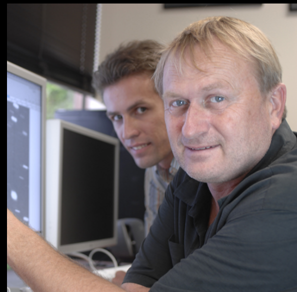
Follow up of the First Known Interstellar Object

Karen Meech
Institute for Astronomy

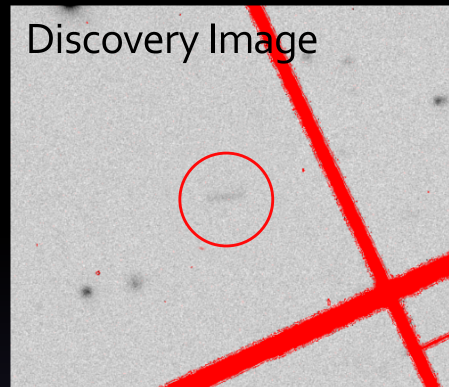
Gemini Science Meeting, July 23 2018

The Discovery 2017

R. Weryk



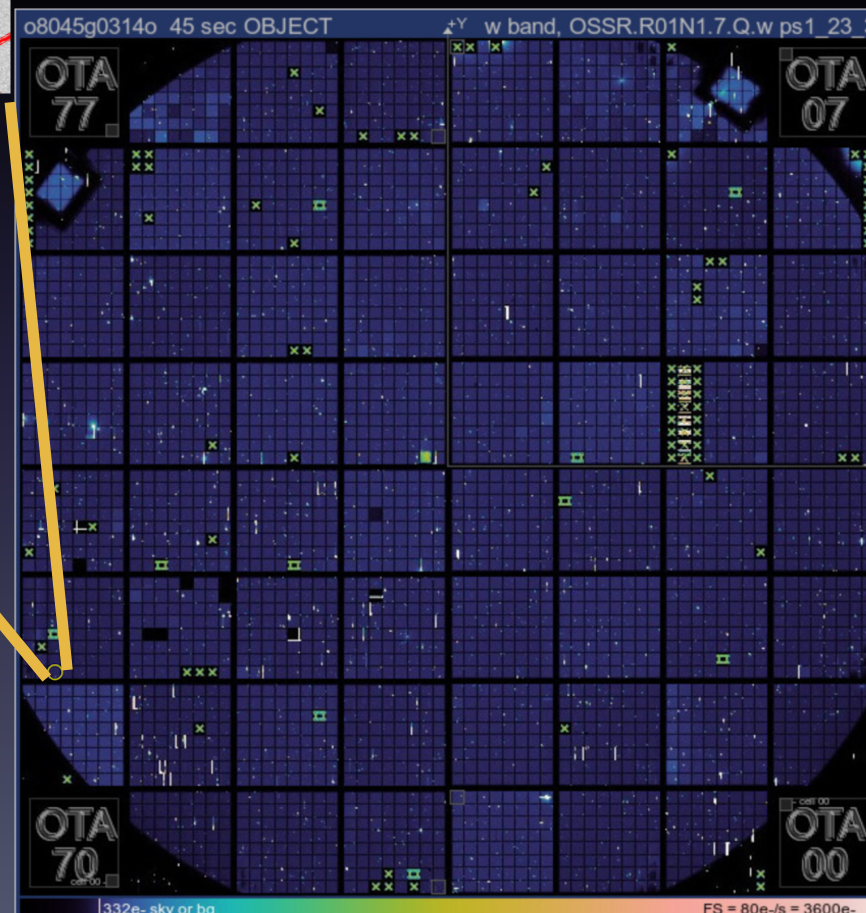
M. Micheli, R. Wainscoat



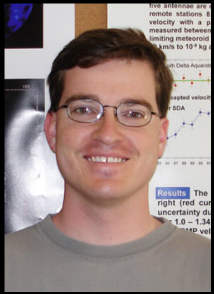
Tracked on stars

- 10/19 – Discovered by PS1 → P10Ee5V

PanSTARRS1 (1.8m)



The Discovery 2017



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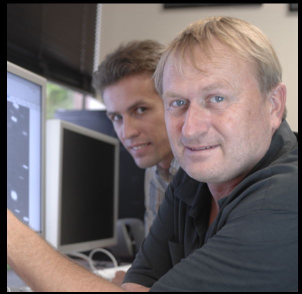

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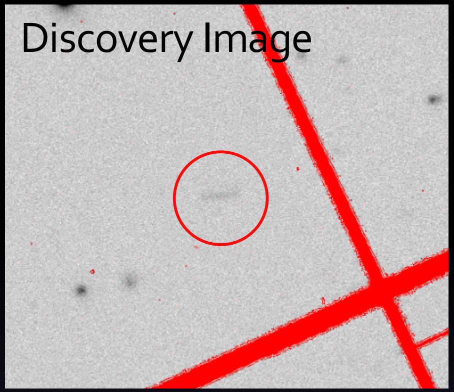
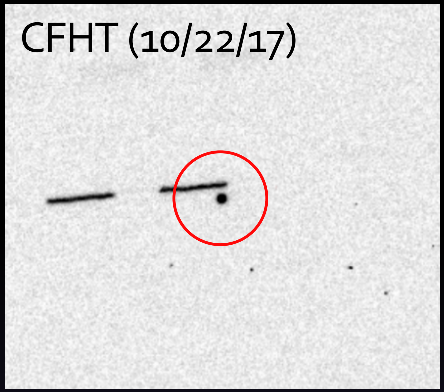


