242. Oumuamua, Borisov and ATLAS

RAPID DEVELOPMENT in the observational and theoretical understanding of exoplanet formation over the past 20–30 years led to the inevitable hypothesis that interstellar space should be populated with planetesimals and comets, created in – and ejected from – other exoplanetary systems. If they pass through our own solar system on their journey through space, these 'interstellar objects' could be distinguished from bound solar system bodies ($e \lesssim 1$) by their hyperbolic orbits ($e \gg 1$).

Early searches, and estimates of expected numbers, failed to identify any such objects (e.g. McGlynn & Chapman, 1989; Jewitt, 2003; Moro-Martín et al., 2009; Engelhardt et al., 2017), while the first candidates C/2007 W1 (Boattini; Królikowska & Dybczyński, 2013; Dybczyński & Królikowska, 2015) and C/1853 E1 (Secchi; Branham, 2012), were subsequently rejected (Cook et al., 2016).

THE FIRST confirmed examplar, Oumuamua, was discovered with Pan–STARRS (R. Weryk) on 2017 October 18, 40 d after pericentre, and within the orbit of Mercury, at $V = 22$ mag (Meech et al., 2017). It is a minor body some 100-m in size, and on a hyperbolic orbit with $e = 1.19$, and an approach velocity $v_\infty = 26\,\mathrm{km\,s^{-1}}$.

Within three months of its discovery, some 30 studies had examined its orbit and, from photometry and spectroscopy, its shape, rotation and surface properties. Some 200 refereed papers have followed. Amongst these was speculation that it could be an 'alien' source.

Gaia has been used to probe its past trajectory and possible origin, and I described some of the early studies along these lines in essay 25.

The challenge in pin-pointing the origin of Oumuamua (and subsequent discoveries) results from our limited knowledge of star positions and their space motions. Traveling through interstellar space at $26\,\mathrm{km\,s^{-1}}$, it would take a million years to cross 25 pc. Throughout that time, all the stars in our solar neighbourhood are moving, and it will have been further deflected by close star encounters on its journey. Its origin can only be deduced by following its motion backwards in time, taking into account the Galaxy's gravitational potential, and the individual perturbations from stars passed along its way.

IN A pre-Gaia study, Dybczyński & Królikowska (2018) started with 201 763 nearby stars, finding just 7 that Oumuamua would have passed within 1 pc, most occurring over the past 50–100 000 years. The closest, HIP 3757, had a fly-by distance of only 0.04 pc, 118 000 years ago. But none were likely to be the origin of Oumuamua since the fly-bys occurred with large relative velocities, $\Delta v \sim 50 - 100\,\mathrm{km\,s^{-1}}$, implying a similarly large ejection velocity. Searching further back in time, and again examining more than 200 000 nearby stars, they found only four candidate progenitors. Their most promising, HIP 113020 (GJ 876), is known to host a four-planet system. The encounter occurred 790 000 years ago, with a relative velocity of just $3.9\,\mathrm{km\,s^{-1}}$.

Bailer-Jones et al. (2018) gave more detailed models using Gaia DR2. Their closest encounter, at 0.60 pc some 1 Myr ago, was with the same M-dwarf, HIP 3757, with a relative velocity of $24.7\,\mathrm{km\,s^{-1}}$. They found a more distant encounter with the G5 dwarf HD 292249, at 1.6 pc and 3.8 Myr ago, but with a lower encounter velocity of $\Delta v \sim 10.7\,\mathrm{km\,s^{-1}}$. They found only two others with intermediate encounter distances and velocities.

Hsieh et al. (2021) also used Gaia DR2 to track Oumuamua's past Galactic orbit. They showed that it intersected the solar system close to its maximum vertical and radial excursion from the Galactic plane, properties shared by nearby young stellar associations. They estimated a dynamical age of ~35 Myr, and a space motion consistent with the Carina moving group. However, their simulations of isotropically ejected masses implied an implausibly large ejected mass per star, and hence some incompatability with scenarios that attribute its formation in, and ejection from, a protostellar disk.

Eubanks et al. (2021) used the local velocity distribution of the Gaia EDR3 Catalogue of Nearby Stars (Gaia Collaboration et al., 2021) to predict the velocity-dependent flux of interstellar objects entering the solar system. They predicted, for example, 7 objects per year passing within 1 au of the Sun, with 92% originating from the thin disk population, 4 per decade from the thick disk, and 1 per decade from the halo. At most 3 per century entered the Milky Way from another galaxy.

Other Gaia-based studies of these interstellar objects have followed from the discovery of the second such object, 2I/Borisov, on 2019 August 30. The third, 3I/ATLAS, with an approach velocity to the solar system $v_\infty = 57.976 \pm 0.004\,\mathrm{km\,s^{-1}}$, was discovered by the 'Asteroid Terrestrial-Impact Last Alert System' (ATLAS) search program, Chile, from CCD images originally taken on 2025 February 2 (Sato et al., 2025).

