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Rendezvous with `Oumuamua

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On 19 October 2017 the Panoramic Survey Telescope And Rapid Response System (Pan-STARRS) discovered a rapidly moving object near the Earth. In itself this was nothing unusual but over the course of a few days astronomers realised that this was the first detection of an unbound object travelling through the Solar System. At the time of its discovery, the interstellar visitor, 1I/2017 U1 (`Oumuamua), was quite faint and already speeding away. In the ensuing days, thanks to the efforts of about 10 separate teams, over 100 hours on 2.5- to 10-metre telescopes were devoted to observing the object during the short, exhilarating and frantic period over which it was visible. This is an account of our observations and how they have contributed to the current view that 1I/2017 U1 is an elongated object in an excited rotation state with surface colours similar to those of Solar System comets and asteroids.

Models of the early Solar System suggest that the migration of forming giant planets ejected a large fraction of planetesimals into interstellar space. Most of these planetesimals are expected to be icy — i.e., comet-like — with only a small fraction of them being rocky objects. Depending on the model, the ice to rock planetesimal ratio varies between 400:1 and 10 000:1 (Meech et al., 2016). Assuming similar processes have been taking place elsewhere in the Galaxy, a large number of planetesimals should be wandering through interstellar space, some of them eventually crossing the Solar System.

These interstellar objects (ISOs) are icy planetesimals that are expected to behave like the long-period comets of the Solar System; volatile ices sublimate when the ISO approaches the Sun, developing a coma and a dust tail — features that should make them bright and therefore easy to spot. The rocky ISOs, on the other hand, only reflect sunlight. As their albedo is expected to be extremely low they become dark (after eons of bombardment by high-energy cosmic rays), they would be extremely faint and hard to detect. Overall, because of the overwhelming majority of icy over rocky objects, and thanks to the brighter aspect of the icy ones, the community expected that the first ISO signature would be a comet discovered on a hyperbolic orbit. The hyperbolic orbit would indicate an object not bound to the Sun. With various ongoing all-sky surveys hunting for transient and moving objects (for example, the Catalina Sky Survey, Pan-STARRS, the ESO Public Survey ATLAS, the All-Sky Automated Survey for Super Novae [ASAS-SN]), the time was ripe for such a discovery.

The discovery

We were nevertheless caught by surprise when object P10Ee5V was discovered by Pan-STARRS1 (PS1) at Mauna Kea on 19 October 2017 (Figure 1a). Immediate follow-up observations from the ESA Optical Ground Station discarded the data because of the “unrealistically large eccentricity of the orbit”. Fortunately, pre-discovery images from PS1 and follow-up observations on 20 and 22 October from the Catalina Sky Survey and the Canada-France-Hawaii Telescope (CFHT), respectively, pinned it down to a hyperbolic orbit with an eccentricity of 1.188 ± 0.016 (Figure 2). The IAU’s Minor Planet Center (MPC) registered the discovery under the cometary designation C/2017 U1 (Williams, 2017).

We immediately started a follow-up campaign via a series of Director’s Discretionary Time proposals — using the Very Large Telescope (VLT), Gemini South, the United Kingdom Infra-Red Telescope (UKIRT), the NASA/ESA Hubble Space Telescope (HST) — and additional time on the CFHT. Whilst we were reminded of the Rama spacecraft from the novel by Arthur C. Clarke (1973), our first surprise came from a deep stacked image, confirming what the discovery images indicated; the object does not display any cometary activity (Figure 1b). The deep limiting magnitude reached corresponds to an extremely low dust production limit, amounting to less than 1 kg of micron-sized dust within 750 km of the ISO. The object is therefore similar to asteroids, prompting the MPC to swiftly change its designation to A/2017 U1. However, as its origin from outside the Solar System had now been established without a doubt, the object received its final designation 1I/2017 U1, and a Hawaiian name in honour of the place of its first discovery, `Oumuamua. The number 1I reflects that this is the first interstellar object to be identified, and the Hawaiian name means scout or a messenger from our distant past reaching out to us from far away. We refer to the object as `Oumuamua for the rest of this article.