Tracked on stars



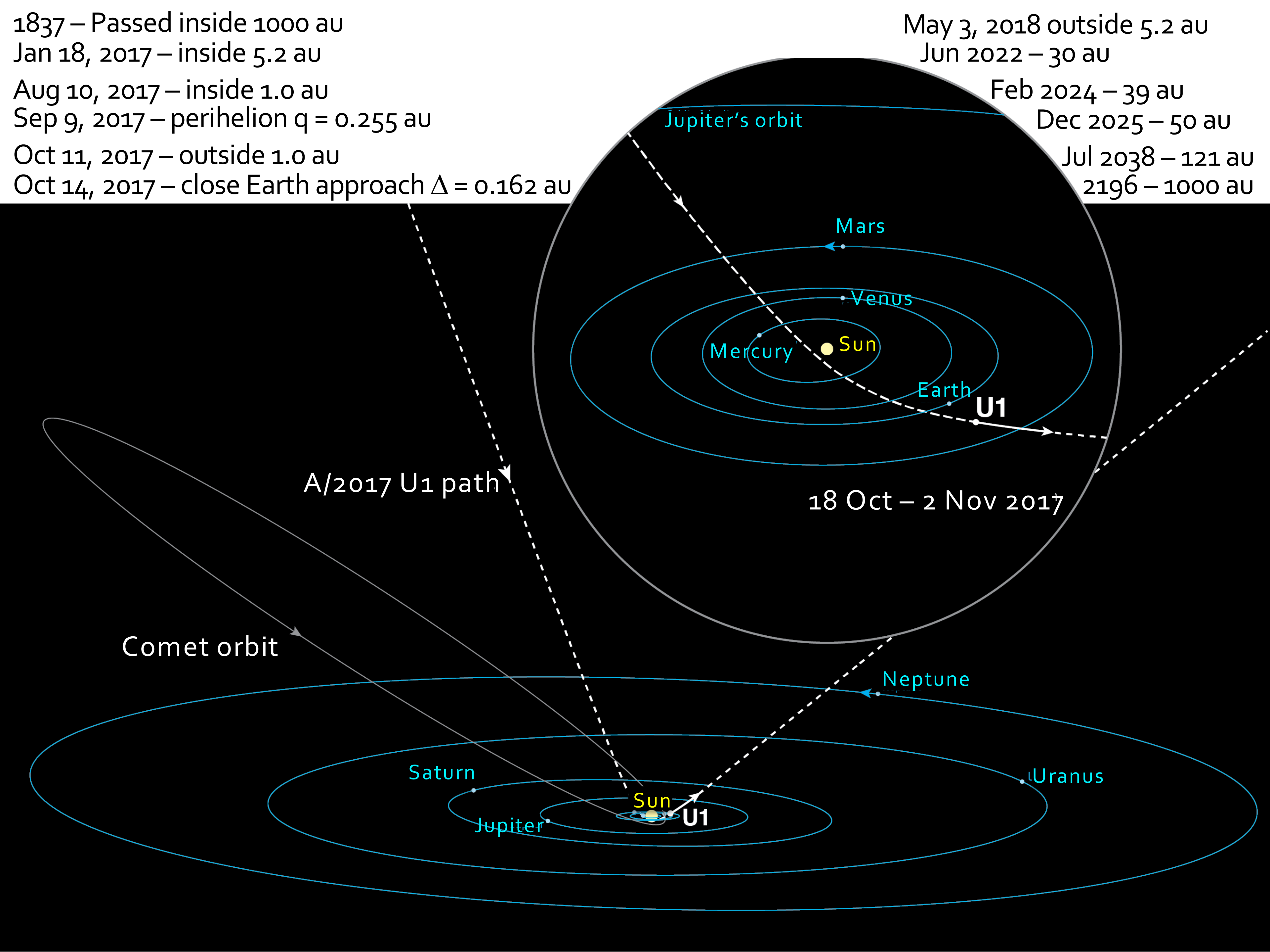
Tracked on object

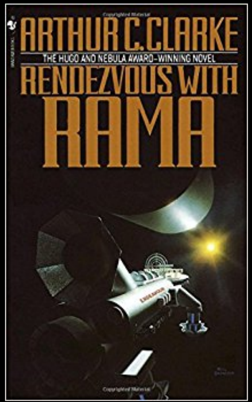
- 10/19 – Discovered by PS1 → P10Ee5V
- 10/18 – Prediscovery images found in PS1 data
  - Follow up ESA ground station – data rejected, large eccentricity
  - Classified as an Earth-orbit crossing asteroid
- 10/20 – Catalina Sky Survey data → classified as short-period comet
- 10/22 – CFHT observations: 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

PanSTARRS1 (1.8m)

ESA Ground (1m)

CFHT (3.6m)


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
Jupiter's orbit
Mars
Venus
Mercury
Sun
Earth
U1
18 Oct – 2 Nov 2017
A/2017 U1 path
Comet orbit
Neptune
Saturn
Uranus
Jupiter
Sun
U1

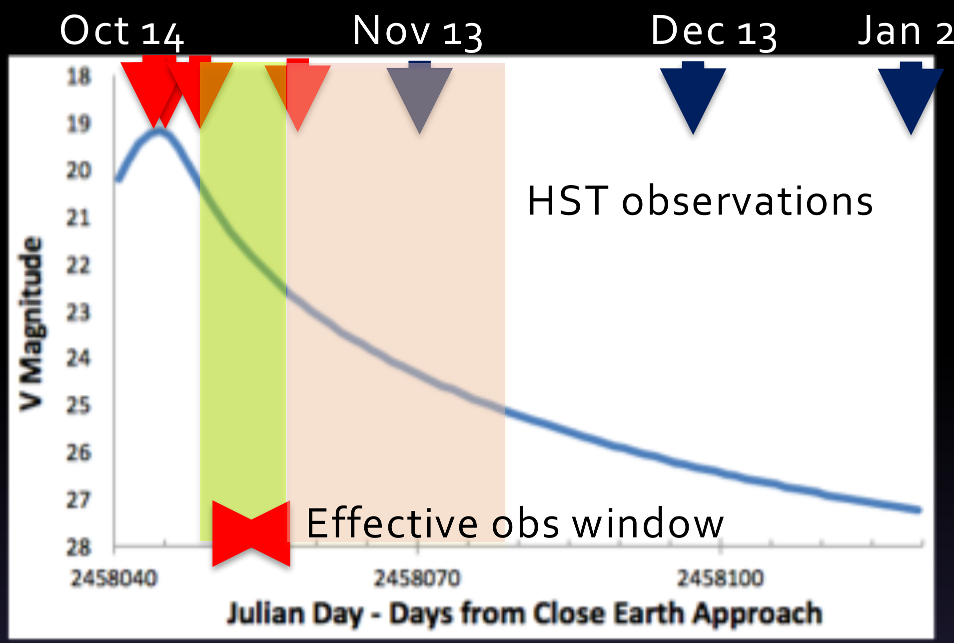


Pub. 1973

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

Sun	Mon	Tue	Wed	Thu	Fri	Sat
← Sep 9 Perihelion						14- Close Earth, CSS Pre-covery
15	16	17	18-PS1 Pre-covery	19-PS1 Discovery	20-Astrometry	21-Astrometry
22- Hyperbolic orbit confirmed	23-DD prop VLT, GS; VLT Approve	24- GS prop Approved; MPEC orbit announce	25-VLT Obs, HST prop submit, UKIRT DD award; ✭	26- VLT, GS obs; HST Approve; PR ✭	27- GS,CFHT, UKIRT, Keck obs	28- UKIRT obs ✭
29 – Hawaiian name	30- ✭	31- Nature paper submit	1	2	3	4
5	6-Ref. Rpt. IAU Name OK	7	8-Resubmit paper	9	10-Paper in production	11

Our Nature paper was accepted Nov. 13 published online on Nov. 20

Nov 21 – Front page coverage!

