3.175
GJ 4274	LP 820-12	0.41594	−0.022642	316.28	0.611
HD 761	HIP 981	0.50883	−6.674040	17.66	178.558
GJ 3404 A	TYC 151-860-1	0.55191	−0.204269	61.21	5.498
Wolf 28	HIP 3829	0.65803	−0.016006	266.49	0.432
2MASS J07200325-0846499		0.90252	−0.094773	60.63	2.552
HD 135226	BD-03 3748	0.91695	−0.423887	73.23	11.408
HD 232979	HIP 21553	1.03139	−0.281024	34.65	7.564
TYC 5855-2215-1		1.04275	−6.751784	39.20	180.616
2MASS J10433508+1213149		1.15503	−0.053937	266.61	1.453
α Centauri B	HIP 71681	1.25515	0.000000	35.39	0.001
Proxima Centauri	HIP 70890	1.30223	0.000000	37.09	0.001
α Centauri A	HIP 71683	1.32516	0.000000	35.03	0.001
α Centauri AB		1.34803	0.000000	36.57	0.001
UCAC4 535-065571		1.42794	−2.140431	5.36	57.564
GJ 358	HIP 47425	1.54383	−0.073742	122.26	1.986
GJ 793	HIP 101180	1.67110	−0.236802	32.72	6.374
Capella	HIP 24608	1.75796	−0.485275	25.83	13.060
GJ 9603	HIP 86916	1.79609	−0.451911	43.43	12.163
Barnard's star	HIP 87937	1.82274	0.000000	134.83	0.001
GJ 4063	TYC 3109-1699-1	1.82991	−0.175405	40.07	4.722
GJ 195 A	Capella H	1.84076	−0.410834	32.61	11.057
HD 200325	HIP 103749	1.85997	−4.379190	12.06	117.531
G 208-45	GJ 1245 B	1.94326	−0.119017	33.73	3.204
HZ 10	WD 0407+179	1.97167	−0.545641	68.15	14.685
HD 8671	HIP 6711	1.97438	−1.106171	37.96	29.765
BD+31 637	TYC 2355-291-1	2.02908	−5.090162	26.82	136.492
GJ 9492	HIP 71898	2.03615	−0.282622	37.33	7.607
L 923-22	GJ 754.1 B	2.05851	−0.176115	59.26	4.741
HD 24546	HIP 18453	2.06574	−0.907453	40.07	24.419
G 208-44	GJ 1245 A	2.07612	−0.122176	31.54	3.289
LP 160-22		2.09918	−0.526624	34.54	14.173
HIP 34603	GJ 268	2.10932	−0.188072	31.99	5.063
2MASS J18212815+1414010		2.11724	−0.251783	35.39	6.777
GJ 65 B		2.15456	−0.039837	34.10	1.073
GJ 909 A	HIP 117712	2.17334	−0.521136	20.37	14.025
Wolf 359	GJ 406	2.20907	−0.027371	30.60	0.738
GJ 876	HIP 113020	2.24392	−0.817099	5.07	21.989
GJ 3376 A	HIP 28267	2.24657	−0.198471	121.88	5.342
Kapteyn's star	HIP 24186	2.28553	−0.010651	270.91	0.288
TYC 8470-213-1		2.30049	−0.172274	229.85	4.637
APMPM J0237-5928		2.30106	−0.097524	97.49	2.626
GJ 3287		2.31517	−1.072967	20.63	28.872
G 203-47	HIP 83945	2.32770	−0.093300	78.09	2.512
HD 91962	HIP 51966	2.36104	−3.529085	11.12	94.802
GJ 433.1	HIP 56662	2.43579	−0.126051	119.04	3.394
HD 175726	HIP 92984	2.46005	−0.772211	33.25	20.781
GJ 688	HIP 86400	2.46025	−0.255395	40.83	6.874
HD 162826	HIP 87382	2.51056	−1.196101	27.79	32.183
η Casiopei B	GJ 34 B	2.52756	−0.205075	25.37	5.520

Notes. Stars are sorted here by the proximity distance. To speed up the selection procedure, the motion of each object was traced individually as a three-body problem under the influence of the full Galactic potential. For its nominal orbit, we recorded the minimum 'Oumuamua – star distance (Min dist), moment of this approach (Epoch), relative velocity (Vrel), and heliocentric distance of the approach (r_hel). A proximity epoch equalling zero means that the star's closest position was at the beginning of the backward numerical integration when 'Oumuamua was at 250 AU from the Sun.

Table A.1. continued.

