Discovering the Universe
‘Oumuamua: Our first interstellar visitor
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Over the last decade, it has become clear that the Universe likes making planets. Not only have we reached the point where we can say that most of the stars, we see in the sky are likely accompanied by a retinue of worlds, we can also recognise a marvellous diversity of planets. Pretty much everything science fiction authors have dreamt of, from planets with double suns in their sky to temperate Earth-like worlds, and plenty they haven’t shown up in our data. With more than five thousand 'exoplanets' (extra-solar planets) in the catalogues already, it is clear that whatever process produces planets must be an efficient one, and capable of operating under a vast range of conditions across the galaxy.

In many ways, this is unsurprising. The physical and chemical processes that sculpted our Solar System, and which produced Earth, must operate throughout the Milky Way, and indeed, throughout the Universe. New observations have given us remarkable glimpses of this process in action. Start with the Orion nebula, visible as a misty patch in the winter night sky, just below the familiar three stars of the belt. This is our nearest large stellar nursery, a place where gas and dust is being converted into stars.

Its true nature was the subject of some debate during the 18th century, though William Herschel, who studied it closely in 1774 had it right when he described it as 'an unformed fiery mist, the chaotic material of future suns'. The brightness of the nebula is in fact due to the influence of some of the new stars it has already produced; look even a small telescope will show the 'Trapezium', a cluster of massive stars, just a few million years old, embedded at the nebula's heart. It is their light that illuminates the gas around them, so that we can see it - much of the rest of Orion harbours a cold and dark part of the same nebula, and it is the powerful winds such stars blow that sculpts the gas around them.

Scattered throughout the nebula are still younger stars, these still enshrouded in the cocoon of dust in which they are born. This dust, heated by the power of these still forming stars, glows brightly in the infrared or microwave regions of the spectrum, but with optical telescopes such as the Hubble Space Telescope they can often appear in silhouette. Peering closely, we can see that the stars themselves are surrounded by extended 'wings' - disks of leftover material that did not collapse onto the stars themselves. This material, flattened into a disk by the laws of angular momentum, is the raw material for future solar systems.

The fact that planetary bodies form in a disk of material explains why, in our Solar System, they all lie in a plane, confined mostly to the zodiac in the sky. (Pluto wanders more than most; we'll see why in a second) ALMA, a telescope sensitive to microwave (what astronomers call sub-mm) radiation set high in the Chilean Andes, has peered closely at many disks around young stars, and seen a surprisingly complex set of dynamical processes. Gaps appear in disks where large planets are sweeping up material with their gravity, growing still further, and where more than one planet inhabits the same region of a disk, their interaction causes waves and ripples in the disk.

What the ALMA images have revealed is that these disks are dynamic, with the orbiting dust and gas affected by the behaviour of the star and by what's happening in the disk itself. Dust, in an astronomical context, means small particles, primarily silicon or carbon, in grains perhaps a tenth of the size of a sand grain. From such tiny pieces, forged in the atmospheres of giant stars and in supernovae, planets can be made. But how?

One piece of the puzzle is that we know, from observations of the chemistry that happens within these protoplanetary disks, that in the outer regions of the disk, where the temperature in freezing, far from the warmth of the star, the grains can grow mantles of water and carbon monoxide. These icy coverings help in the process of planet formation, making it more likely that as two dust grains collide in the chaos of the disk, that they will stick together. As this process of gradual cohesion continues, bigger and bigger grains can be constructed. At first, progress is slow; the Stardust probe, which returned to Earth material collected from Comet Wild-2, captured a few interstellar grains that happened to be passing through the system, and they look like they have been assembled in haste, stuck together at random to create a jagged structure.

Over the course of tens and then hundreds of thousands of years, the process continues. From tiny grains, objects the size of pebbles, and then even boulders, accumulate. At this stage, chemical processes and friction are the crucial processes; gravity only becomes important later, when the growing protoplanet becomes massive enough that it can be held together by self-gravity.

This is a neat picture, and from everything we can see it's a good description of how things actually unfold. However, there's a problem. Once boulders form, collisions are likely to result in a pile of rubble, rather than a larger body. Jumping quickly from the scale where material can agglomerate, to the scale where gravity can grow a planet, is difficult - and it needs to happen fast to match the speed and frequency with which we see planets forming.