COURTESY UNIVERSITY OF HAWAII AT MANOA'S INSTITUTE FOR ASTRONOMY

First observed interstellar object to pass by Earth given Hawaiian name

HONOLULU Star Advertiser
The Pulse of Paradise

By Timothy Hurley
thurley@staradvertiser.com

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

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:** 'Oumuamua • **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 workload, a rail official says

World Resources ~ 100 hrs

PI	Telescope	Allocation	Date Obs	Science
Hainaut/Meech	VLT 8m	3.5 hr	10/25, 10/26	Rotation, shape, color
Fitzsimmons	WHT	< 1 hr	10/25, 10/28	Spectrum
Masiero	Palomar 5m	3 hr	10/25	Spectrum
Ye	Palomar 5m	< 1 hr	10/26	Spectrum
Meech	Gemini 8m	3.5 hr	10/26, 10/27	Rotation, shape, color
Snodgrass	VLT 8m	4 hr	10/27	Spectrum
Guzik	Gemini 8m	9.7 hr	10/27	Rotation
Chambers	UKIRT 3.8 m	9 hr	10/27, 10/28	Color - IR
Magnier	Keck 10 m	3 hr	10/27	Rotation, color
Wainscoat	CFHT 3.6 m	8 hr	10/27, 11/20, 11/21	Rotation, astrometry
Jewitt	NOT 2.5 m	2.3 hr	10/25, 10/30	Rotation, color
Jewitt	WIYN 3.5m	4.5 hr	10/28	Rotation
Bannister	Gemini 8 m	2 hr	10/29	Colors
Bolin	APO 3.5m	4 hr	10/29	Rotation
Knight	DCT 4 m	2.8 hr	10/30	Rotation
Meech	HST 1.8 m	9 orbits	11/21, 11/22, Dec, Jan	Astrometry
Sheppard	Magellan 6.5m	3 hr	11/21, 11/22	Rotation
Trilling	Spitzer	32.6 hr	11/21	Albedo, size

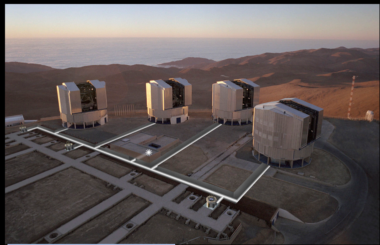
AstroPh papers posted (44)

- Oct. 31 – Meech et al – Discovery/char — 2017 Nature 552, 378 — (11/20/17)
- Oct. 31 – Mamajek – ISO kinematics — 2017 Rsch Notes AAS 1, #1 id21
- Nov. 1 – Marcos – pole, pericenter….
- Nov. 2 – Masiero – spectrum
- Nov. 2 – Knight –light curve — 2017 ApJ 851 #2 L31 — (Dec 20)
- Nov. 3 – Trilling – implications — 2017 ApJ 850 #2 L38 — (Dec 1)
- Nov. 3 – Gaidos – origin location — 2017 Rsch Notes AAS 1, #1 id13
- Nov. 7 – Laughlin – consequences — 2017 Rsch Notes AAS 1, #1 id43
- Nov. 7 – Ye – color, activity search — 2017 ApJ 851 #1 L5 — (Dec 10)
- Nov. 12 – Cyncynates – dark matter?
- Nov. 14 – Hein – ISO mission
- Nov. 14 – Zwart – ISO origin — 2018 MNRAS 479, L17 — (Sep 2018)
- Nov. 14 – Bolin – rotation — 2018 ApJ 852 #1 L2 — (Jan 2018)
- Nov. 15 – Jewitt – characterization — 2017 ApJ 850 #2 L36 — (Dec 1)
- Nov. 16 – Bannister – colors — 2017 ApJ 851 #2 L38 — (Dec 20)
- Nov. 22 – Schneider – is U1 interstellar? — 2017 Rsch Notes AAS 1, #1 id18
- Nov. 22 – Ferrin – 1I might be a comet?
- Nov. 23 – Feng – Origin local assoc. — 2018 ApJ 852 #2 L27 — (Jan 2018)
- Nov. 27 – Raymond – Implications — 2018 MNRAS 476, 3031 — (May 2018)
- Nov. 28 – Zuluaga – Origin – Methods — 2018 AJ, 155, 236 — (June 2018)
- Nov. 30 – Fraser – Rotation – tumbling — 2018 Nature Astron — (2/9/2018)
- Dec. 1 – Drahus – 1I is tumbling — 2018 Nature Astron — (May 2018)
- Dec. 12 – Domokos – explain shape — 2017 Rsch Notes AAS #1, id50

