It came from outer space:
Interstellar visitor 1I/’Oumuamua

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Outline

- Discovery, orbit, (e of comets, Oort cloud, why unusual)
- Reaction, challenges, observations, lots of arxiv posts
- Results
  - Lack of activity
  - Spectrum, comparison with known objects
  - Lightcurve, shape (vs albedo effects), tumbling?
- Expectations, how many interstellar visitors, why they should be comets
- Thermal model, ice survival (age), strength, comparison with comets
- Where did it come from?
- Expected discovery rate with LSST
Discovery

• Discovered 18 October 2017 by Pan-STARRS survey
  – Unusual initial orbit solution prompted follow up (search for earlier data not found automatically, new observations with CFHT)

• By 25th October a hyperbolic orbit with eccentricity 1.2 was confirmed, discovery announced as comet C/2017 U1 (PANSTARRS)

• Passed perihelion at q=0.25 AU in early September, relatively close approach to Earth (0.16 AU) in mid-October

• Outbound at discovery, fading fast
Orbit

Path of A/2017 U1

Location of A/2017 U1 when discovered by PanSTARRS on 19 October 2017

Orbit of a comet within solar system

A/2017 U1
Comet orbits

Jupiter family: short period (< 10yr), e~0.5
Halley type: ~100yr, e~0.9
Oort cloud comets: > 10,000yr, e~1
Comet orbits

Comet orbits can be classified into three types based on their eccentricity:
- Circular orbits have an eccentricity of 0.
- Parabolic orbits have an eccentricity of 1.
- Hyperbolic orbits have eccentricities greater than 1.

The diagram shows a distribution of comet orbits with respect to their eccentricity. 'Oumuamua, a distant interstellar object, has an eccentricity just above 1, indicating a hyperbolic orbit.
Rapid reaction

• Scramble for telescope time.
  – HST, VLT (FORS), Gemini, CFHT, UKIRT (Meech et al)
  – LT, WHT (Fitzsimmons et al)
  – VLT (X-shooter) (Snodgrass et al)
  – Gemini (Bannister et al, Drahus et al)
  – Palomar 200” (Masiero, Ye et al)
  – DCT (Knight et al)
  – APO (Bolin et al)
  – NOT, WIYN (Jewitt et al)
  – Spitzer (Trilling et al)
Narrow window for observations
Narrow window for observations
Narrow window for observations

Fast Moving Object P10Ee5V
15 arcseconds/minute
Rapid Reaction (2)
Rapid Reaction (2)
Rapid Reaction (2)
Masiero Palomar Optical Spectrum of Hyperbolic Near-Earth Object A/2017 U1

Mamajek Kinematics of the Interstellar Vagabond 1I/'Oumuamua (A/2017 U1)

de la Fuente Marcos Pole, Pericenter, and Nodes of the Interstellar Minor Body A/2017 U1

Gaidos Origin of Interstellar Object A/2017 U1 in a Nearby Young Stellar Association?

Trilling Implications for planetary system formation from interstellar object 1I/2017 U1 ('Oumuamua)

Knight The rotation period and shape of the hyperbolic asteroid A/2017 U1 from its lightcurve

Laughlin On the Consequences of the Detection of an Interstellar Asteroid

Ye 1I/2017 U1 ('Oumuamua) is Hot: Imaging, Spectroscopy and Search of Meteor Activity

Hein Project Lyra: Sending a Spacecraft to 1I/'Oumuamua (former A/2017 U1), the Interstellar Asteroid

Zwart The origin of interstellar asteroidal objects like 1I/2017 U1

Cyncynates Could 1I/'Oumuamua be macroscopic dark matter?

Bolin APO Time Resolved Color Photometry of Highly-Elongated Interstellar Object 1I/'Oumuamua

Jewitt Interstellar Interloper 1I/2017 U1: Observations from the NOT and WIYN Telescopes

Schneider Is 1I/2017 U1 really of interstellar origin?

Bannister Col-OSSOS: Colors of the Interstellar Planetesimal 1I/2017 U1 in Context with the Solar System

Dybczynski On the dynamical history of the recently discovered interstellar object A/2017 U1 - where does it come from?

Ferrin 1I/2017 U1 (Oumuamua) Might Be A Cometary Nucleus

Feng 'Oumuamua as a messenger from the Local Association

Zuluaga A general method for assessing the origin of interstellar small bodies: the case of 1I/2017 U1 (Oumuamua)

Raymond Implications of the interstellar object 1I/'Oumuamua for planetary dynamics and planetesimal formation

Nature Meech A brief visit from a red and extremely elongated interstellar asteroid

Fraser 1I/'Oumuamua is tumbling

Drahus Tumbling motion of 1I/'Oumuamua reveals body’s violent past

Cuk 1I/'Oumuamua as a Tidal Disruption Fragment From a Binary Star System
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<td>Domokos</td>
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WHAT IS IT? COMET, ASTEROID?
SPACESHIP...?
Comets v asteroids

• Comets:
  – Icy, eccentric orbits, show activity (coma/tails)

• Asteroids:
  – Rocky, circular orbits, no activity

• Recent picture is more confusing
  – Active asteroids (main belt comets)
  – Damocloids/Manx comets
  – Extinct comets

Comets v asteroids

- Observationally, comets have extended profile
- Comparison of surface brightness profile with PSF (from stars) reveals faint coma
- Example shows start of activity in 67P
- Can reveal activity fainter than is visible by eye in image
- Can still hide weak activity within seeing disc

Snodgrass et al 2016, A&A
Asteroid?