The measured colours from the object’s surface indicate a linear reflection spectrum with a fairly red slope (Figure 3), which is typical of cometary nuclei, D-type

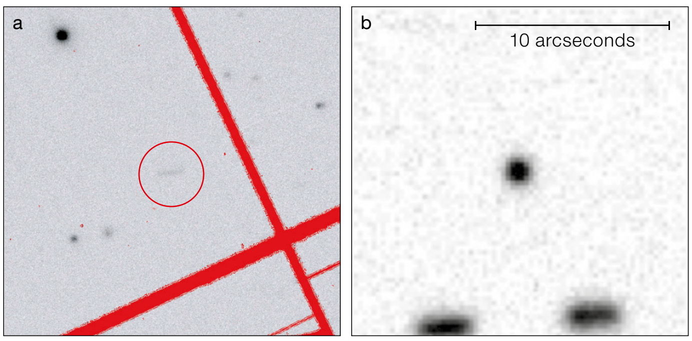

Figure 1. (a) The discovery image of `Oumuamua on 19 October 2017 with Pan-STARRS. The object is the faint trail in the centre of the circle. (b) A deep image, combining VLT and Gemini South *g*- and *r*-band data, illustrating the object’s asteroidal appearance. Reproduced from Meech et al. (2017).

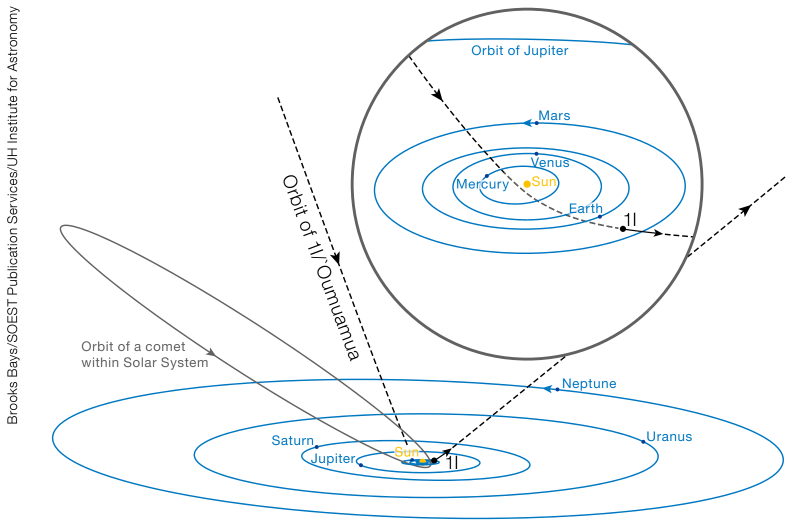

Figure 2. The orbit of `Oumuamua, showing that it entered the Solar System from above the plane of the planets, passing inside Mercury's orbit at perihelion on 9 September 2017 and making its closest approach to Earth on 14 October 2017. `Oumuamua passed beyond the distance of Jupiter at 5.2 au in early May; while moving fast, it will still be inside the Solar System for the duration of our lifetimes. It will reach the outer edge of the Kuiper belt by the end of 2025, cross over the heliopause sometime in the late 2030s and won't even reach the innermost edge of the Oort cloud at 1000 au until nearly 2200.

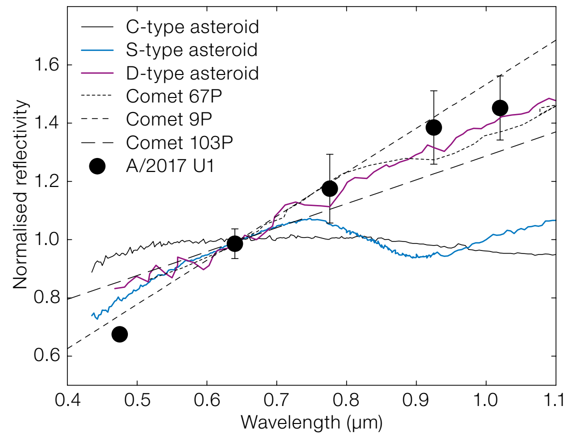

Figure 3. The reflectivity of the surface of `Oumuamua is consistent with D-type asteroids and comets (Meech et al., 2017).

asteroids from the outer asteroid belt, and some trans-Neptunian objects. In other words, `Oumuamua's surface seems similar to that of objects in the outer Solar System. This may suggest an organic-rich surface (as seen on comets) or a surface with iron-rich minerals. Another team observed the very faint `Oumuamua with the wide-band ultraviolet-infrared spectrograph, X-shooter, on the VLT (Fitzsimmons et al., 2018). This attempt resulted in a noisy spectrum that was in agreement with the reddish photometric colours, and the lack of emission lines set independent limits on the cometary activity.

