Follow up of the First Known Interstellar Object

Karen Meech
Institute for Astronomy
Gemini Science Meeting, July 23 2018
The Discovery 2017

- 10/19 – Discovered by PS1 \(\rightarrow\) P10Ee5V

Discovery Image

Tracked on stars

PanSTARRS1 (1.8m)
The Discovery 2017

• 10/19 – Discovered by PS1 ⇒ P10Ee5V
• 10/18 – Prediscovery images found in PS1 data
  – Follow up ESA ground station – data rejected, large eccentricity
  – Classified as an Earth-orbit crossing asteroid
• 10/20 – Catalina Sky Survey data ⇒ classified as short-period comet
• 10/22 – CFHT observations: orbit is hyperbolic: \( e = 1.188 \)
• 10/24 – The Minor Planet Center posted a name: C/2017 U1
• 10/26 – MPEC 2017-U183 – named A/2017 U1
1837 – Passed inside 1000 au
Jan 18, 2017 – inside 5.2 au
Aug 10, 2017 – inside 1.0 au
Sep 9, 2017 – perihelion q = 0.255 au
Oct 11, 2017 – outside 1.0 au
Oct 14, 2017 – close Earth approach Δ = 0.162 au

May 3, 2018 outside 5.2 au
Jun 2022 – 30 au
Feb 2024 – 39 au
Dec 2025 – 50 au
Jul 2038 – 121 au
2196 – 1000 au
Naming A/2017 U1

- **P10EeV5 → C/2017 U1 → A/2017 U1 →** Short “working names” (U1, Rama)
  - Consulted with Ka’iu Kimura (Hawaiian navigator), Larry Kimura (Hawaiian linguistics expert)

- **Proposal of ‘Oumuamua**
  - ‘Ou = to reach out for, mua = first, in advance of (duplication→emphasis)
  - Scout or distant messenger sent from our distant beginnings to reach out to us or build connections with us

- **The Official name (Nov. 6) 1I/2017 (‘Oumuamua)**
The Timeline

### What do we want to know?
- Size & shape, mass, density
- Rotation period
- Composition
  - Color, spectral features?
  - Comet or asteroid?
  - Gas chemistry?
- Orbit
- Origin & implications

<table>
<thead>
<tr>
<th>Sun</th>
<th>Mon</th>
<th>Tue</th>
<th>Wed</th>
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<th>Fri</th>
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<tr>
<td>← Sep 9 Perihelion</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18-PS1 Precovery</td>
<td>19-PS1 Discovery</td>
<td>20-Astrometry</td>
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<td>22- Hyperbolic orbit confirmed</td>
<td>23-DD prop VLT, GS; VLT Approve</td>
<td>24- GS prop Approved; MPEC orbit announce</td>
<td>25-VLT Obs, HST prop submit, UKIRT DD award; ★</td>
<td>26- VLT, GS obs; HST Approve; PR ★</td>
<td>27- GS, CFHT, UKIRT, Keck obs</td>
<td>28- UKIRT obs ★</td>
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<td>29 – Hawaiian name</td>
<td>30- ★</td>
<td>31- Nature paper submit</td>
<td>1</td>
<td>2</td>
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<td>6-Ref. Rpt. IAU Name OK</td>
<td>7</td>
<td>8-Resubmit paper</td>
<td>9</td>
<td>10-Paper in production</td>
<td>11</td>
</tr>
</tbody>
</table>

Our Nature paper was accepted Nov. 13 published online on Nov. 20
Aloha… "Oumuamua

First observed interstellar object to pass by Earth given Hawaiian name

By Timothy Hurley

Following a speedy yet far-reaching analysis, University of Hawaii astronomers Monday unveiled a description of their discovery last month of the first interstellar object seen passing through our solar system.

The assessment?

“This thing is quite strange,” said Karen Meech of UH’s Institute for Astronomy and lead author of the study, which appeared Monday in the journal Nature.

The rapidly rotating interstellar asteroid — about 2,625 feet long, or roughly seven football fields or more — is named ʻOumuamua.

INTERSTELLAR ASTEROID

The recently identified interstellar asteroid is described as likely a dark red, long, metallic or rocky object. It is now headed out of our solar system.