WHT image from Oct 25th, Fitzsimmons et al
Asteroid?

Combined Gemini images, Drahus et al
No activity in profile – asteroid?

Jewitt et al.
Composition

- Can also test for asteroid- or comet-like composition
- Spectroscopy reveals composition
  - emission features in gas coma (comets)
  - Solid-state absorption features in reflected continuum (asteroids)
  - E.g. bands at ~0.7 μm due to phyllosilicates, or ~0.95 μm (pyroxines and olivines)

Comet spectrum (Feldman et al 2004)
Bus-DeMeo Taxonomy Key

S-complex

C-complex

X-complex

End Members

http://smass.mit.edu/busdemeoclass.html

Spectrum

Palomar 200", Masiero
Spectrum

Fitzsimmons et al
Size, shape, physical properties

- Calibrated gives size (assuming albedo) from reflecting area
- Relative photometry over time-series (lightcurve) gives
  - Rotation rate from periodicity
  - Shape from lightcurve amplitude
  - Constraints on density / strength of material (balance of centrifugal and gravity forces)

\[
\frac{a}{b} = 10^{0.4 \Delta m}
\]

- Colour photometry can complement spectra
Lightcurve

Jewitt et al., inc. Knight et al. data

P = 8.26 hr (two-peaked)
Various lightcurve studies give period 7-8 hours
Knight et al first partial lightcurve (on arXiv Nov 5)
Meech et al one first to be published, combines multiple observations
Lightcurve amplitude very large (2.5 mag)
Implies a highly elongated body

\[ \frac{a}{b} = 10^{0.4 \Delta m} \approx 10 \]
WTF?

Hey, you know that asteroid that tumbled past from another star system? It's apparently really long and skinny. Like a ratio of 6:1 or 10:1. Weird. Wonder what it's shaped like.

Without more data, it would be irresponsible to speculate further.

So... you're going to? Absolutely.

Here are some objects with a similar shape ratio: the 1:4:9 monolith from 2001: A Space Odyssey. A star destroyer. A huge eggplant emoji.

A statue of weird Al. An iPhone. XXXXX. Voltron. A giant space coffin. But who could be inside? We can only guess. I'll start:

This is all based on how many data points, again? One. But it's a perfect fit!

https://xkcd.com/1919/  22nd Nov
WTF?
WTF?
Questions

• What is it made of?
  – Comet or asteroid?
• Why the unusual shape?
• Where did it come from?
• How many are out there?
COMPARISON WITH EXPECTATIONS
Expectations

- Various studies estimating expected rate of discovery
- Most recent (pre `Oumuamua) by Engelhardt et al. (2017, AJ 153:133), inc. PS1 etc. survey efficiencies
- Detection rates depend on many things, including size distribution and comet/asteroid like behaviour
- Much easier to detect comets at same size, due to activity (larger reflecting area -> brighter)
Formation of ISOs

- Two ways of forming ISOs:
  - Direct ejection due to gravitational interaction with (giant) planet
  - Escape from Oort clouds due to stellar encounters

- Modern planet formation models include migration and eject a lot of planetesimals

- In both cases, most ISOs will be icy
  - Planetesimals forming near giant planets will be icy
  - Oort cloud mostly icy bodies
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- Most planetesimals ejected early and from initially larger distance from star
- Most are small bodies
Can it be icy?

• Spectrum looks like an icy body
• Expectation that bringing an icy body to 0.25 AU will cause activity
• No activity seen

• Comets have low thermal inertia
• This thing was going fast
• Can ice survive under insulating layer?
Can it be icy?

Fitzsimmons et al.
Can it be icy?

- Lack of activity doesn’t rule out sub-surface ice
- Comet surfaces are expected to build up mantle / de-volatised layer over long periods of cosmic ray bombardment
- Predictions 10cm – 2m (Guilbert-Lepoutre et al 2015, SSR 197:271)
- Compatible with this, but can ice support the odd shape?
  - Implied density (if rubble pile) ~ 2000 kg/m$^3$ (not ice)
  - Small enough to be monolith? Strength?
Strength of asteroids

![Graph showing the frequency of asteroids of different diameters. The graph includes points representing binary, tumbler, and spin barrier asteroids.]
Strength

- Required strength for ~1000 kg/m$^3$ is only few Pa
- Talcum powder has strength of ~10 Pa
- How strong is a comet?
- Bulk comets thought to be strengthless
  - E.g. modelling of breakup of SL9 around Jupiter
- Rosetta results show strength on scales of cliffs (up to km) of 3-15 Pa, locally > 2 MPa (MUPUS)
IS IT REALLY CIGAR-SHAPED?
Lightcurves