Star name	Alternative name	Min. dist [pc]	Epoch [Myr]	Vrel [km s^{-1}]	r_hel [pc]
HD 113376	HIP 63797	2.52972	−2.856293	40.47	76.776
GJ 1095	HIP 35136	2.54526	−0.197668	81.92	5.321
GJ 411	HIP 54035	2.54679	0.000000	93.39	0.001
HD 201671	HIP 104539	2.55447	−10.508025	10.14	279.312
2MASSI J1835379+325954		2.58023	−0.122667	39.52	3.302
2MASS J05565722+1144333		2.60458	−0.085689	144.85	2.307
Aldebaran	HIP 21421	2.60688	−0.492455	40.82	13.254
Sirius	HIP 32349	2.63821	0.000000	31.91	0.001
GJ 9105 C	HD 18143C	2.67215	−0.534272	28.67	14.379
GJ 725 B	HIP 91772	2.70964	−0.058137	39.30	1.566
CD-56 1032	HIP 22738	2.75803	−0.613484	17.28	16.510
GJ 725 A	HIP 91768	2.77896	−0.058064	36.82	1.564
GJ 54.1	HIP 5643	2.79505	−0.070215	32.52	1.891
[D75b] Star 1	G 217-32	2.82886	−0.790870	17.31	21.283
GJ 752	HIP 94761	2.83223	−0.070143	66.46	1.889
GJ 15 A	HIP 1475	2.87070	−0.048115	39.20	1.296
LP 412-31		2.87170	−0.357225	38.54	9.615
GJ 644	HIP 82817	2.87451	−0.146364	36.53	3.940
TYC 7693-1161-1		2.90315	−0.734088	47.41	19.755
η Casiopei	HIP 3821	2.90499	−0.212720	23.37	5.726
GJ 729	HIP 92403	2.91228	−0.027389	21.15	0.738
GJ 15 B	HD 1326B	2.91483	−0.048154	38.84	1.297
TYC 5325-1808-1		2.93291	−10.121533	7.94	269.220
HD 317657	TYC 7375-47-1	2.93350	−0.408810	327.01	11.003
Teegarden's star	GAT 1370	2.94180	−0.027297	86.90	0.736
GJ 376 B	HD 86728B	2.95912	−0.255745	53.14	6.884
TYC 5172-2349-1		3.00558	−4.680653	35.14	125.576
GJ 702	HIP 88601	3.01970	−0.218690	19.04	5.887
Ruiz 207-61		3.09432	−0.146225	89.76	3.936
GJ 159.1	HG 8-7	3.09673	−0.329203	79.37	8.861
HD 18768	HIP 14181	3.09713	−0.474439	99.02	12.769
GJ 213	HIP 26857	3.10918	−0.048199	104.39	1.298
GJ 644 C		3.12047	−0.147195	37.54	3.963
GJ 752 B	VB 10	3.12731	−0.085166	61.00	2.293
GJ 905	Ross 248	3.15691	0.000000	68.58	0.001
GJ 160.1	HIP 19255	3.17841	−0.872863	22.35	23.489
δ Capricorni	HIP 107556	3.20613	−1.557216	7.20	41.893
HD 172051	HIP 91438	3.21372	−0.230299	52.90	6.199
ϵ Eridani	HIP 16537	3.21684	0.000000	33.32	0.001
GJ 701	HIP 88574	3.24097	−0.121593	58.79	3.274
GJ 643	HIP 82809	3.25322	−0.147410	37.72	3.968
GJ 887	HIP 114046	3.26819	−0.002325	93.26	0.064
LHS 1817	LP 86-173	3.27213	−0.097496	134.53	2.625
Wolf 1059	LHS 5131	3.27918	−0.090442	258.71	2.435
GJ 109	HIP 12781	3.33010	−0.212547	29.78	5.721
GJ 447	HIP 57548	3.38087	0.000000	47.70	0.001
2MASS J16452211-1319516		3.38729	−0.174101	45.74	4.687
HD 132730	TYC 8681-841-1	3.39323	−3.989147	15.80	107.110
GJ 866	LP 820-64	3.40568	0.000000	78.04	0.001
GJ 745 A	HIP 93873	3.41696	−0.121135	62.74	3.261
G 123-45		3.42044	−0.463265	22.31	12.468
HD 174153	HIP 92519	3.43893	−0.646559	77.15	17.400
GJ 3988	LHS 3262	3.44475	−0.119955	70.73	3.229
GJ 663 A	TYC 6820-326-1	3.44561	−0.261330	14.76	7.034
GJ 745 B	HIP 93899	3.45640	−0.121402	62.52	3.268
GJ 170	LHS 1674	3.45761	−0.403927	25.86	10.871
BD+50 860B	TYC 3339-1311-1	3.47850	−1.406654	26.18	37.845
61 Cygni A	HIP 104214	3.48546	0.000000	88.99	0.001
61 Cygni B	HIP 104217	3.49692	0.000000	86.54	0.001

Table A.2. Final list of 57 stars or star systems used as perturbers in our final dynamical model of 'Oumuamua's motion.

