Investigation on the Potential Origin of ‘Oumuamua

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Abstract

‘Oumuamua, or 1I/2017 U1 in formal classification, is the first interstellar visitor to our system that we have recorded. Since its discovery, a problem of particular interest is determining the exact origin point of the interstellar object; thus, our project attempts to pinpoint the original system of ‘Oumuamua before it began its galactic journey.

We present the result of our attempt of constraining the potential origin system of ‘Oumuamua. We combined the orbital parameter of ‘Oumumaua from Minor Planet Centre (MPC) and JPL Horizons with astrometric measurements of ~7.1 million stars from *Gaia* DR2 to trace back the stellar kinematic history in the past 10 million years. Propagating the errors in a Monte Carlo (MC) fashion, we identified 36 close encounters with ‘Oumuamua within 2 pc; ‘Oumuamua even approached 7 out of the 36 stars within a distance of 1 pc! We think the most probable home candidate is GJ 195A due to its binary nature, and HIP 3757 due to a combined consideration of closest approach time, distance and relative speed.

Constraining Orbit

Our first objective in determining the extrasolar origin was establishing orbital parameters of ‘Oumuamua within our solar system. We utilized data from the Minor Planet Center and JPL Horizons to reconstruct ‘Oumuamua’s orbital path in 3D, and began a rotation, leading into a coordinate transformation. We carried out the first rotation for longitude of ascending node, second rotation for inclination, and third rotation for argument of periapsis. We transformed these heliocentric coordinates into galactocentric coordinates so that it is a lot simpler to work with the velocity vectors and *Gaia* data set.

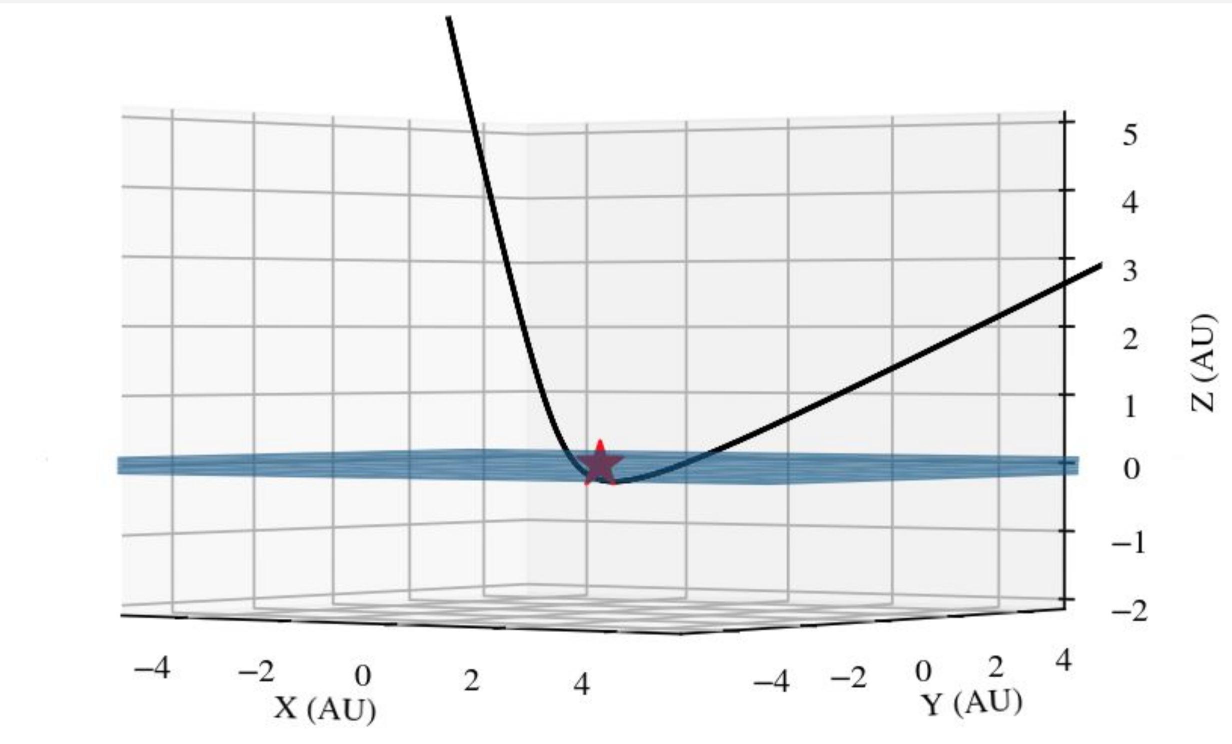

Figure 1: The orbit of ‘Oumuamua within the Solar System based on our rotations. The blue plane is the Earth’s orbital plane.