A potential solution to this fundamental mystery at the heart of planet formation appeared unexpectedly on the 19th of October 2017. Discovered by the Pan-STARRS telescope on Haleakalā, Hawai'i, the object in question was visible only as a point of light moving against the background stars. In this, it was no different from the thousands of asteroids discovered by the survey since its start in 2008, but what set this new object apart was its trajectory. Unlike anything ever before seen, the velocity and angle of approach of the new object's origins seemed to lie beyond our Solar System, in interstellar space. By the time of discovery, it had already passed through its closest approach to the Sun, and was receding into deep space, never to return.

Such a discovery caused a great deal of excitement, and a little confusion. Initially categorised first as an asteroid, and then - because comets tend to come from the outer solar system - as a comet, Pan-STARRS' discovery was eventually given the designation 1I - the first interstellar object - and the name 'Oumuamua, Hawai'ian for 'The scout from really, really far away'.

The largest telescopes in the world were quickly trained on 'Oumuamua, though none would ever show it as more than a dot. It was clear that our interloper was small, perhaps a few hundred meters across, but it was also rapidly changing in brightness as it travelled. These changes are evidence of an unusual shape, with initially modelling suggesting that 'Oumuamua was cigar-shaped, perhaps 200m long and only 20m or so across; if it was rotating, then the brightness changes can be explained by the difference between seeing it edge-on and side-on.

In fact, it appears the object was not just rotating, but rather tumbling - think of a table tennis bat given a flick as it is thrown upwards. Later models, with more data and time, suggest a more pancake like shape, with a width to thickness ratio of 6:1 instead of the more extreme 20:1 that was originally reported, but its shape was far from the only odd thing about 'Oumuamua.

There had been predictions of interstellar objects, and their properties. (A few objects in the past, including 1957's Comet Arend-Roland, had previously been suspected of coming from beyond the Solar System, though none of these claims ever lasted long). Presumably 'Oumuamua formed in a disk of material around a young star, and its composition should reflect its origins. Objects which form in the balmy temperatures found in the parts of the disk close to the star should be mostly rocky, and those which form further out will be icy. As it should be easier for objects further from the star to escape from its gravitational pull, we should expect interstellar objects to be icy.

'Oumuamua's colour - a dark, dullish red - matched what we'd expect from bodies that had spent a long period of time in the outer Solar System, exposed to cosmic rays - high energy particles - which can affect the chemistry of the surface. But we know what happens when icy bodies from the outer solar system come close to a star; they become comets, growing first a diffuse atmosphere known as a coma as material on their surface sublimates, and then growing sometimes spectacular tails. Yet 'Oumuamua refused to do either of these things; in no observation made in the few months it remained visible to us did it appear as anything other than a point of light - no coma ever developed.

As 'Oumuamua departed the Solar System, a further mystery developed. As it travelled away from the Sun, our star's gravity will have been pulling on it, resisting its escape. Though it was going far too fast to be captured, the effect of this pull on the fleeing object's speed should have been measurable - and yet, observations showed that there was also a distinct acceleration away from the Sun. Some force must have been pushing the object away from us, hastening its exit.

A few short months after it was first seen, 'Oumuamua became too faint to be seen with even the largest telescopes on the planet. We will never see it again - and despite some very optimistic proposals, it is moving too fast for any spacecraft to catch up with it, and it left behind mostly a host of unanswered questions: what was it made of? Where did it come from? Why was it tumbling? And why was it speeding up?

One alluring explanation immediately came to mind. In Rendevouz with Rama, Arthur C Clarke depicts the passage through the Solar System of a mysterious cylindrical craft, cigar-shaped as 'Oumuamua might be, which defies explanation even when astronauts board and explore it. In the story, Rama is undoubtedly artificial: could the first interstellar object, travelling on a similar trajectory, be similarly the creation not of the processes of planet formation, but of a guiding intelligence. Was this a reconnaissance visit to the Solar System?

The idea was bolstered by the fact that studies of its trajectory before its arrival here, 'Oumuamua was moving with the galactic tide, being close to what's called the local standard of rest, the average motion of nearby stars. If you think it's artificial, you can imagine it floating like a buoy in the Milky Way, travelling along with us before firing its engines and swinging by for purposes unknown.