Star name	Mass [$M_\odot$]	X [pc]	Y [pc]	Z [pc]	Vx [pc Myr^{-1}]	Vy [pc Myr^{-1}]	Vz [pc Myr^{-1}]	Ref.
HIP 3757	0.4	−4.869905	8.163363	−23.203674	−52.989230	46.668895	−204.591445	1,1,1,2,3
GJ 4274	0.14	3.223762	2.957145	−6.039148	141.140365	94.217546	−267.797888	4,5,6,2,7
TYC 151-860-1	0.23	−11.260623	−6.162569	−0.094524	−66.113087	−53.790236	−5.867103	5,8,9,10,11
HIP 3829, Wolf 28	0.68	−1.210292	1.945959	−3.594159	−72.175698	69.395114	−257.111463	12,12,12,13,14
2MASS J07200325-0846499	0.08	−4.426203	−4.074046	0.317199	−60.908353	−59.344984	1.872151	4,15,15,16,17
TYC 5009-283-1	1.0	23.021112	−1.443553	21.958699	43.238409	−24.467213	42.944681	18,18,18,19,2
HIP 21553	0.6	−8.799950	4.438152	0.669586	−43.309867	−8.021714	−1.980970	1,1,1,20,21
2MASS J10433508+1213149	0.08	−4.833887	−6.430379	12.182001	−83.878243	−136.754016	229.107657	4,22,22,22,23
α Cent AB + Proxima system	2.17	0.935517	−0.893740	0.017400	−29.182899	1.017810	12.535209	12,12,12+24,25+26+27,28
UCAC4 535-065571	0.205	8.142407	6.867308	4.863749	−8.368095	−19.233016	−5.616024	4,5,9,10,21
HIP 47425	0.34	−0.270092	−9.499987	1.460452	−33.489157	−143.256893	18.063286	1,1,1,29,30
HIP 101180	0.39	−1.342284	7.662756	2.093016	−20.645740	9.234058	−5.321937	1,1,1,31,32
HIP 24608	5.06	−12.482300	3.914475	1.044814	−36.754471	−14.635561	−9.310078	12,12,12,33,34
HIP 86916	0.5	4.967614	16.744254	10.225582	2.385149	14.079262	12.221230	1,1,1,35,32
TYC 3109-1699-1	0.2	2.479393	6.336940	2.491140	10.607473	10.433390	0.444911	5,8,36,37,38
HIP 87937	0.16	1.516300	0.911399	0.443149	−144.200647	4.701043	18.610843	12,12,12,31,41
HZ 10	1.0	−34.764964	2.772228	−15.508177	−75.377293	−14.473130	−34.971842	5,5,39,40,42
HIP 6711	1.39	−25.879842	31.269062	−13.945369	−35.841132	5.440825	−18.856965	1,1,1,13,43
GJ 1245 ABC system	0.28	0.868629	4.410703	0.672563	6.129215	4.675136	−11.727727	5,5+44,45,10+46,47
HIP 71898	0.48	−2.134723	7.105483	8.076950	−12.242474	1.061814	21.798225	1,1,1,31,50
L 923-22	0.1	9.336853	5.513232	−1.784881	38.014847	11.743817	−7.341221	48,5,49,37,30
HIP 34603	0.33	−5.917432	0.108014	2.143010	−44.405820	−22.043392	−7.659702	12,12,12,33,51
GJ 65 AB	0.21	−0.697183	0.119872	−2.527542	−44.334435	−18.602954	−19.451010	52,52,52,53+54,55
HIP 117712	1.09	−5.173173	9.260300	2.469058	−18.194848	−4.381304	−0.938894	12,12,12,13,56
GJ 406	0.09	−0.583077	−1.198362	1.984705	−28.448478	−48.653982	−13.935499	4,5,45,37,45
HIP 28267	1.3	−20.646959	−11.843636	−5.640298	−110.785271	−92.744647	−36.941301	1,1,1,31,57
HIP 113020	0.334	1.441102	1.905640	−4.034279	−12.583839	−20.164310	−12.213344	12,12,12,37,58
TYC 8470-213-1	1.0	15.179662	−15.745125	−34.620438	82.441710	−102.422426	−208.063306	1,1,1,2,2