Linear Motion Approximation

We assume the stars and ‘Oumuamua are travelling in a flat galactic potential (i.e. on unaccelerated orbit). This is the same technique as the one used in Bailor-Jones et al. (2018), De Rosa & Kalas (2019) and Ma et al. (in prep), the latter two use this technique to study stellar kinematics in Sco-Cen association.

The approximation can be justified as follows. Since ‘Oumuamua follow a hyperbolic orbit, we could assume that its path exhibits asymptotic behaviours when the comet is far from the Sun. On top of this, the stars take hundreds of millions of years to finish a single orbit around the Milky Way, so we could also assume that the paths of the stars are straight lines as we are only “integrating” up to ~10Myr ago from the presence. Therefore, we only need to look for the leaving asymptotes of the ‘Oumuamua’s orbit, and apply linear motion equation, $\mathbf{x}(t) = \mathbf{v}(t) + \mathbf{x}_0$, to speculate ‘Oumuamua’s and the stars’ positions in the past.

Identifying Close Encounters

The time at which the distance between ‘Oumuamua and a star is the least is given by

$$t_{\rm ca} = -\frac{(\mathbf{r_2} - \mathbf{r_1}) \cdot (\mathbf{v_2} - \mathbf{v_1})}{|\mathbf{v_2} - \mathbf{v_1}|^2}$$

where $\mathbf{r}_2$-$\mathbf{r}_1$, $\mathbf{v}_2$-$\mathbf{v}_1$ are the relative position and relative velocity between ‘Oumumua and any star in the galactocentric coordinate, respectively. Then, we plug the time into the kinematic equation of linear motion and obtain the distance of closest approach.

$$d_{\rm ca} = |(\mathbf{r_2} - \mathbf{r_1}) + (\mathbf{v_2} - \mathbf{v_1})t_{\rm ca}|$$

If the minimum distance for ‘Oumuamua with a star is less than 2 pc (twice the Hill radius of sun-like star under galactic potential), the corresponding star is classified as a potential source or home candidate of ‘Oumuamua.

We sample all ~7.1 million stars in Gaia DR2 that have full 6D-astrometric measurement and positive parallax values. We propagated the measurement uncertainties using MC technique, creating 10^2 trials initially for computential convenience. For each trial, we draw the astrometry of both stars based on a multivariate normal distribution using the correlation coefficient in the *Gaia* DR2 and drew the radial velocities from a Gaussian distribution. We decide to use the median values of the t_{ca} and d_{ca} distributions as the outputs and to involve them for the subsequent work. The 16th- and 84th-percentiles were used as the lower and upper uncertainties of the final result, respectively. In this crude first round, we used 20 pc and ~100 Myr as thresholds to avoid missing events. We then repeat everything above on the filtered sample, but now using 10^6 trials. The output of this round leads to our final result of this project.

Home Candidate	Closest Approach Time (Myr)	Closest Approach Distance (pc)	Relative Speed (km/s)
UAUC4 599-020182	-2.27 (+0.10/-0.11)	0.85 ± 0.05	17.54
HIP 3757	-1.07 ± 0.02	0.62 ± 0.03	22.68
HAT 168-04154	-4.35 (+0.19/-0.21)	0.62 (+0.32/-0.21)	17.14
GJ 195 A	-0.51 ± 0.01	0.97 ± 0.03	25.50
Gaia DR2 905966833617688352	-5.41 (+0.17/-0.18)	0.99 (+0.36/-0.25)	23.45
TYC 2932-385-1	-2.32 ± 0.05	0.30 (+0.08/-0.12)	30.30
TYC 1016-1103-1	-2.3 ± 0.02	0.82 ± 0.12	62.61

Table 1: The table gives the information of all the stars that had a minimum distance < 1 pc with ‘Oumuamua.