- Name: ʻOumuamua
- Discovered: Oct. 19
- Origins: Beyond our solar system
- Age: Millions of years
- Status: Passing through
- Telescope: Pan-STARRS 1

Approximate length: **2,625 feet** (800 meters)

HART board delays $18M increase for rail contractor

Most of the higher costs are due to a heavier work load, a rail official says

By Nancy Faber
<table>
<thead>
<tr>
<th>PI</th>
<th>Telescope</th>
<th>Allocation</th>
<th>Date Obs</th>
<th>Science</th>
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<tbody>
<tr>
<td>Hainaut/Meech</td>
<td>VLT 8m</td>
<td>3.5 hr</td>
<td>10/25, 10/26</td>
<td>Rotation, shape, color</td>
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<td>Fitzsimmons</td>
<td>WHT</td>
<td>&lt; 1 hr</td>
<td>10/25, 10/28</td>
<td>Spectrum</td>
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<td>Masiero</td>
<td>Palomar 5m</td>
<td>3 hr</td>
<td>10/25</td>
<td>Spectrum</td>
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<tr>
<td>Ye</td>
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<td>10/26</td>
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<td>Snodgrass</td>
<td>VLT 8m</td>
<td>4 hr</td>
<td>10/27</td>
<td>Spectrum</td>
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<td>Guzik</td>
<td>Gemini 8m</td>
<td>9.7 hr</td>
<td>10/27</td>
<td>Rotation</td>
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<td>Chambers</td>
<td>UKIRT 3.8 m</td>
<td>9 hr</td>
<td>10/27, 10/28</td>
<td>Color - IR</td>
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<td>Magnier</td>
<td>Keck 10 m</td>
<td>3 hr</td>
<td>10/27</td>
<td>Rotation, color</td>
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<td>Wainscoat</td>
<td>CFHT 3.6 m</td>
<td>8 hr</td>
<td>10/27, 11/20, 11/21</td>
<td>Rotation, astrometry</td>
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<td>Jewitt</td>
<td>NOT 2.5 m</td>
<td>2.3 hr</td>
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<td>Bannister</td>
<td>Gemini 8 m</td>
<td>2 hr</td>
<td>10/29</td>
<td>Colors</td>
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<tr>
<td>Bolin</td>
<td>APO 3.5m</td>
<td>4 hr</td>
<td>10/29</td>
<td>Rotation</td>
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<tr>
<td>Knight</td>
<td>DCT 4 m</td>
<td>2.8 hr</td>
<td>10/30</td>
<td>Rotation</td>
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<td>Meech</td>
<td>HST 1.8 m</td>
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<td>11/21, 11/22, Dec, Jan</td>
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<td>Sheppard</td>
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<td>3 hr</td>
<td>11/21, 11/22</td>
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<td>Spitzer</td>
<td>32.6 hr</td>
<td>11/21</td>
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<td>Oct. 31</td>
<td>Meech et al</td>
<td>Discovery/characterization</td>
<td>2017 Nature 552, 378</td>
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<td>Oct. 31</td>
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<td>ISO kinematics</td>
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<td>pole, pericenter....</td>
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<td>Nov. 22</td>
<td>Ferrin</td>
<td>1I might be a comet?</td>
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<td>Nov. 27</td>
<td>Raymond</td>
<td>Implications</td>
<td>2018 MNRAS 476, 3031</td>
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<td>Nov. 28</td>
<td>Zuluaga</td>
<td>Origin – Methods</td>
<td>2018 AJ, 155, 236</td>
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<td>Dec. 1</td>
<td>Drahus</td>
<td>1I is tumbling</td>
<td>2018 Nature Astron</td>
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<td>Dec. 12</td>
<td>Domokos</td>
<td>explain shape</td>
<td>2017 Rsch Notes AAS #1, id50</td>
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</table>
AstroPh papers posted