`Oumuamua: cigar or pancake?

The second surprise was that the object displayed huge photometric variations; the flux changes by at least a factor of 10! Neglecting the effect of the solar phase illumination, this implies that the geometric cross-section of the object varies by a factor of 10, which indicates an elongation of 10. The fairly high solar phase angle at the time of the observations could make this elongation smaller, but the unknown geometry of the direction of the rotation axis makes the implied elongation a lower limit. Overall, the large-to-small axis ratio of the body is ~ 10:1.

The photometric light curve does not constrain the third dimension of `Oumuamua. For the rotation to be stable, the third axis should be small — similar to the short axis — which has given rise to the highly popular cigar-shaped artist's impression. However, collecting more data and combining ours with those of other teams, it became apparent that the light curve is not periodic (Figure 4), and that the object is in an excited state of complex rotation. Studying the rotation in detail, we found a spin state with two fundamental periods at 8.67 ± 0.34 hours and 3.74 ± 0.11 hours. The object could be spinning in a short-axis mode — where the short principal axis of the object circulates around the total angular momentum vector (TAMV) — or in a long-axis mode — where the long axis circulates around the TAMV. Interestingly, `Oumuamua could be either an elongated cigar-shaped object, in which case it would be in a state close to its lowest rotational energy, or an extremely oblate spheroid, pancake-shaped, close to its highest energy for its angular momentum (Figure 5).

Assuming the object has the standard dark albedo of distant Solar System objects, its brightness can be converted to a size. For the cigar shape, this leads to radii of 400 m and 40 m. Also, assuming that the object has a density typical of comets or asteroids in the Solar System (1000 to 3000 kg m^{-3}), its rotational periods indicate that it must have some modest, but non-zero, cohesive strength — otherwise the centrifugal forces would tear it apart. A pancake-shaped object could be held together by gravity only for densities above 1500 kg m^{-3}.

`Oumuamua: final glimpses and a last surprise

We continued to monitor `Oumuamua as it receded in order to improve the determination of its orbit, with the aim of extrapolating it back to its origin. The last datapoint was acquired with the HST on 2 January 2018, when the object was very close to its detection limit. The position of `Oumuamua was carefully measured on over 200 ground- and space-based images, including the recently published Gaia Data Release 2 (DR2) catalogue. This brought another surprise; the object was not following a purely gravitational orbit! A gravitational orbit accounts for the orbits of the eight planets, Pluto, Ceres, the largest asteroids and relativistic effects. Systematic residuals in the fit indicated an additional non-gravitational force non-gravitational force (see Figure 6). The best fit corresponds to a non-gravitational acceleration A/r^2, with A = (14.92 ± 0.16) 10^{-6} m s^{-2}, i.e., a ~ 30-σ detection. This detection of non-gravitational acceleration survived a series of tests; it is neither the result of an artefact caused by a subset of the data, nor the result of some unaccounted biases. The non-gravitational effect is also