• Lightcurve variation not necessarily due to shape
• In most small bodies, shape controlled lightcurve is a reasonable assumption
  – Very few seen to have clear albedo variations
• Should ISOs be the same?
• Moderate elongation and associated albedo variation (ends v sides)??
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Lightcurves

`Oumuamua models (end members)
Rotational variation

Fitzsimmons et al
All lightcurve data – it is tumbling
Tumbling, with red side(s)

- Tumbling interpretation means that phasing of colours is difficult to do
- Can’t map differences
- Colours / spectroscopy around this peak show that difference can be due to red patch(es) and otherwise more neutral colours
- Also, tumbling model doesn’t require such large elongation: $a/b > 5$

Fraser et al
Tumbling, with red side(s)
Tumbling

- Fraser et al, Drahus et al, independently find 'Oumuamua to be tumbling
- Belton et al 2018 follow up with additional photometry from November
  - Find various possible frequencies and shape implications
  - SAM (minimum energy) = cigar
  - LAM = cigar to pancake (max energy)
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Damping timescale $> 10^{11}$ yrs

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IMPLICATIONS
Comparison with comets

• Composition looks like icy body
• Other properties do not rule it out
• Is time spent in interstellar space unusual?
• Age is difficult to estimate, but can’t be so ancient:
  – Universe only ~3x age of solar system
  – Planetary systems only form once there are metals (so not first generation of stars)
  – Also low speed w.r.t. LSR implies youth (Feng et al 2017)
• Probably not very different in age to Oort cloud comets
  – Oort cloud experiences similar cosmic ray rate
  – Oort cloud comets should be similar?
Oort cloud comet
Sizes of comets

$q = 1.97$

$1.26\ km$

Snodgrass et al 2011
Implications for Oort cloud comets

• `Oumuamua is much smaller than known comets (typically > 1km)
• Combined with elongation, nowhere is deeper than ~20m from surface
• Could be de-volatised
• Oort cloud comets of similar size will have had similar cosmic ray bombardment
• Should expect that there is a population of small and inactive ‘comets’ from Oort cloud
Loss of volatiles in its home system?

- Raymond, Armitage & Veras 2018:
  - 0.1-1% of comets have disruptive encounters with giant planets before ejection
  - Most then pass close to star before leaving
  - Could be devolatised, and potentially elongated

- Or, could be rocky body from binary system (Jackson et al 2018)
Where did it come from?

• Came from approx Solar apex, i.e. direction Solar system is moving relative to local standard of rest
• Speed (~30 km/s) similar to Sun motion – we ran into it
• From direction of Vega, but Vega wasn’t there when it was
• Integration of trajectory and star motions doesn’t find parent system (Dybcynski & Krolikowska, Ye et al, Zuluaga et al, Zwart et al, Feng & Jones, Zhang)
How many more are out there?

- Size distribution of asteroids or comets implies many more small bodies than larger one
- If they are inactive they are harder to detect
- Very approximate calculation (based on N=1 in 10 years of surveys) from Laughlin & Batygin 2017:
  - Space density of similar objects of order $\sim 1/100 \text{ AU}^{-3}$
  - This implies $\sim 2 \times 10^{26}$ such objects in the galaxy
  - Galactic mass in such bodies is $M_{\text{tot}} \sim 10^{11} \text{ M}_\odot$ (for density of 1000 kg/m$^3$).
  - Ejection of these bodies implies more Jupiter-like (giant at a>5 AU) exoplanets to find
Implications for planet formation

- Papers from Trilling et al, Raymond et al.
- Around 1 $M_\oplus$ (0.1-10) of ISOs ejected per solar mass star
- Dominated (by number) by small and icy bodies, asteroid-like composition unlikely
- Systems with distant Jupiters more efficient, hot Jupiters don’t eject bodies easily
  - E.g. Solar System models suggest > 10 $M_\oplus$ ejected, above average
  - True population depends on size distribution and ejection processes

Raymond et al 2017
Future prospects

- Hein et al suggests a mission to intercept, catching up at ~100 AU...
- Can expect more ISOs
- Probably there are larger ones, but small ones more common
- Are they all inactive?
- Will be a surprise if they are all so elongated...
- **Predicted discovery rate for LSST is ~1/yr**
- Can expect to find some inbound, longer to study (and ELTs/JWST to respond with)
  - ~10 year wait for one suitable for intercept mission, if ready
Summary

- Rapid response to characterise 1st ISO during short observing window
- Surface properties match icy outer-Solar System bodies as expected, but no comet-like activity
  - Thermal model suggests that this can be explained by devolatised surface layer
- Lightcurve implies extremely elongated shape, tumbling
  - Comet-like strength enough to support this
- Small size could explain earlier loss of volatiles
- Implications for planet formation.
  - Currently, $N_{\text{models}} > N_{\text{data points}}$
- Many more discoveries expected in LSST era
Only possible conclusion