HIP 24186	0.39	−1.057028	−2.982685	−2.299061	19.991822	−294.248666	−54.060419	12,12,12,31,59
APMPM J0237-5928	0.22	0.989962	−5.626783	−7.766258	−23.371954	−73.481326	−93.028655	5,60,61,2,62
HIP 83945	0.266	2.166005	5.597234	4.406165	26.034702	41.869697	19.607791	12,12,12,37,47
HIP 56662	0.935	−4.247950	−1.484937	15.153736	−41.484216	−15.924967	109.922558	12,12,12,63,64
HIP 86400	0.85	9.274425	4.883523	3.336740	17.935902	−0.693717	11.375820	12,12,12,19,65
HIP 35136	0.9	−15.269627	2.598365	6.739659	−81.650214	−1.684617	33.045457	12,12,12,31,66
HIP 54035	0.46	−1.054711	−0.094472	2.316283	47.197616	−54.908745	−75.981741	12,12,12,31,67
2MASSI J1835379+325954	0.07	2.435869	4.513765	1.611691	21.323286	−0.059501	−3.403988	4,68,9,69,9
2MASS J05565722+1144333	0.15	−12.556104	−3.645129	−1.479015	−148.572944	−78.990706	0.269334	4,44,9,70,71
HIP 32349	2.99	−1.815217	−1.874932	−0.379090	13.087100	−2.296652	−12.179029	12,12,12,13,72
GJ 725 AB system	0.58	0.039863	3.202252	1.441291	−25.325856	−11.833516	26.619384	1,1,1,31,47
HIP 22738	0.7	−1.192678	−8.579194	−6.955349	−9.646365	−35.215095	−20.407536	12,12,12,29,50
HIP 5643	0.13	−0.692360	0.466957	−3.594156	−29.284995	0.424845	−23.796103	12,12,12,31,30
GJ 752 AB system	0.55	4.481805	3.820433	−0.338091	53.884411	−8.729523	−5.101046	4+1,73+1,73+1,10+20,47
GJ 15 AB system	0.65	−1.519073	3.023091	−1.128502	−50.153963	−12.747165	−3.667871	1+4,1+44,1+74,31+37,21
HIP 92403	0.17	2.855273	0.650863	−0.493625	−12.182465	−1.279999	−7.549572	12,12,12,31,21
Teegarden's star	0.08	−2.883244	1.034454	−2.310472	−66.768384	−73.067253	−56.387473	4,44,61,10,21
HIP 88601	1.62	4.320600	2.483796	1.001895	6.169135	−19.189299	−14.679349	12,12,12,75,76
Ruiz 207-61	0.08	−2.466202	−13.392706	−4.316815	−44.855241	−106.443188	−26.577086	4,68,45,77,78
HIP 26857	0.18	−5.590121	−1.363571	−0.933193	−91.980164	−91.361241	8.418275	12,12,12,79,47
Ross 248	0.12	−1.032642	2.838561	−0.920011	33.153204	−76.262790	0.284634	4,80,80,37,21
HIP 91438	0.9	12.669348	2.882727	−1.537885	38.206785	−2.328500	−4.403618	12,12,12,19,81
δ Capricorni	2.06	6.511185	5.075845	−8.523903	−7.436483	−18.343120	−11.762829	12,12,12,33,82
HIP 16537	0.85	−2.098618	−0.549497	−2.374208	−3.862226	7.417522	−21.063553	12,12,12,31,83
HIP 88574	0.5	6.950725	3.231218	1.200757	33.830913	14.644326	−19.358860	12,12,12,31,30
HIP 114046	0.53	1.299173	0.211052	−2.999850	−96.274433	−13.614020	−51.028239	12,12,12,84,30
HIP 57548	0.16	0.004397	−1.712804	2.914646	18.364701	5.194591	−33.949087	1,1,1,37,21
GJ 866 ABC system	0.30	1.249826	1.390358	−2.847040	−69.843346	−1.090148	42.215336	4,85,86,25,87
61 Cyg AB system	1.33	0.464345	3.442752	−0.354214	−95.544501	−55.395340	−8.848684	12,12,12,31,88