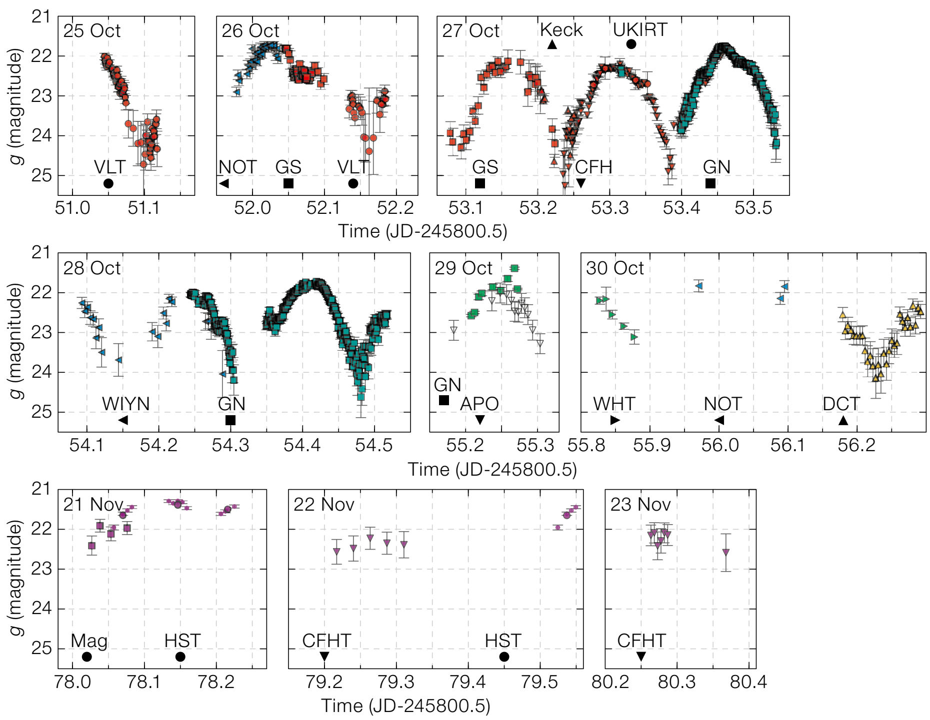

Figure 4. The 2017 lightcurve of `Oumuamua, converted to g band and corrected for geometry and light-time travel. The non-periodic variations indicate that the object is in a complex rotation state. These data are consolidated from observations at the VLT, Nordic Optical Telescope (NOT), Gemini South (GS), Keck Observatory, UKIRT, CFHT, Gemini North (GN), WIYN Observatory (WIYN), Apache Point Observatory (APO), William Herschel Telescope (WHT), Discovery Channel Telescope (DCT), Magellan (Mag) and HST (reproduced from Belton et al. 2018).

detectable when considering the ground-based data alone, or using the Hubble data complemented with a few of the first high-quality ground-based images.

We considered a series of hypotheses to explain the non-gravitational acceleration: the Yarkovsky effect — the anisotropic emission of thermal photons by a rotating body produces a small force; friction — drag opposite to the velocity vector; an impulsive force — for instance caused by a collision; a binary or fragmented object — causing a changing offset between the centre of light and the centre of mass; a magnetic effect — if `Oumuamua was strongly magnetised it would interact with the solar wind; and finally, either radiation pressure or cometary-type outgassing — each of which would produce a radial acceleration.

Except for the last two, all of these hypotheses have major flaws and cannot reproduce the observations; several are simply unrealistic in this case. Radiation pressure is observed to have an r^{-2} dependency and has been detected in the orbit of some asteroids, but the observed acceleration would imply an unrealistic bulk density. `Oumuamua would need to be very large and dark and with a density about three orders of magnitude lower than Solar System objects. Porosity of the body cannot account for this low density, and the alternative of a millimetre-thick hollow shell is unphysical.

To explore whether cometary activity could account for the acceleration, we modelled its thermal evolution using a 3D model, which suggested that any CO ice could have been sublimating over the whole volume of the body (at a temperature ~ 30 K or higher). CO_2 ice would have sublimated over a large fraction of the body (at 80 K or above), and water ice within 1 m of the surface (at 160 K or more). A detailed sublimation model was run to evaluate the gas and dust production rates and the corresponding acceleration. This was successful; the dust and gas production rate can reproduce the magnitude of the acceleration assuming a low-density object (450 kg m^{-3}), an ice-to-dust mass ratio of three and a CO-to-H_2O ratio of 0.25. While these values are at either the low or the high end of the ranges found in comets, they are still realistic. Assuming the dust released was composed of fairly large grains, they would have escaped detection in the deep images. The lack of detection of gas by any observer was also problematic.