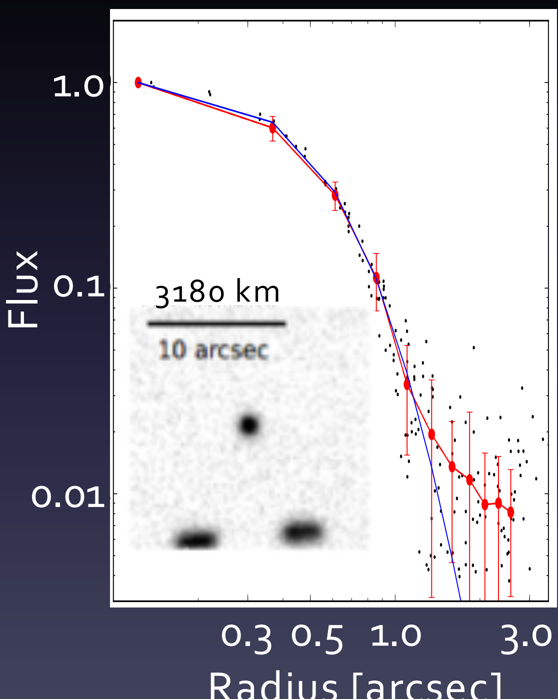
AstroPh papers posted

Dec 13 – Jackson – ejection from binary	2018 MNRAS, 478, L49	(July 2018)
Dec 17 – Wright – not a SS object	2017 Rsch Notes AAS #1, id38	
Dec 18 – Cuk – tidal fragment from binary	2018 ApJ 852 #1, L15	(Jan 1)
Dec 18 – Fitzsimmons – spectra & thermal	2017 Nature Ast.	(12/17 2017)
Dec 19 – Gaidos – characterizing 1I, binary	2018 MNRAS 477, 5692	(July 2018)
Dec 19 – Hansen – ejection from post MS *	2017 Rsch Notes AAS #1, id55	
Dec 21 – Zhang – backtracking the orbit	2018 ApJ 852 #1, L13	(Jan 1)
Jan 9 – Do – Number density of ISO	2018 ApJL 855, L10	(Mar 2018)
Jan 10 – Enriquez – Breakthrough Listen	2018 Rsch Notes AAS #2, Id9	
Jan 13 – Rafikov – Disruption by WD	2018 ApJ 861, 35	(July 2018)
Feb 5 – Hoang – spinup & disruption	2018 ApJ 860, 42	(June 2018)
Feb 6 – Katz – Prolate shape	2018 MNRAS 478, L95	(July 2018)
Feb 26 – Tingay – Search for Radio	2018 ApJ, 857, L1	(April 2018)
Mar 18 – Raymond – shape	2018 ApJ, 856, L7	(Mar 2018)
Mar 18 – de la Fuente Marcos – Radiants	2018 MNRAS 476, L1	(May 2018)
Mar 27 – McNeill – Density and Strength of 1I	2018 ApJ 857, L1	(April 2018)
Mar 27 – Park – Limits on OH outgassing	2018 AJ 155, 185	(May 2018)
Apr 10 – Belton – Excited spin state of 1I	2018 ApJL 856, #2, L21	(April 2018)
Apr 11 – Seligman – in Situ exploration	2018 Astron J, 155, id17	(May 2018)
Jun 27 – Micheli – Non grav acceleration	2018 Nature	(6/27 2018)

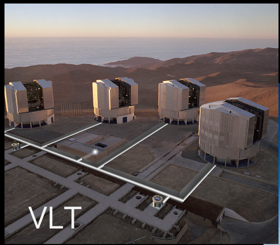
43 papers to date; 34 published as referreed papers.



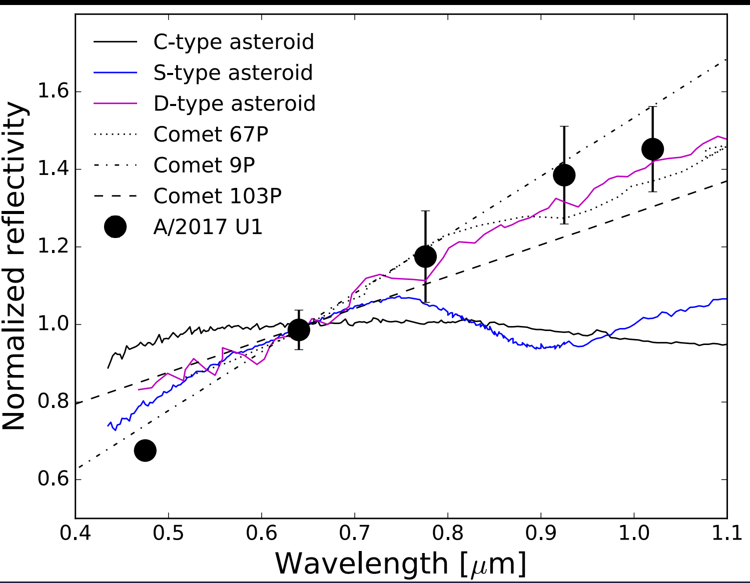
Average size & Activity

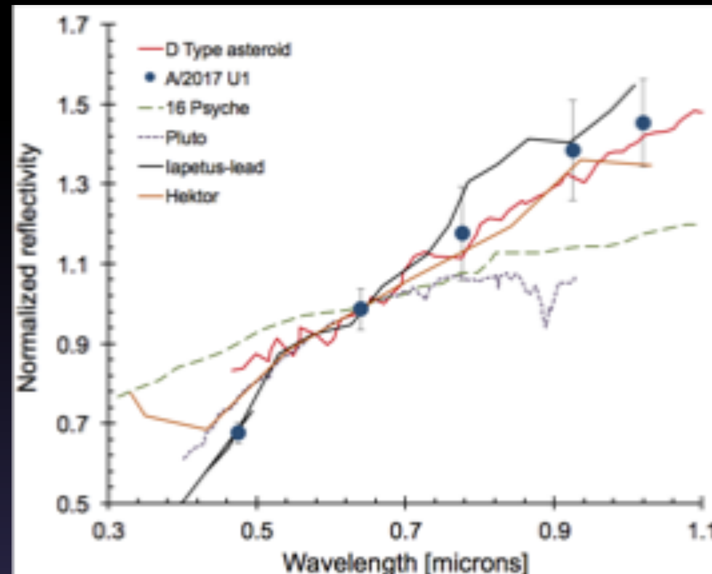


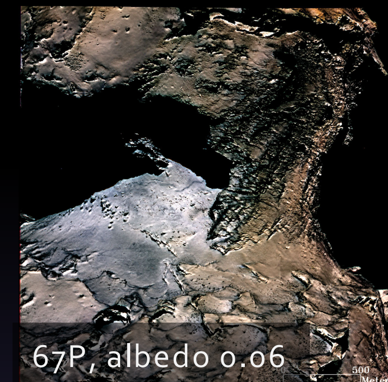
- Brightness is related to size (and how reflective)
  - Combine all the 8-m telescope data
  - Average radius 102 ± 4 m
    - H_V (median) = 22.4, p_V = 0.04 (assumed)
- Dust Limits
  - Compare shape of stars to `Oumuamua: Maximum amount of dust is about 1 kg within 750 km from nucleus
- Icy or rocky?
  - 1 billion years exposure to cosmic rays should not remove all ice if it exists near surface