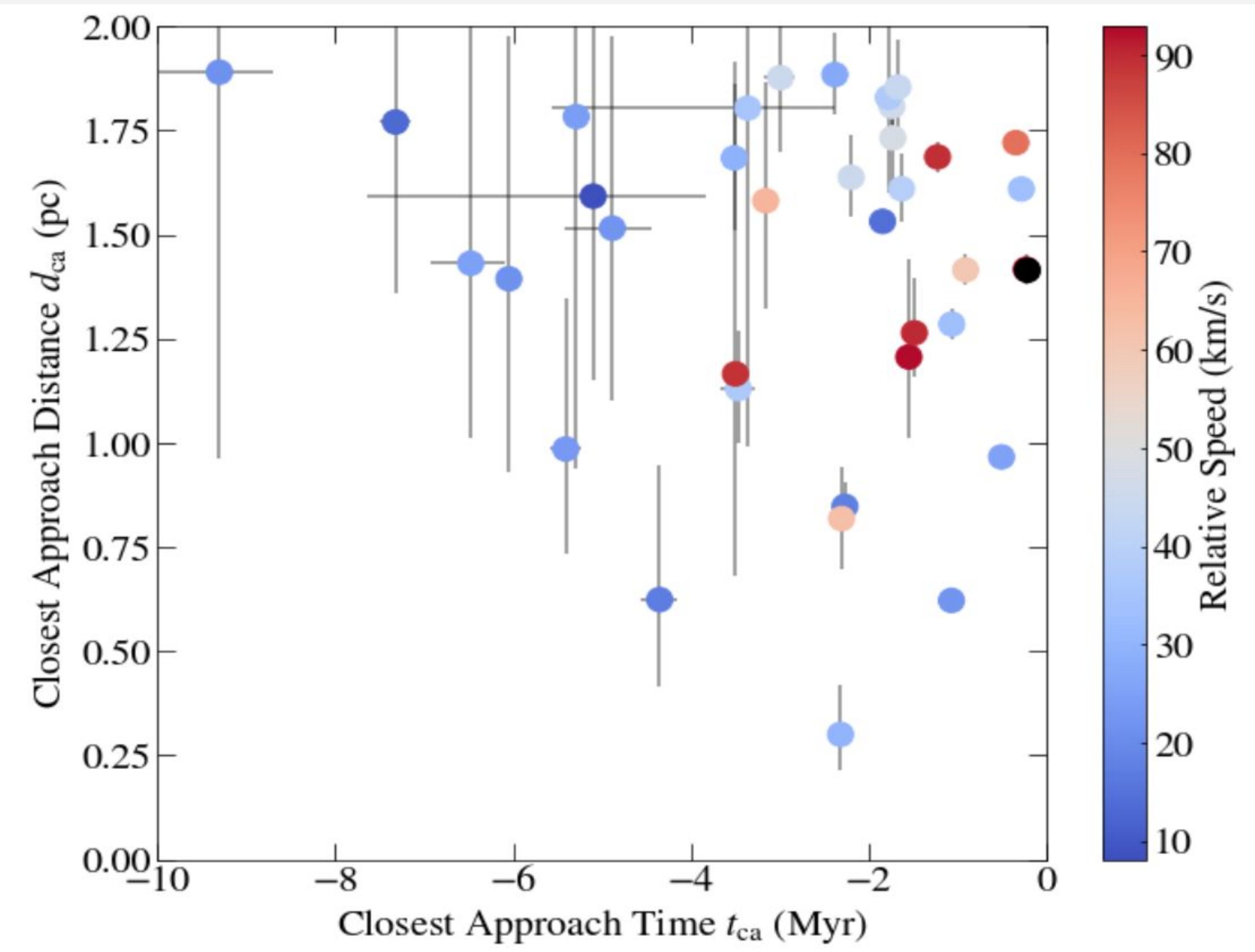

Figure 2: The plot shows all the stars that had a minimum distance < 2 pc with ‘Oumuamua and the time at which the close encounters occurred. Note: the black data point on the right is an outlier, having RV of 418 km/s. It could possibly be an escaping star from the Galaxy.