Notes. Heliocentric Galactic velocities are in parsec per Myr. To obtain velocities in km s^{-1}, each component must be divided by 1.0227. Stars are presented here in the same sequence as in Table A.3. In the last column we include references for all data used to produce this table. For each star or stellar system we present sources of: positions, proper motions, parallaxes, radial velocities and masses in this order. In some cases of multiple systems we present individual member references connected with a plus sign.

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Table A.3. Minimal distances between the 10 000 clones of 'Oumuamua and 57 stars included in our research.

Star name	Min. dist [pc]	Epoch [Myr]	Rel. velocity [km s^{-1}]	dist_hel [pc]
HIP 3757	0.042 : 0.044 : 0.047	0.1179 : 0.1179 : 0.1180	208.00 : 207.96 : 207.92	3.17 : 3.17 : 3.18
GJ 4274	0.411 : 0.412 : 0.413	0.0227 : 0.0227 : 0.0227	316.28 : 316.27 : 316.27	0.61 : 0.61 : 0.61
TYC 151-860-1	0.543 : 0.551 : 0.559	0.2044 : 0.2046 : 0.2047	61.24 : 61.21 : 61.17	5.50 : 5.51 : 5.52
HIP 3829, Wolf 28	0.644 : 0.644 : 0.645	0.0152 : 0.0152 : 0.0152	266.50 : 266.49 : 266.52	0.41 : 0.41 : 0.41
2MASS J07200325-0846499	0.899 : 0.900 : 0.901	0.0953 : 0.0953 : 0.0954	60.65 : 60.63 : 60.60	2.56 : 2.57 : 2.57
TYC 5009-283-1	0.920 : 0.924 : 0.928	0.4271 : 0.4270 : 0.4268	73.18 : 73.23 : 73.29	11.48 : 11.49 : 11.50
HIP 21553	1.013 : 1.023 : 1.033	0.2772 : 0.2774 : 0.2778	34.67 : 34.65 : 34.62	7.45 : 7.47 : 7.49
2MASS J10433508+1213149	1.154 : 1.157 : 1.160	0.0540 : 0.0540 : 0.0540	266.60 : 266.62 : 266.63	1.45 : 1.45 : 1.46
α Cen AB + Proxima system	1.294 : 1.294 : 1.294	0.0000 : 0.0000 : 0.0000	35.27 : 35.27 : 35.27	0.00 : 0.00 : 0.00
UCAC4 535-065571	1.372 : 1.427 : 1.484	2.1292 : 2.1395 : 2.1490	5.40 : 5.36 : 5.32	57.33 : 57.54 : 57.73
HIP 47425	1.517 : 1.519 : 1.521	0.0758 : 0.0758 : 0.0758	122.26 : 122.26 : 122.26	2.04 : 2.04 : 2.04
HIP 101180	1.659 : 1.671 : 1.683	0.2346 : 0.2345 : 0.2344	32.71 : 32.72 : 32.72	6.32 : 6.31 : 6.30
HIP 24608	1.732 : 1.748 : 1.764	0.4927 : 0.4927 : 0.4928	25.79 : 25.83 : 25.87	13.28 : 13.26 : 13.25
HIP 86916	1.790 : 1.794 : 1.799	0.4533 : 0.4533 : 0.4532	43.40 : 43.43 : 43.46	12.19 : 12.20 : 12.21
TYC 3109-1699-1	1.820 : 1.822 : 1.823	0.1705 : 0.1710 : 0.1715	40.04 : 40.07 : 40.10	4.58 : 4.60 : 4.62
HIP 87937	1.823 : 1.823 : 1.823	0.0000 : 0.0000 : 0.0000	134.80 : 134.83 : 134.86	0.00 : 0.00 : 0.00
HZ 10	1.964 : 1.975 : 1.986	0.5450 : 0.5449 : 0.5447	68.20 : 68.15 : 68.10	14.65 : 14.66 : 14.68
HIP 6711	1.958 : 1.976 : 1.995	1.1063 : 1.1068 : 1.1074	37.99 : 37.96 : 37.93	29.73 : 29.78 : 29.83
GJ 1245 ABC system	2.023 : 2.024 : 2.024	0.1238 : 0.1225 : 0.1229	32.31 : 32.33 : 32.35	3.33 : 3.30 : 3.31
HIP 71898	2.025 : 2.038 : 2.052	0.2844 : 0.2845 : 0.2848	37.30 : 37.33 : 37.36	7.64 : 7.66 : 7.67
L 923-22	2.051 : 2.056 : 2.060	0.1790 : 0.1769 : 0.1771	59.23 : 59.26 : 59.30	4.81 : 4.76 : 4.77
HIP 34603	2.091 : 2.098 : 2.105	0.1819 : 0.1818 : 0.1815	31.95 : 31.99 : 32.03	4.90 : 4.89 : 4.88
GJ 65 AB	2.151 : 2.152 : 2.153	0.0438 : 0.0438 : 0.0438	34.15 : 34.10 : 34.05	1.18 : 1.18 : 1.18
HIP 117712	2.138 : 2.166 : 2.194	0.5135 : 0.5135 : 0.5134	20.37 : 20.37 : 20.37	13.80 : 13.82 : 13.83
GJ 406	2.207 : 2.208 : 2.209	0.0295 : 0.0295 : 0.0295	30.57 : 30.60 : 30.63	0.80 : 0.80 : 0.79