Surface Composition






67P, albedo 0.06

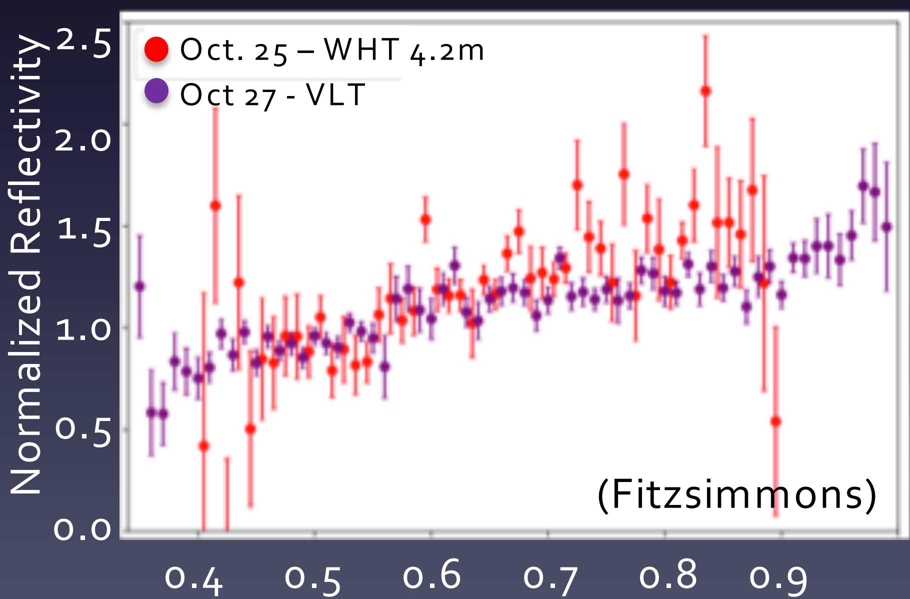

Iapetus, albedo 0.05-0.5

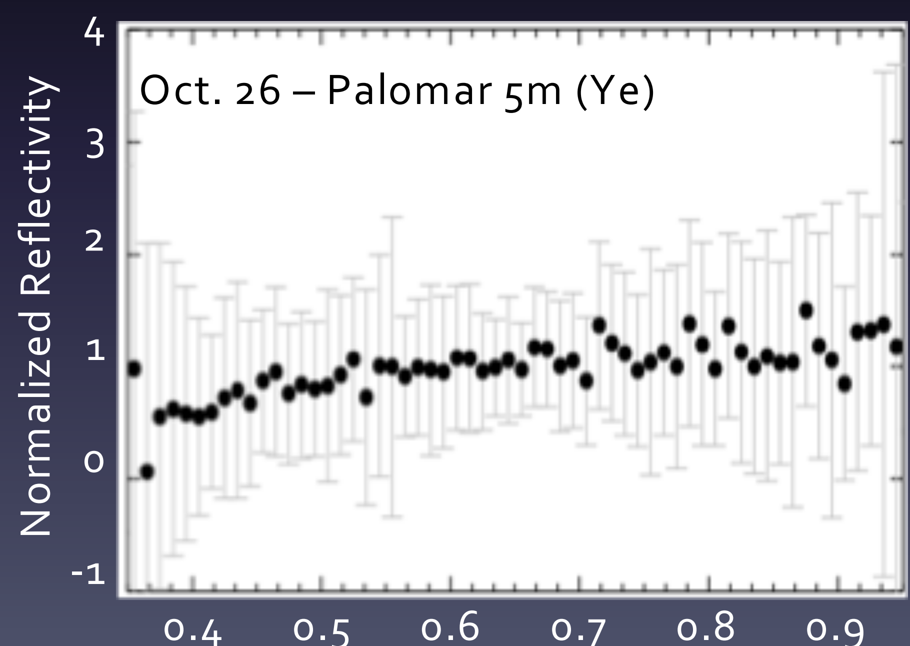

Pluto, albedo 0.49-0.66

- 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

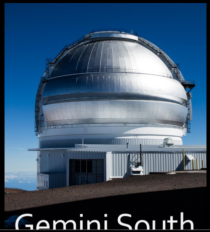
Comet or Asteroid?

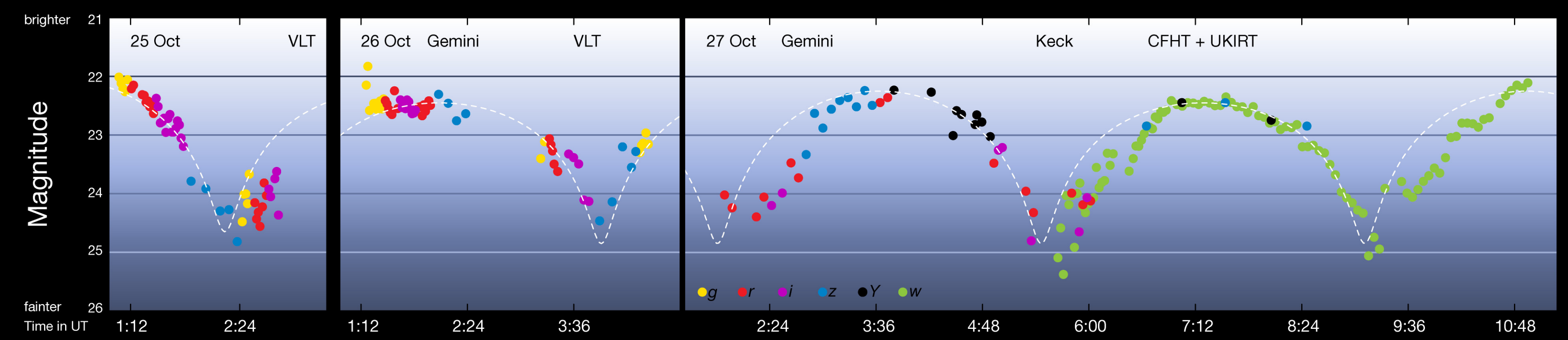
- Consistent with being a Comet:
  - Color matches comets – several groups – slopes 10-30% / 100 nm
  - The surface at closest approach to sun reaches 600°K - thermal models: could have ice at some depth (Fitzsimmons et al (2017) Nature Astron)
- Limits on possible outgassing at 1.4 (Oct 26) and 1.9 au (Nov 12)
  - Sensitive upper limits on Q(CN) < 2 x 10^{22} molec / s (suggesting Q(H_2O) < 10^{24-25}) (Ye et al 2017)
  - Radio Q(OH) – 1.7 x 10^{27} molec / sec (Park et al, 2018)