- Dec 13 – Jackson – ejection from binary
- Dec 17 – Wright – not a SS object
- Dec 18 – Cuk – tidal fragment from binary
- Dec 18 – Fitzsimmons – spectra & thermal
- Dec 19 – Gaidos – characterizing 1I, binary
- Dec 19 – Hansen – ejection from post MS *
- Dec 21 – Zhang – backtracking the orbit
- Jan 9 – Do – Number density of ISO
- Jan 10 – Enriquez – Breakthrough Listen
- Jan 13 – Rafikov – Disruption by WD
- Feb 5 – Hoang – spinup & disruption
- Feb 6 – Katz – Prolate shape
- Feb 26 – Tingay – Search for Radio
- Mar 18 – Raymond – shape
- Mar 18 – de la Fuente Marcos – Radiants
- Mar 27 – McNeill – Density and Strength of 1I
- Mar 27 – Park – Limits on OH outgassing
- Apr 10 – Belton – Excited spin state of 1I
- Apr 11 – Seligman – in Situ exploration
- Jun 27 – Micheli – Non grav acceleration

2017 Rsch Notes AAS #1, id38 (July 2018)
2018 ApJ 852 #1, L15 (Jan 1)
2018 MNRAS 477, 5692 (July 2018)
2017 Rsch Notes AAS #1, id55 (Jan 1)
2018 ApJL 855, L10 (Jan 1)
2018 Rsch Notes AAS #2, Id9 (Mar 2018)
2018 MNRAS 478, L95 (July 2018)
2018 MNRAS 476, L1 (May 2018)
2018 AJ 155, 185 (May 2018)
2018 ApJL 856, #2, L21 (April 2018)
2018 Astron J, 155, id17 (May 2018)

43 papers to date; 34 published as refereed papers.
Average size & Activity

- Brightness is related to size (and how reflective)
  - Combine all the 8-m telescope data
  - Average radius $102 \pm 4$ m
    - $H_V$ (median) = $22.4$, $p_V = 0.04$ (assumed)
- Dust Limits
  - Compare shape of stars to `Oumuamua: Maximum amount of dust is about 1 kg within 750 km from nucleus
- Icy or rocky?
  - 1 billion years exposure to cosmic rays should not remove all ice if it exists near surface
It is “red” like comets. . . . Spectral slope 23±3 % / 100 nm

- Palomar 10/25 – 30% / 100 nm
- WHT 10/25 – 16% / 100 nm
- Palomar 10/26 – 10±6 % / 100 nm
- Gemini 10/28 (Bannister) – 22±15 % / 100 nm
- Fitzsimmons 17±2.3 / 9.3±0.6 % / 100 nm (WHT/VLT)

Organic compounds (kerogen), pyroxene, metallic iron, iron oxides
Comet or Asteroid?

- **Consistent with being a Comet:**
  - Color matches comets – several groups – slopes 10-30% / 100 nm
  - The surface at closest approach to sun reaches 600°K - thermal models: could have ice at some depth (Fitzsimmons et al (2017) Nature Astron)

- **Limits on possible outgassing at 1.4 (Oct 26) and 1.9 au (Nov 12):**
  - Sensitive upper limits on $Q(\text{CN}) < 2 \times 10^{22}$ molec / s (suggesting $Q(\text{H}_2\text{O}) < 10^{24-25}$) (Ye et al 2017)
  - Radio $Q(\text{OH}) – 1.7 \times 10^{27}$ molec / sec (Park et al, 2018)
How fast does it spin?
‘Oumuamua’s shape
Complex Rotation

- **High energy rotation**
  - $8.67 \pm 0.34$ h - precesses around L vector
  - LAM – 6.58, 13.15 or $54.48$ hr
  - SAM – 13.15 and $54.48$ hr

- **Excited rotation** (Burns & Safronov, 1973)
  - Stresses cause frictional dissipation of E
  - Damping timescale for density $10^3$, $P \sim 10$ hr
    - $\tau \sim 10^8 (1 \text{ km/RN}^2) \sim 10^9-10$ yr for 'Oumuamua
  - Causes? Collision=ejection from star system, outgassing?
HST Program – “Which way home?”