HIP 28267	2.211 : 2.215 : 2.219	0.1951 : 0.1955 : 0.1958	121.92 : 121.88 : 121.84	5.25 : 5.26 : 5.28
HIP 113020	2.219 : 2.241 : 2.264	0.7902 : 0.7907 : 0.7917	5.04 : 5.07 : 5.11	21.29 : 21.28 : 21.28
TYC 8470-213-1	2.263 : 2.268 : 2.276	0.1738 : 0.1743 : 0.1746	229.86 : 229.85 : 229.83	4.67 : 4.69 : 4.71
HIP 24186	2.273 : 2.274 : 2.274	0.0115 : 0.0115 : 0.0115	270.91 : 270.91 : 270.90	0.31 : 0.31 : 0.31
APMPM J0237-5928	2.274 : 2.278 : 2.282	0.0954 : 0.0953 : 0.0953	97.45 : 97.49 : 97.52	2.57 : 2.57 : 2.56
HIP 83945	2.297 : 2.298 : 2.299	0.0889 : 0.0888 : 0.0888	78.12 : 78.09 : 78.05	2.40 : 2.39 : 2.39
HIP 56662	2.419 : 2.421 : 2.425	0.1282 : 0.1288 : 0.1293	119.01 : 119.04 : 119.06	3.45 : 3.47 : 3.49
HIP 86400	2.459 : 2.461 : 2.463	0.2552 : 0.2548 : 0.2544	40.88 : 40.83 : 40.79	6.88 : 6.86 : 6.84
HIP 35136	2.533 : 2.542 : 2.551	0.1990 : 0.1995 : 0.1998	81.94 : 81.92 : 81.91	5.35 : 5.37 : 5.38
HIP 54035	2.547 : 2.547 : 2.547	0.0000 : 0.0000 : 0.0000	93.39 : 93.39 : 93.39	0.00 : 0.00 : 0.00
2MASSI J1835379+325954	2.569 : 2.569 : 2.570	0.1173 : 0.1173 : 0.1162	39.48 : 39.52 : 39.55	3.15 : 3.16 : 3.13
2MASS J05565722+1144333	2.605 : 2.608 : 2.612	0.0854 : 0.0854 : 0.0854	144.89 : 144.85 : 144.81	2.30 : 2.30 : 2.30
HIP 32349	2.638 : 2.638 : 2.638	0.0000 : 0.0000 : 0.0000	31.89 : 31.91 : 31.94	0.00 : 0.00 : 0.00
GJ 725 AB system	2.747 : 2.748 : 2.748	0.0573 : 0.0573 : 0.0573	37.89 : 37.87 : 37.85	1.54 : 1.54 : 1.54
HIP 22738	2.740 : 2.758 : 2.776	0.6045 : 0.6042 : 0.6145	17.30 : 17.28 : 17.26	16.25 : 16.26 : 16.56
HIP 5643	2.792 : 2.794 : 2.796	0.0721 : 0.0721 : 0.0721	32.55 : 32.52 : 32.48	1.94 : 1.94 : 1.95
GJ 752 AB system	2.840 : 2.841 : 2.842	0.0775 : 0.0775 : 0.0775	65.63 : 65.67 : 65.71	2.08 : 2.09 : 2.09
GJ 15 AB system	2.875 : 2.876 : 2.876	0.0526 : 0.0526 : 0.0526	39.14 : 39.11 : 39.07	1.41 : 1.42 : 1.42
HIP 92403	2.911 : 2.912 : 2.913	0.0270 : 0.0270 : 0.0262	21.16 : 21.16 : 21.15	0.73 : 0.73 : 0.71
Teegarden's star	2.941 : 2.942 : 2.942	0.0277 : 0.0277 : 0.0277	86.95 : 86.90 : 86.85	0.75 : 0.75 : 0.75
HIP 88601	3.007 : 3.015 : 3.023	0.2105 : 0.2103 : 0.2102	19.06 : 19.04 : 19.01	5.67 : 5.66 : 5.65
Ruiz 207-61	3.047 : 3.052 : 3.052	0.1509 : 0.1538 : 0.1537	89.73 : 89.76 : 89.77	4.07 : 4.14 : 4.14
HIP 26857	3.101 : 3.103 : 3.105	0.0457 : 0.0458 : 0.0458	104.41 : 104.39 : 104.36	1.23 : 1.23 : 1.24
Ross 248	3.157 : 3.157 : 3.157	0.0000 : 0.0000 : 0.0000	68.56 : 68.58 : 68.61	0.00 : 0.00 : 0.00
HIP 91438	3.202 : 3.206 : 3.210	0.2344 : 0.2345 : 0.2346	52.86 : 52.90 : 52.94	6.30 : 6.31 : 6.32
δ Capricorni	3.168 : 3.212 : 3.259	1.5214 : 1.5259 : 1.5317	7.20 : 7.20 : 7.21	40.88 : 41.05 : 41.26
HIP 16537	3.217 : 3.217 : 3.217	0.0000 : 0.0000 : 0.0000	33.32 : 33.32 : 33.32	0.00 : 0.00 : 0.00
HIP 88574	3.225 : 3.231 : 3.236	0.1173 : 0.1173 : 0.1173	58.81 : 58.79 : 58.76	3.16 : 3.16 : 3.15
HIP 114046	3.268 : 3.268 : 3.268	0.0023 : 0.0023 : 0.0023	93.31 : 93.26 : 93.21	0.06 : 0.06 : 0.06
HIP 57548	3.381 : 3.381 : 3.381	0.0000 : 0.0000 : 0.0000	47.71 : 47.70 : 47.70	0.00 : 0.00 : 0.00
GJ 866 ABC system	3.406 : 3.406 : 3.406	0.0000 : 0.0000 : 0.0000	78.05 : 78.04 : 78.04	0.00 : 0.00 : 0.00
61 Cyg AB system	3.491 : 3.491 : 3.491	0.0000 : 0.0000 : 0.0000	87.79 : 87.83 : 87.86	0.00 : 0.00 : 0.00