Oumuamua and Borisov are both sub-km in size, but have very different physical properties (Jewitt & Seligman, 2023): Oumuamua was unresolved and asteroid-like, whereas Borisov was more comet-like, being a source of both gas and dust. With an estimated space density of $\sim 0.1\,\mathrm{au^{-3}}$, they are generally considered to be planetesimals originating from the protoplanetary disks of other stars, ejected by planetary scattering.

Both showed non-gravitational acceleration: in the case of Oumuamua (in the absence of measurable mass loss) attributed to the recoil from sublimating super-volatiles or the action of radiation pressure on a nucleus with a very low mass column density. Borisov is a strong source of CO and H_2O, which account for its activity and its non-gravitational acceleration (Jewitt et al., 2020).

ATLAS has generated considerable interest due to its specific spectroscopic and morphological features (e.g. Seligman et al., 2025), further fuelled by suggestions that it might be a product of alien technology (Hibberd et al., 2025), and with an orbit directed towards the inner solar system rather than being randomly drawn from an isotropic velocity distribution (Loeb, 2025).

While perihelion occurred on the other side of the Sun, precluding observations from Earth, its orbit resulted in close approaches with various spacecraft between September–November 2025 (Psyche, the Mars spacecraft array, and JUICE), with others likely to pass close to or through its cometary tail post-perihelion (Eubanks et al., 2025).

Certain properties of ATLAS have been inferred from Gaia, in particular studies of its origin and age, although whether it originates from a member of the thin or thick disk populations remains uncertain.

Eubanks et al. (2025) used Gaia EDR3 to examine its pre-encounter kinematics, and showed that it is likely to be an object from the thick disk. However, in addition to investigating its spectral and rotation properties, de la Fuente Marcos et al. (2025) used N-body simulations, and kinematic analogs extracted from Gaia DR3, to suggest that its parent system is rather part of the thin disk.

Hopkins et al. (2025b) also used Gaia DR3, in conjunction with models of protoplanetary disk chemistry and Galactic dynamics, to infer an age of more than 7.6 Gyr, with both velocity and radiant within the expected range for such an origin.

Various studies of ATLAS's Galactic orbit, integrated within the Galactic potential, have investigated its origin and dynamical evolution.

Guo et al. (2025) identified 25 encounters within 1 pc from a sample of 30 million Gaia DR3 stars. But with all encounter speeds $>20\,\mathrm{km\,s^{-1}}$, none is considered to be a plausible host via known ejection mechanisms. Because of its velocity distribution and dominant star number density, they favoured a thin disk origin.

Pérez-Couto et al. (2025) integrated its orbit backward in time for 10 Myr, together with more than 3 million Gaia DR3 stars. They identified 93 encounters within 2 pc although, again, none resulted in a significant perturbation. They concluded that no stellar flybys within the past 10 Myr and 500 pc, from stars contained in DR3, can account for its present trajectory, or be associated with its source. Again, they suggested that it originated from the thin-disk population.

Kakharov & Loeb (2024) performed Monte Carlo orbit integrations for all 3 objects using 10 000 trajectories per object. They found median $z_{\max}$ values of 0.02 kpc for Oumuamua, 0.12 kpc for Borisov, and 0.48 kpc for ATLAS. Their Bayesian age inference indicates a young stellar system origin for Oumuamua (~1.0 Gyr), an intermediate-age population for Borisov (~3.8 Gyr), and an old thick-disk origin for ATLAS (~9.6 Gyr).

In Gaia-based studies of the formation of these interstellar objects, Portegies Zwart (2021) simulated the formation and evolution of Oort clouds around the 200 nearest stars ($d < 16$ pc) from Gaia DR2, over the past 1 Gyr. They showed how planets and asteroids can escape the local stellar gravity, remaining in a similar orbit around the Galactic centre, forming dense streams of interstellar asteroids and planets.

Hopkins et al. (2025a) used a realistic space distribution of stars from Gaia DR3 to show that the velocity distribution of interstellar objects is more textured than a smooth Gaussian, with moving groups caused by Galactic resonances dominating the distribution. Oumuamua and Borisov have entirely normal places within these distributions, the former within the non-coeval moving group that includes the Pleiades cluster, and Borisov within the Coma Ber moving group.

Gregg & Wiegert (2025) used Gaia-based studies to suggest that even the nearby triple system α Cen will be the source of interstellar objects in our solar system, albeit at undetectably low densities.

The Vera Rubin Observatory should detect several new interstellar objects over its 10-year LSST survey (e.g. Levine et al., 2021; Marčeta & Seligman, 2023; Merritt et al., 2025). Assisted by Gaia, these will provide further insights into what is presumably an enormous and previously unknown Galactic population.