The idea was respectable enough that radio telescopes were turned to follow 'Oumuamua, in the hope of capturing signals sent back to home base, though nothing was found. If this is a scout for some distant intelligence, it was keeping its own counsel. As it became clear that 'Oumuamua may have been more of a pancake shape instead of a cigar, those thinking about spacecraft became more excited. One plausible mode of travel through the galaxy is to use a solar sail, propelled by light across the cosmos. (Such a craft could use sunlight, or perhaps be pushed by powerful lasers). Such a sail would need to present a broad front, just as 'Oumuamua seemed to do.

The most serious effort to consider how to make such a craft is Breakthrough Starshot, a privately funded effort whose lead is Harvard cosmologist Avi Loeb. Seeing in 'Oumuamua a larger version of exactly what he would like his team to build, Loeb has become the primary advocate for its status as an alien spacecraft. In his book 'Extraterrestrial; he puts the odds of the properties that it displays all occurring naturally at a trillion to one.

Is he right? For all that I would love to be visited by an alien spacecraft, he is not. Those who spend their lives studying the small bodies of the Solar System will point out that the most extraordinary thing about 'Oumuamua is that we spent much time considering it at all - few objects of its size and class have ever been observed with facilities like the Very Large Telescope, which provided the most detailed observations of the campaign. And while its shape is unusual, it is not without precedent in the Solar System, and nor is the colour.

What about the acceleration? If only 'Oumuamua was a comet, this would be no problem. As comets heat up, they do not melt uniformly. The spectacular images sent back from ESA's Rosetta spacecraft, which accompanied Comet 67/P Churyumov–Gerasimenko as it swung around the Sun, show dramatic jets shooting from weak points on the nucleus' icy surface. Such jets could easily act as rocket engines, propelling an object around the Solar System, or in this case, out of it. (Their effect makes it hard to predict the long-term trajectory of such bodies, to the annoyance of those wanting to check that they won't hit Earth in the next millennium).

But 'Oumuamua wasn't a comet. Or was it? Some studies suggest that there could have been enough activity to account for the observed acceleration without forming a visible coma. In this picture, 'Oumuamua may have wandered amongst the stars for billions of years, its process exposed to the harsh environment of interstellar space. Prolonged bombardment of its surface by cosmic rays may have meant that volatile species - water, carbon monoxide and so on - would have been lost from the outer layer, leaving an icy core surrounded by a depleted, dark crust. Essentially, the object would have been a cosmic Magnum - crispy shell and all - and this would have allowed for the possibility of some activity where the shell is broken, while keeping most of its icy safe. Others have reached for more exotic compositions - Darryl Seligman and colleagues in Chicago have suggested that 'Oumuamua may be a hydrogen iceburg, formed not in a solar system but in the cold conditions that prevail in star-forming regions. (Later versions of the same idea suggest that hydrogen may be produced by processing water within the object's core; in both cases, hydrogen would not have shown up in our observations).

Whatever it is made of, 'Oumuamua focused attention on the presence of such objects in the galaxy. It turns out that we shouldn't have been surprised by the presence of a small passing interstellar object, and not only because of the visit a few years later by a second object, Borisov, which behaved much more like a normal comet as it, too, swept through the Solar System. (As far as I know, no one has claimed that Borisov was a spacecraft). The first clue comes from studying our own Solar System, and in particular from its outer reaches.

Pluto is no longer considered a major planet, in part because of its presence amongst the myriad bodies in the Kuiper Belt. Several of its neighbours, like Eris and Makemake, are large (perhaps approaching the size of Pluto itself), but most of the objects we see are much smaller. From the distance of the Earth, these worlds appear as no more than points of light, making studying them an experience rather like watching 'Oumuamua, drawing conclusions from no more than measurements of colour and changes in brightness.

What we do know is that many of these objects are double, not single objects but pairs, either in orbit around each other or joined together after a gentle collision. The best example might be the small Kuiper Belt object now known as Arrokoth, which was visited by the New Horizons spacecraft after its reconnaissance of Pluto. For those of us who worry about how planets were formed, this was almost the most exciting part of the mission - while it was fun to see the dramatic diversity of Pluto's surface, the material in that body has been processed, altered chemically by its assembly into a large world. Arrokoth is much closer to a primordial building block, a glimpse of what all of the worlds of the Solar System must have been made of.