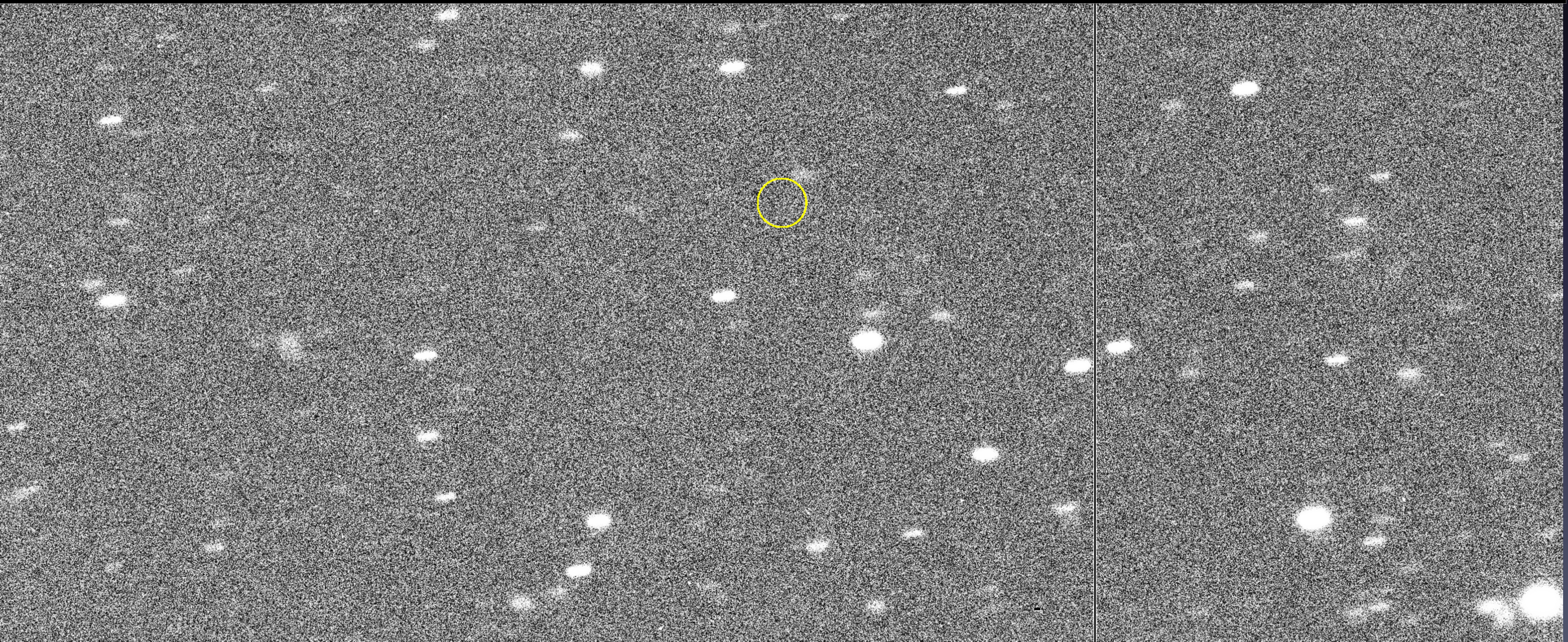




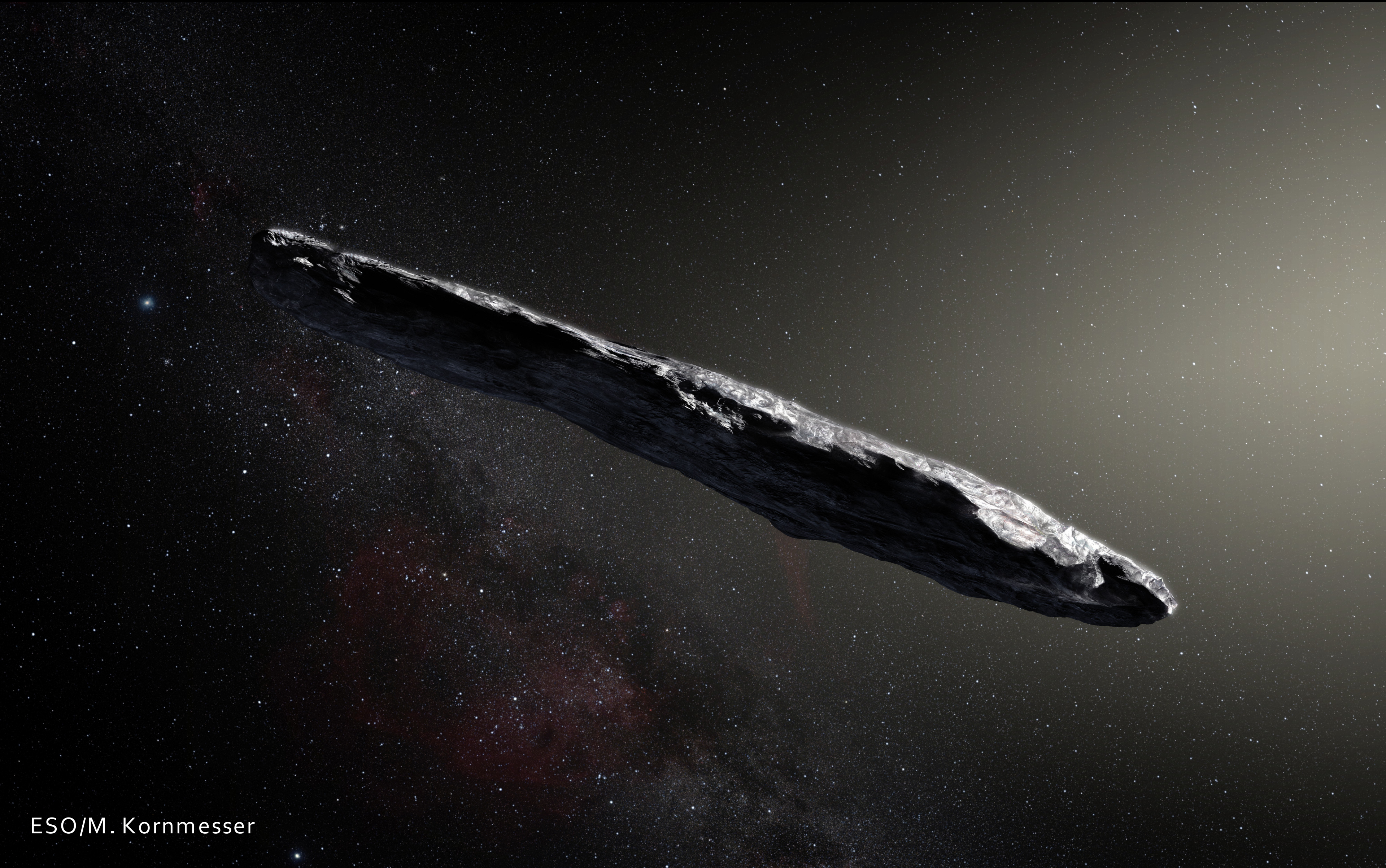
How fast does it spin?