- **Goal**
  - Extend orbit out to 2.5 mo from discovery

- **Awarded 9 orbits**
  - Visits in Nov. 21-22, Dec. 12, and Jan. 2, 2018
  - Plan was to know the rotation well enough by January that only 1 orbit needed
  - Excited rotation → can’t predict max brightness in Jan – requested 4 more orbits (object seen in only 2 out of 5 orbits)

- **Objectives**
  - to get 10” and 1 m/s precision on asymptote direction & velocity
  - Place strict limits on the detection of non-gravitational acceleration
  - Improve our ability to trace the orbit backward and figure out where it came from
Analyzing the Astrometry  
(M. Micheli & D. Farnocchia)

- Dataset: 177 ground, 30 HST positions
- Trajectory cannot be fit only with gravity from Sun, 8 planets, moon, Pluto and 16 largest asteroids and relativistic effects
- Residuals deviate by more than 5σ, non-systematic
- Addition of a radial acceleration $A_1 g(r)$, $g(r) \propto r^{-2}$, $A_1 = (4.92 \pm 0.16) \times 10^{-6}$ m s$^{-2}$
- Acceleration directed radially away from the Sun
- Non-grav acceleration similar to that of comets
## Possible Mechanisms

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Description</th>
<th>Issues</th>
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</thead>
<tbody>
<tr>
<td>Outgassing</td>
<td>Falls as $r^2$, directed radially away (+along orbit and out of plane), seen with comets</td>
<td>Gas should have been seen unless CN-depleted; Must be lacking in small dust</td>
</tr>
<tr>
<td>Solar Radiation pressure</td>
<td>Falls as $r^2$, directed radially away, seen with some asteroids</td>
<td>Acceleration magnitude required 1I bulk density $10^3$-$10^4$ x less than asteroids (aerogel), or would have to be a hollow shell, few mm thick</td>
</tr>
<tr>
<td>Yarkovsky Effect</td>
<td>Rotating body experiences force from anisotropic emission of thermal photons</td>
<td>Observed acceleration too high; this affects along track motion, not radial</td>
</tr>
<tr>
<td>Friction aligned with velocity</td>
<td>Drag forces – aligned with direction of motion</td>
<td>Wrong direction and should be deceleration, not acceleration</td>
</tr>
<tr>
<td>Impulsive velocity change</td>
<td>Can be caused by a collision – i.e. a single event</td>
<td>Acceleration seen in multiple subsets of data (i.e. continuous)</td>
</tr>
<tr>
<td>Binary object</td>
<td>Center of motion follows gravity trajectory, but tracking the brightest component only wouldn’t</td>
<td>No secondary object seen to sizes 100x smaller than 1I; this size insufficient to cause this effect</td>
</tr>
<tr>
<td>Photocenter offset</td>
<td>Surface characteristics displacing optical photocenter</td>
<td>For 800m object, largest offset would be 0.005” – several orders of mag &lt; than observed residuals</td>
</tr>
<tr>
<td>Magnetized object</td>
<td>Interaction with solar wind affects motion (seen with asteroid Braille)</td>
<td>Even with high magnetization, effect is too small by a factor $10^5$</td>
</tr>
</tbody>
</table>
Outgassing Models: Dust & Gas

- **Image Enhancement to search for dust**
  - Subsets of data
  - Model with 2x our limit on dust

- **Thermal model**
  - Est mass and required acc $\rightarrow Q = 10$ kg/s
  - Best fit param (Table) gives $Q_{\text{dust}} = 0.2$ kg/s, $Q_{\text{H}_2\text{O}} = 2.5$ kg/s

- **Implications**
  - This outgassing rate should have produced abundant µm-sized dust
  - Removal during passage through ISM?
  - Non detection of CN $\rightarrow$ unusual chemistry

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### Table: Parametric Values

<table>
<thead>
<tr>
<th>Param</th>
<th>Value</th>
<th>Param</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k$ [w/m/K]</td>
<td>0.7</td>
<td>Porosity</td>
<td>60%</td>
</tr>
<tr>
<td>Radius, $p$</td>
<td>102, 0.04</td>
<td>Depth to H$_2$O/CO ice</td>
<td>18 cm, 3.6 m</td>
</tr>
<tr>
<td>Ice/dust</td>
<td>3</td>
<td>$Q_{\text{H}_2\text{O}} @ 1.4$ au</td>
<td>4.9E25</td>
</tr>
<tr>
<td>CO/H$_2$O</td>
<td>0.25</td>
<td>$Q_{\text{CO}} @ 1.4$ au</td>
<td>4.5E25</td>
</tr>
</tbody>
</table>

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*From A'Hearn 1995; Cochran 2012*
A Variety of formation Theories

Tidal disruption, giant planets, volatile stripping with close solar passages (Raymond 2018)

Tidal disruption, in WD system, (Rafikov 2017)

Tidal disruption, in binary system, (Cuk 2017)

Heating during supergiant phase – loss of volatiles → fluidized to Jacobi ellipsoid shape, (Katz 2018)

Planetesimal shredding during SN explosion (Tucker 2018)

Erosion from high speed low mass objects (abrasion) (Domokos, 2017)

Rotational spin up & fragmentation, gravitational re-assembly, (Hoang 2018)

Macroscopic dark matter, (Cyncynates 2017)
Why is this important?