Notes. Here we present variation intervals roughly equivalent to the $\pm 4\sigma$ deviations, obtained from among the 10 000 encounters. In the last column we present a heliocentric distance for this event. Epochs are in the past, but minuses are omitted. Proximity epochs equal to zero mean that the star's closest position is at the beginning of the backward numerical integration (but they are still acting as perturbers).

Appendix B: Geometry examples of 'Oumuamua encounters with selected stars

Below we present six plots of the example geometries of the close 'Oumuamua – star passages. We use here a heliocentric, non-rotating, right-handed rectangular frame. The XY plane is parallel to the Galactic disk plane and the OX axis is directed to the Galactic Centre at the beginning of the calculation. Green lines depict the 'Oumuamua motion while the red ones show the star trajectory. Open circles mark the starting positions of 'Oumuamua and the star.

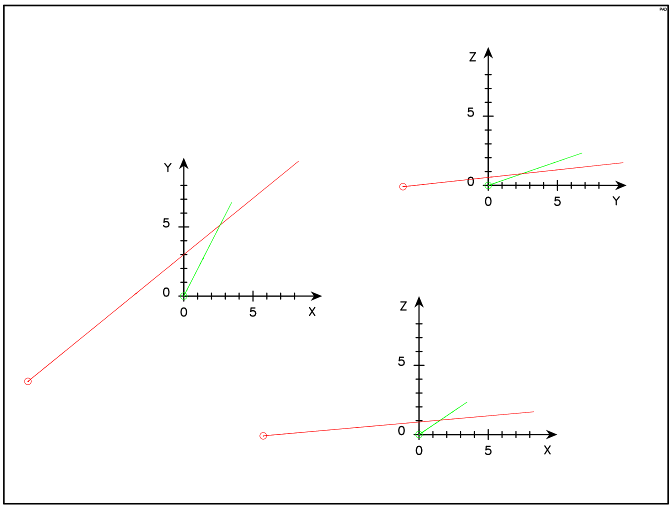

Fig. B.1. Geometry of the encounter of 'Oumuamua with the star G 108-21 0.2 Myr ago. Depicted is 0.3 Myr of their motion.

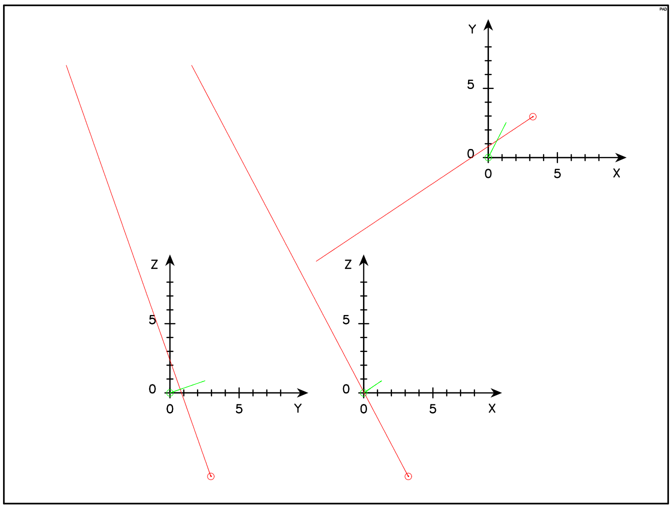

Fig. B.2. Geometry of the encounter of 'Oumuamua with the star GJ 4274 23 kyr ago. 112 kyr of motion of these bodies is shown here.