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Figure 5. Left: Artist's impression of `Oumuamua in the case of a low energy rotation state. Right: Painting by William Hartmann, commissioned by Michael Belton, visualising `Oumuamua's shape for the high-energy rotation state (reproduced with the artist's permission).

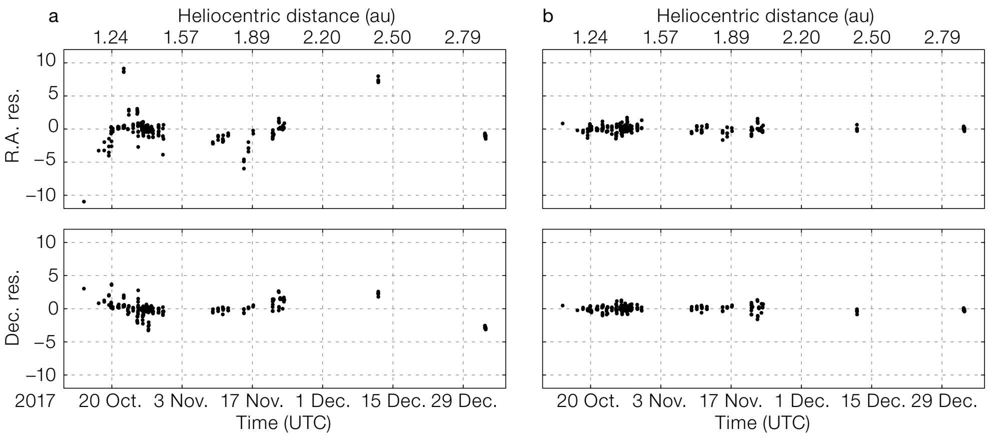

Figure 6. Residuals from the astrometry of `Oumuamua produced by comparing its measured position with the interpolation based on (a) the gravity-only best-fit solution, and (b) a solution including a radial non-gravitational acceleration scaling as r^{-2}. Each point has been scaled to its formal measurement error. Reproduced from Micheli et al. (2018).

If `Oumuamua had similar CN:H_2O abundance ratios to those seen in comets from the Solar System, CN emission should have been seen by spectroscopic observations (Ye, 2017; Fitzsimmons, 2017). While CN is a minor species seen in comets (typically < 1% the abundance of water), it fluoresces strongly in the blue and is often the first gas species detected in comets as they approach the Sun. This means that `Oumuamua as a comet is depleted in CN compared to comets in the Solar System. Overall, we found that cometary activity can account for the measured non-gravitational acceleration, indicating that `Oumuamua is a tiny comet, with unusual but not unrealistic characteristics.

The non-gravitational component of `Oumuamua's motion complicates the quest for its origin. While we can model it accurately over the observed arc, extrapolating it backward in time will require additional care as we do not know when or where the onset of sublimation took place. This results in larger uncertainties in the direction of the incoming asymptote of the orbit. Nevertheless, the search would have been fundamentally flawed if the non-gravitational acceleration had not been discovered. The asymptotic direction of the incoming orbit points towards the current position of Vega. However, to travel from that point would take about 600 000 years. Because of Vega's proper motion, it is not plausible that `Oumuamua was ejected from that system. The incoming velocity of `Oumuamua was very close to the mean motion of stars in the solar neighbourhood. As younger stars tend to have smaller velocity dispersions than older ones, this hints that `Oumuamua could have its origin in a nearby young stellar system. The recent release of Gaia's DR2 catalogue gives us the opportunity to search for it. It is, however, possible that `Oumuamua has been wandering the Galaxy for billions of years.

The discovery of `Oumuamua as an icy body confirms models of formation of our planetary system, and also suggests that similar objects are crossing the Solar System, awaiting discovery. While quantifying this population and predicting their discovery rate are not simple, we estimate that one interstellar object with a diameter of 250 m or more is present at any time within 1 au from the Sun; we caution that this is an order-of- magnitude estimate and assumes no visible cometary activity. The discovery of such objects will enable us to measure their composition, which in turn will make it possible to determine the elemental abundances in extrasolar planetary systems. While we are ready to observe these interstellar objects using ground based and space telescopes, it may be necessary to send a spacecraft after one of them, which comes with many attendant challenges.

Acknowledgements

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