• Rare opportunity to study a sample of another solar system
  – Is the planet formation process similar everywhere?
  – Is the composition of small bodies the same everywhere?

• How much of this material is out there?
  – Because of the high velocity → more hazardous
  – Probability less than that of LPCs (which are less than NEOs)

• Where did ‘Oumuamua come from?
  – Many groups have tried to assess 1I/2017 U1’s star of origin

<table>
<thead>
<tr>
<th>Date</th>
<th>V wrt Sun</th>
<th>V wrt Earth</th>
<th>Energy [Mton]</th>
<th>x Hiroshima</th>
<th>x KT impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep 9, 2017</td>
<td>87 km/s</td>
<td>68.3 km/s</td>
<td>17,900</td>
<td>1.2 million</td>
<td>0.0007</td>
</tr>
<tr>
<td>Oct 14, 2017</td>
<td>48 km/s</td>
<td>60 km/s</td>
<td>14,000</td>
<td>1 million</td>
<td>0.0006</td>
</tr>
</tbody>
</table>
Forever caressed by blackest space, the hurtling megalith returns –

Earthlings’ prodigal creator in dense, velvet-wrapped disguise.

Its secret pilots seek adulation, sweet desolation, eternal cold burn;

Sapien’s myths rewritten when revealed the cosmic truth inside.

http://driftwoodbeer.com/beers/oumuamua/

Go.ted.com/karenjmeech
Back up Slides
Where did it come from?

- Initial direction from the direction of Vega
  - Could this be coming from the Vega debris disk? - no
- Can it be a comet from our Solar System – perturbed by Planet X?
  - To be undiscovered planet needs to be near galactic plane (U1’s radiant has galactic latitude of -16°)
  - The radiant of the recently proposed planet X is not close to U1’s
- Motion similar to local neighborhood
  - May have been “recently” ejected (10’s Myr)

<table>
<thead>
<tr>
<th>Lead Author</th>
<th>Galactic (v=(U, V, W)) km/s</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Meech</td>
<td>-11.2, -22.4, -7.6</td>
<td>Similar to stars in solar neighborhood, from a younger system?</td>
</tr>
<tr>
<td>Mamajek (31 Oct)</td>
<td>-11.3, -22.4, -7.6</td>
<td>Not from (\alpha) Cen Oort cloud</td>
</tr>
<tr>
<td>Gaidos (3 Nov)</td>
<td>-11.3, -22.4, -7.6</td>
<td>Possible origin in proto planetary disk from Carina/Columba association</td>
</tr>
<tr>
<td>Zwart (13 Nov)</td>
<td>-11.4, -22.4, -7.7</td>
<td>Passed by 5 stars with somewhat close encounters</td>
</tr>
<tr>
<td>Feng (27 Nov)</td>
<td>-11.4, -22.4, -7.7</td>
<td>Integrate orbit back 100 Myr – 109 stars with “close” encounters; young</td>
</tr>
</tbody>
</table>
Search for Radio Signals

• **Breakthrough Listen Experiment**
  – (Enriquez et al 2018)
  – GBT: Dec 13 (8 hr) from 1-12 GHz (L, S, C, X band)
  – No signal detected to a level of EIRP~0.08 W (3000 x weaker than the Dawn s/c downlink)
  – Also searched for OH emission at 1612, 1720 MHz

• **Murchison Widefield Array (Nov 28)**
  – Serendipitous – SKA precursor
  – Searched for signs of technology:
    • impulsive narrow signals, limit 7 kW
    • persistent narrow signals, limit 840 W
    • impulsive broadband signals, limit 100 kW

(Tingay et al 2018)