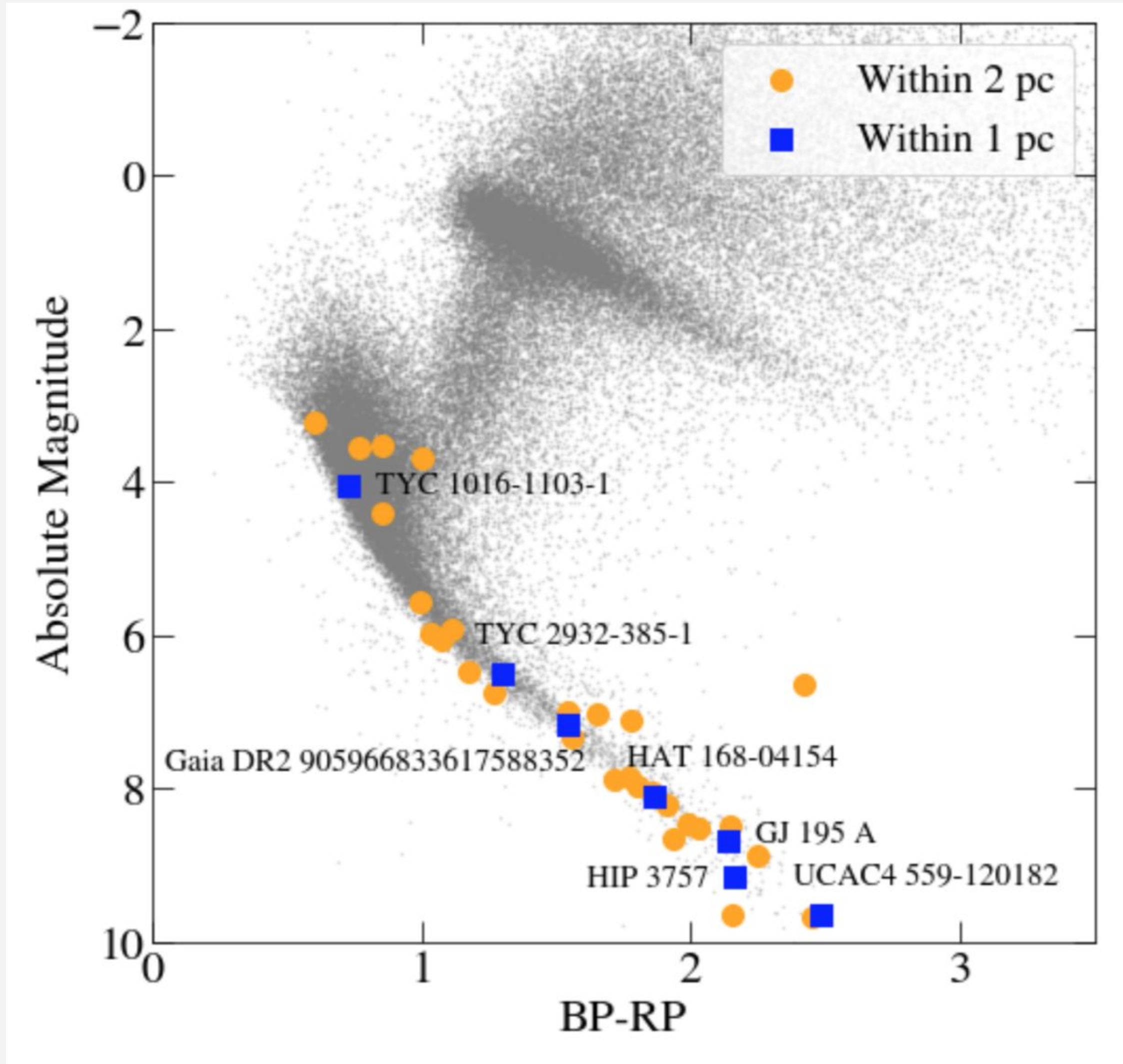

Figure 3: The figure shows the position of all the stars involved in close encounters with ‘Oumuamua on the HR Diagram.

Result & Discussion

Creating 1 million trials, we identified 36 close encounters with ‘Oumuamua in the past 10 million years using our linear motion model. Seven of them 36 stars have potential encounters with ‘Oumuamua within a distance of 1 pc (see Table 1). Most of the encounters have a relative speed between ~20-30 km/s, although outliers do exist. Also, the seven encounters with 1 pc of ‘Oumuamua’s trajectory mostly involve the less massive K and M dwarfs as well.

It is worth noticing that our value of closest approach distance and closest approach time of HIP 3757 (M2.5V) is consistent with the values obtained by Bailor-Jones et al. (2018), which are ~0.6 pc and ~ 1Myr, respectively. This suggests that our calculation is indeed correct.

It is also worth noticing that GJ 195 A (M2.5V) is in a binary system, which makes it a very interesting home candidate for ‘Oumuamua, because it could offer a possible ejection mechanism for the comet. ‘Oumumua could be orbiting around one member of the binary but perturbed by other members of the system and thus accelerated up to the escape speed, eventually reaching us.

Future Work

Our sampling of stars is limited to those containing full 6D astrometry measurement and positive parallax values, which only comprises of ~0.5% of the entire *Gaia* DR2 archive. We might be missing many potential encounters, especially those with stars not bright enough to have Gaia *RV* measurement. Since we have constructed all the algorithm to trace the past trajectories of ‘Oumuamua and any stars, we could wait for the new release of *Gaia* DR3 (scheduled between 2020 and 2021). We then could run the code again on DR3, and hopefully, we would find more potential source stars and get more accurate results. Moreover, constructing a table including the presence of binary and planetary systems would also help explain the mechanism of ‘Oumuamua’s ejection mechanism.

References

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