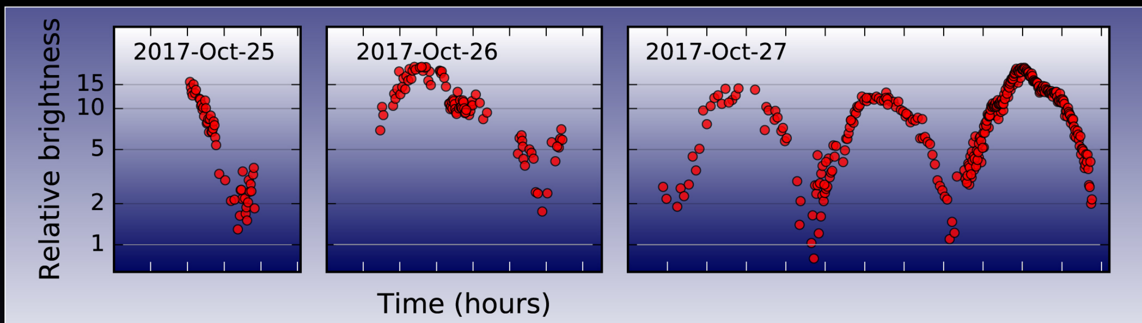


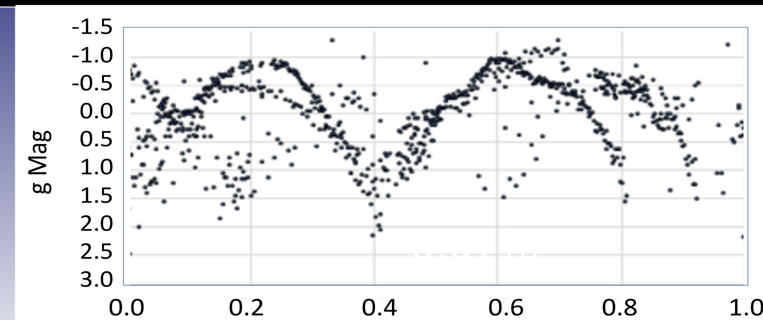
‘Oumuamua’s shape

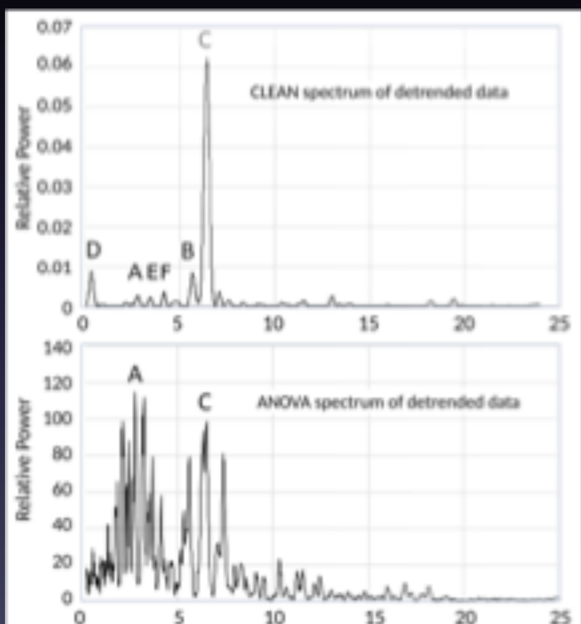


ESO/M. Kornmesser

Complex Rotation







Belton et al. (2018) ApJL, 856, Issue 2, L21

Fraser et al. *Nature Astron*, 2/9/18

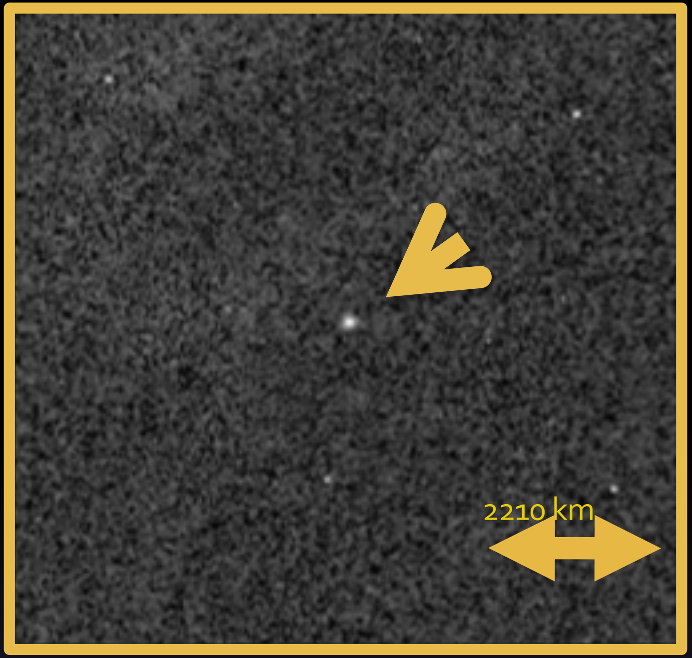
Drahus et al. *Nature Astron May 2018*

- High energy rotation
  - 8.67±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~10 hr
    - $\tau \sim 10^8 (1\ \mathrm{km}/R_N^2) \sim 10^{9-10}$ yr for 'Oumuamua
  - Causes? Collision=ejection from star system, outgassing?


Wm K Hartmann
Mar 2018

HST Program – “Which way home?”

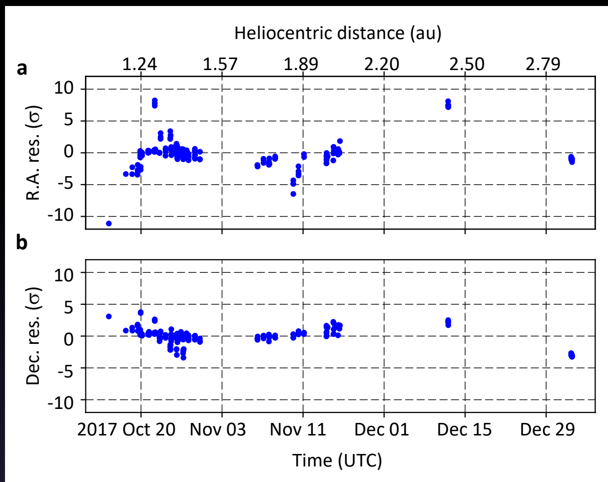
- Goal
  - Extend orbit out to 2.5 mo from discovery
- Awarded 9 orbits
  - Visits in Nov. 21-22, Dec. 12, and Jan. 2, 2018
  - Plan was to know the rotation well enough by January that only 1 orbit needed
  - Excited rotation → can’t predict max brightness in Jan – requested 4 more orbits (object seen 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