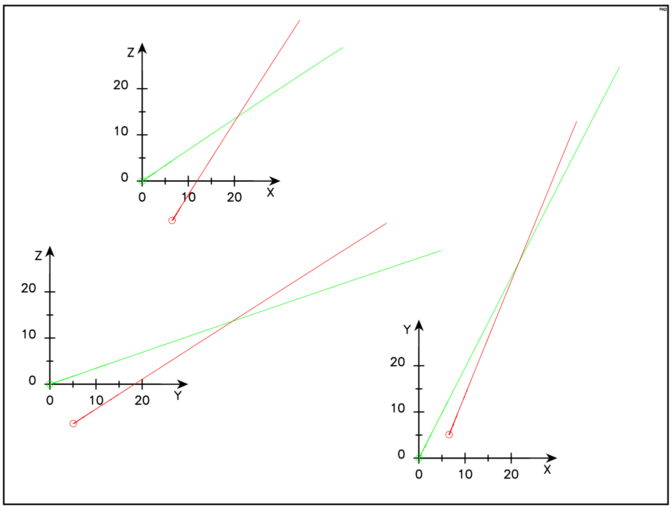

Fig. B.3. Geometry of the encounter of 'Oumuamua with the star δ Capricorni 1.5 Myr ago. Their past motion over 3.74 Myr is shown.

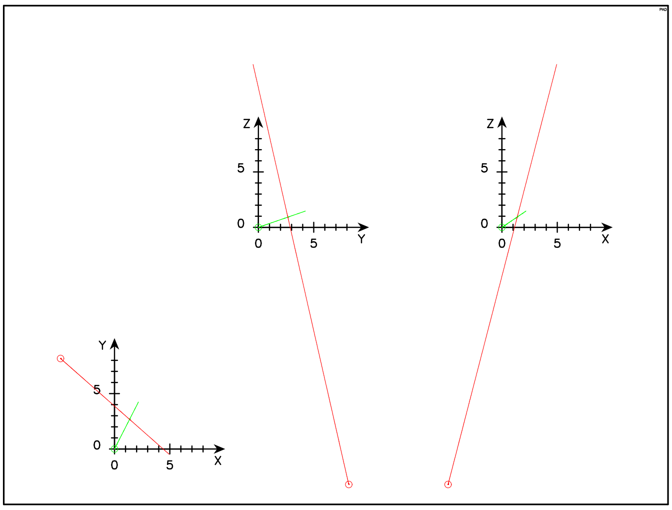

Fig. B.4. Geometry of the encounter of 'Oumuamua with the star HIP 3757 118 kyr ago. 186 kyr of motion of these bodies is shown here.

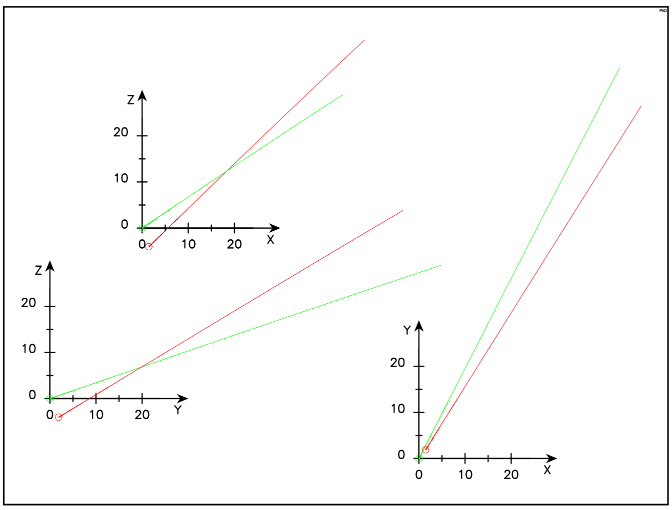

Fig. B.5. Geometry of the encounter of 'Oumuamua with the star HIP 113020 0.8 Myr ago. Past motion during 3.74 Myr is shown.

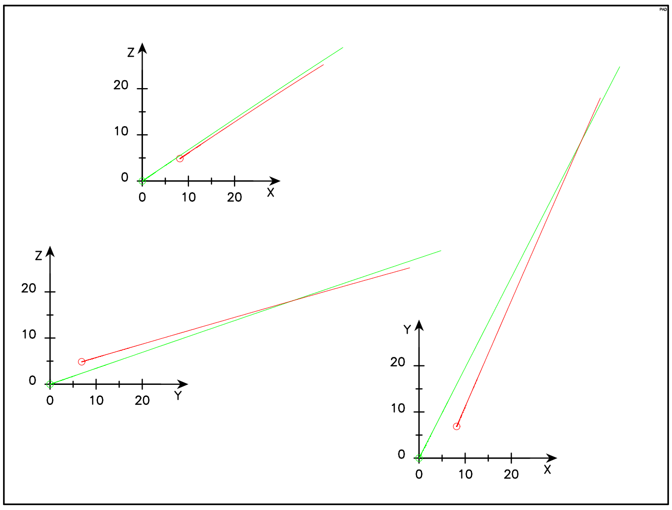

Fig. B.6. Geometry of the encounter of 'Oumuamua with the star UCAC4 535-065571 2.14 Myr ago. Past motion during 3.74 Myr is shown.