243. Interstellar object streams

INTERSTELLAR OBJECTS are small asteroid- or comet-like bodies, ejected from other exoplanetary systems, and now passing through *our* solar system. Just three are known today: 1I/Oumuamua, 2I/Borisov, and 3I/ATLAS, discovered in 2017, 2019, and 2025 respectively.

As I detailed in essay 242, Gaia is contributing to an understanding of their origin, by allowing their Galactic orbits, and those of nearby stars, to be propagated backwards in time. Past intersections, or flybys, might point to the star system from which they originated, perhaps further corroborated by estimates of the stellar ages.

As yet, no stars have been identified as the likely source of any of these three interstellar objects. And recent models, outlined below, hint at why this failure to identify their origin might not be unexpected.

As more of these objects are discovered over the coming decade (with the Vera Rubin LSST and other surveys), such prospects should improve. And they will be guided by some fascinating simulations that I will focus on here. These point to the likely occurrence of *streams* of such interstellar 'visitors' or 'vagabonds'.

READERS WITH an appreciation of the other types of celestial streams that Gaia is probing will quickly appreciate the principles. Similar to the way in which the dissolution of open clusters through Galactic tidal forces leads to tidal tails of escaping stars, and as the breakup of galaxies accreted by the Milky Way leads to the existence of vast extended halo streams, models of protoplanetary material escaping from other exoplanet systems suggests the there will be prominent *streams* of interstellar objects leaving their host stars.

These streams maintain some spatial and kinematic coherence over periods of order 1 Gyr. What the simulations show is that there is a reasonable probability that we might be able to detect more than one such object from any given stream. And while they may appear to come from different directions in space, the kind of backward orbit propagation already being conducted with the Gaia data may offer improved prospects of associating their origin to a specific star system.

THESE SORTS of general informative simulations could be conducted without recourse to the Gaia data. But applying them to real data offers the possibility of examining the origin of known interstellar objects with respect to plausible interstellar object streams.

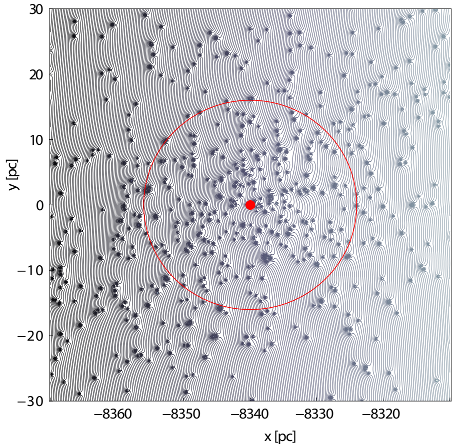
The simulations that I will focus on here were carried out by Portegies Zwart (2021). He used Gaia DR2 to select the 200 nearest stars, which lie within ~16 pc.

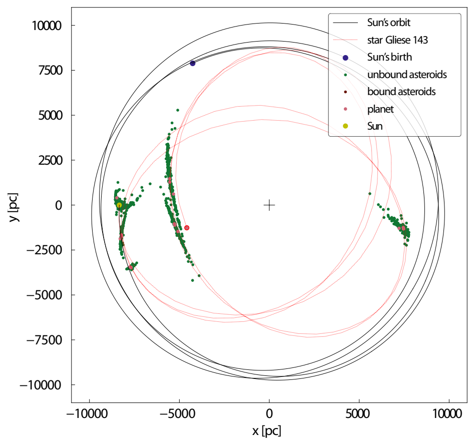
He first used the Gaia astrometry, and an assumed Galactic potential, to propagate their positions back in time to 1 Gyr ago. He then simulated the formation and evolution of an Oort-like cloud around each star. Then running the orbits forwards in time, with the host stars themselves arriving back at their starting position, he traced how each system's asteroids (and indeed some planets) can escape the local stellar gravity field to form a tidal stream accompanying each star through space.

He found that their orbits soon become isotropic, and circularised, because of the Galactic tidal field, and eventually form an Oort cloud of radius $10^4 - 10^5$ au. The majority, typically more than 97%, become unbound from their parent star to become free floating in the Galactic potential. The key point is that these escaping asteroids remain in a similar orbit around the Galactic centre as their host star, forming dense streams of 'rogue' interstellar asteroids (and occasionally planets).