On approaching New Years Eve 2018, initial images from the probe showed something looking rather like a bowling pin - or, some suggested, a champagne bottle. The closest images from the flyby show a snowman shape, with two bodies joined at a neck which showed signs of a low velocity impact. For such events to have been as common as they seem to have been in the Kuiper Belt, its density must once have been at least a thousand times greater than it is today.

The images of protoplanetary disks from ALMA I mentioned earlier showed how dynamic the early days of the Solar System must have been. Close studies of the properties of the Kuiper Belt, and simulations of the behaviour of our planetary system show that the giant planets, and Jupiter in particular, must have migrated into their current positions, movement which would have had a catastrophic influence on the small bodies of the outer solar system. A very conservative estimate suggests that our Solar System alone expelled 10^16 objects, scattering them into the Milky Way's disk and adding to the population of interstellar objects.

If every star does the same, then small icy bodies such as 'Oumuamua or Borisov will be the most common macroscopic objects in the galaxy. The surprise is not that we've seen two of these things, but that we haven't managed to find more. A quick calculation suggests that something at least the size of 'Oumuamua must be passing through the Solar System, within the orbit of Neptune, at all times, though their diminutive size, darkness and speed means that no more have yet been identified.

It is this flux that might make interstellar objects such as 'Oumuamua the solution to the planetary mystery with which I started this lecture. Though the Orion nebula looks like an impressive object to us, it is still pretty tenuous, with a lower density than a good laboratory vacuum. Interstellar objects roaming the galaxy will pass through it, and, if they encounter a forming star, they may get drawn into the material that ends up in the protoplanetary disk that will inevitably form. Or they may, a little later, be captured by the disk itself as they pass through. Even if such processes are rare, the sheer number of interstellar objects in the galaxy today mean that any disk will come with a starter set of planetary building blocks, large enough at a few hundred meters across for gravity to begin to hold them together in the chaotic environment of the disk.

Planet formation may proceed rapidly because of a jump start provided by the arrival of objects such as 'Oumuamua. A system or two may have had to get started the old-fashioned way, but the objects expelled from these first planetary systems would, we think, have quickly spread through the galaxy, promoting planet formation and therefore the release of more interstellar objects. Even the Earth's formation may have begun with the capture of something very like 'Oumuamua.

Testing this idea involves doing much more to understand the population of interstellar objects that exists today. Together with Michele Bannister in New Zealand, and PhD student Matthew Hopkins, I've been working on using what we know about the history of star formation in the Milky Way to predict what future visitors might be like. Prospects are good for the Vera Rubin Observatory, an 8m class telescope which will survey the whole southern sky every three nights starting next year, which is expected to discover something between a few dozen and a few hundred interstellar objects over the course of its ten-year survey. If each stimulates half as much thought, and generates half as many questions, as did 'Oumuamua, you should expect to hear much more about interstellar objects before too long.

References and Further Reading

Images of star formation in the Orion nebula are featured here: https://esahubble.org/images/opo9545l/ and seen in context here: https://hubblesite.org/contents/news-releases/1995/news-1995-45.html

A summary of ALMA's observations of planet-forming disks is here: https://almascience.eso.org/alma-science/planet-forming-disks and there's a recent review in the 2020 Annual Review of Astronomy and Astrophysics by Sean Andrews: https://arxiv.org/abs/2001.05007

The best summary of observations of 'Oumuamua is 'here: 'The Natural History of 'Oumuamua: https://arxiv.org/abs/1907.01910'

For the hydrogen hypothesis, try : Seligman and Laughlin 2020 https://arxiv.org/abs/2005.12932 and Bergner & Seligman 2023: https://www.nature.com/articles/s41586-022-05687-w

Avi Loeb's argument that 'Oumuamua is likely a spacecraft is published as 'Extraterrestrial' (John Murray, 2021), but see my review in the LRB: https://www.lrb.co.uk/the-paper/v43/n11/chris-lintott/flying-pancakes-from-space and a detailed rebuttal by Wright, Desch and Raymond here: https://medium.com/@astrowright/oumuamua-natural-or-artificial-f744b70f40d5

A good overview of the results of New Horizon's encounter with Arrokoth is given by Keane et al. 2022: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2021JE007068

The remarkable idea that planet formation might be accelerated by interstellar objects is due to Pfalzner and Bannister (2019): https://arxiv.org/abs/1903.04451

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