The solar system will, in turn, occasionally pass through such asteroid streams, potentially giving rise to occasional close encounters, of which Oumuamua, Borisov, and ATLAS may be examples. His simulations show that the direction from which an individual object arrives cannot easily be traced back to the original host, although multiple objects from the same source might help to identify their origin.

He found that the solar system is actually in the bow or wake of the tidal stream of ten of these nearby stars. Overall, he estimated that the local density of such leftovers from the planet-formation process contributes to a local density of 1.2×10^{14} pc^{-3}, implying that $\gtrsim 0.1$ of the known interstellar visitors originate from the obliterated debris disks of these specific nearby stars.





Portegies Zwart (2021)

I SHOW HERE two figures from his study. Above left (his Figure 3) shows the equipotential surface of the 795 stars within 50 pc of the Sun (central red circle) projected on the Galactic xy-plane. The outer red circle, at 16 pc, contains the 200 nearest stars. Above right (his Figure 8a) shows the Galactic orbits of just one of these nearby stars, Gliese 143 (GJ 143), with the position of the star and its associated asteroids today, and at look-back times of 1.0, 0.8, 0.6, 0.4, and 0.2 Gyr.

Amongst his various conclusions, Portegies Zwart (2021) showed that if multiple objects originate from the same stellar source, they do not necessarily come from the same direction, or with a similar velocity. If it could be argued that multiple intruders have a similar origin, it may be possible to identify the star from which they originated.

As an example, the time that Oumuamua has been floating freely in space has been estimated to be less than 1 Gyr (e.g. Hallatt & Wiegert, 2020) while, in his simulations, tidal tails remain coherent for considerably longer. It is then conceivable, he argues, that Oumuamua is still a member of the leading or trailing arm of debris around its parent star, such that we might expect more objects entering the solar system from the same general Galactic direction.[1]

THERE ARE OTHER effects and complications involved in determining the origin and nature of these interstellar objects. For example, the star responsible for some given interstellar object or stream may no longer exist (Hopkins et al., 2023). Further complicating the dynamical considerations, ejected objects within open clusters may initially remain within the cluster potential, eventually escaping from it (Hands et al., 2019).

MORE DETAILED MODELS of these sorts of interstellar object streams have accordingly been developed. In their more recent simulations, Forbes et al. (2025) concluded that the Sun is currently immersed in $\sim 10^7$ cluster-derived streams, many of which may be composed of even larger numbers, $\gtrsim 10^{10}$, of individual stellar streams. Such streams nevertheless contribute very different interstellar object encounter rates to the observable volume, ranging from 10^{-15} per year, to ~0.1 per year. The Sun may occasionally pass through streams with significantly higher encounter rates.

They found that it is considerably more likely for multiple interstellar objects in the observed population to have come from the same star *cluster*, rather than from the same *star*. While the latter are likely to have similar incoming velocities and radiants, the former will be considerably more spread out, due to the higher internal velocity dispersions of their streams, and therefore difficult to distinguish from unrelated objects.

They also concluded that almost all interstellar objects will not be traceable back to their host star, with typical distances to the progenitor (which may no longer be extant) ranging from 1 to several hundred kpc, although progenitors from the same star may be as close as ~100 pc. They estimated that only with 100–1000 detected objects would it be likely to find objects originating from the same star.

A chemo-dynamical model based on the stellar population within 200 pc from Gaia DR3, the Ōtautahi–Oxford model, was further developed by Hopkins et al. (2025a). Applied to the third interstellar object discovery, ATLAS, Hopkins et al. (2025b) concluded that it is very unlikely that it shares an origin with either of the previous two interstellar objects, Oumuamua or Borisov.

[1] Concerning the computations, he comments (his §5.1): *The evolution of each star… was computed in 3–7 days on a one GPU and 6 cores. The total computer time spent sums up to about 1000 hours on GPU and 6000 CPU hours. With 180 W h^{-1} per GPU and 12 W h^{-1} per CPU, our total energy consumption for the calculations is about 250 kWh. With* 0.283 *kWh kg^{-1} (Wittmann et al., 2013) results in 200 tonnes CO_2, quite comparable to launching a rocket into space (Portegies Zwart, 2020).*