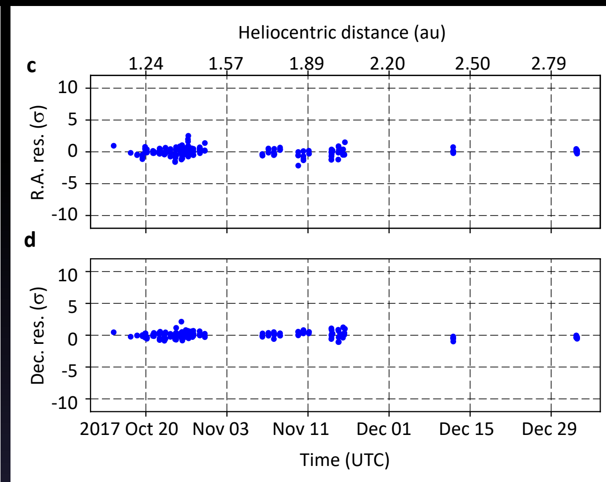


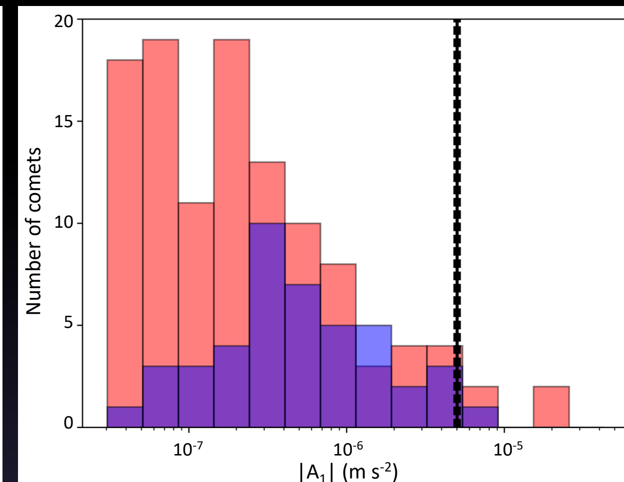
‘Oumuamua from HST

Analyzing the Astrometry

(M. Micheli & D. Farnocchia)







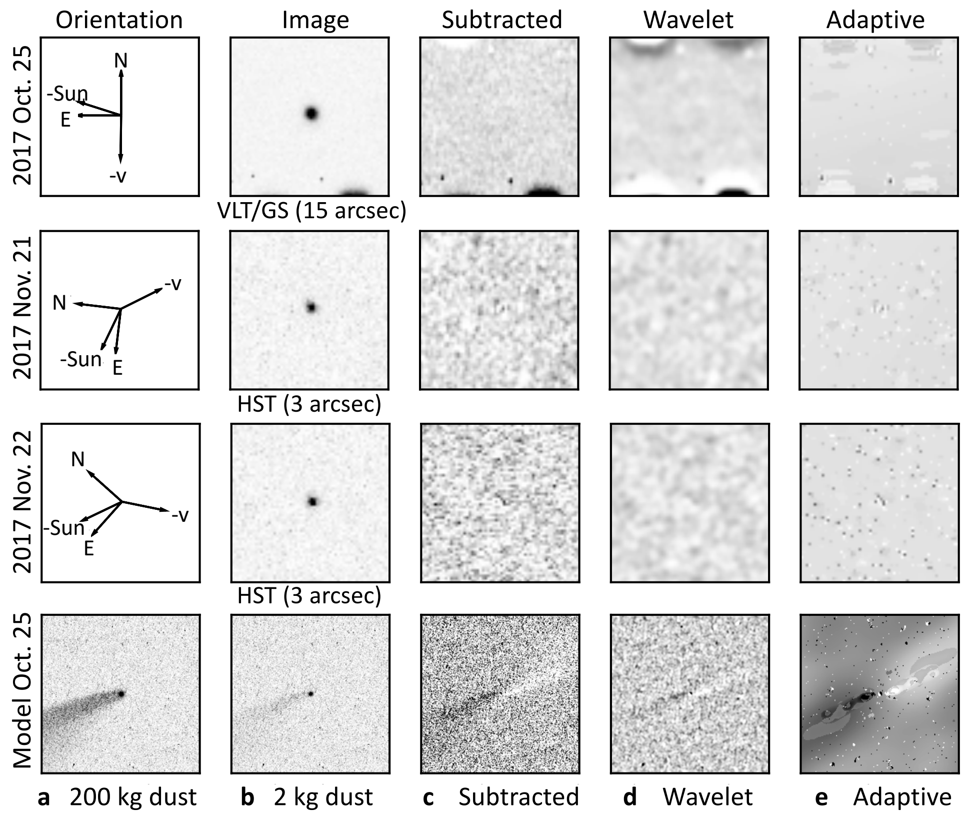
- Dataset: 177 ground, 30 HST positions
- Trajectory cannot be fit only with gravity from Sun, 8 planets, moon, Pluto and 16 largest asteroids and relativistic effects
- Residuals deviate by more than 5σ, non-systematic
- Addition of a radial acceleration A_1 g(r), g(r) $\propto r^{-2}$, $A_1 = (4.92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

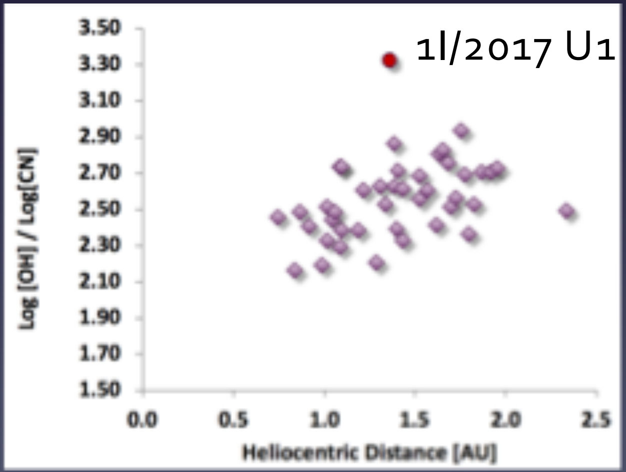
Possible Mechanisms

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

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 → Q = 10 kg/s
  - Best fit param (Table) gives Q_{dust} = 0.2 kg/s, Q_{H_2O} = 2.5 kg/s
- Implications
  - This outgassing rate should have produced abundant μm-sized dust
  - Removal during passage through ISM?
  - Non detection of CN → unusual chemistry

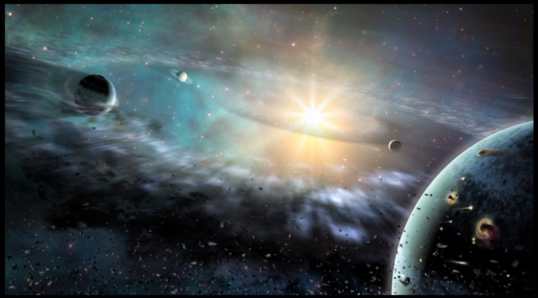




From A'Hearn 1995; Cochran 2012

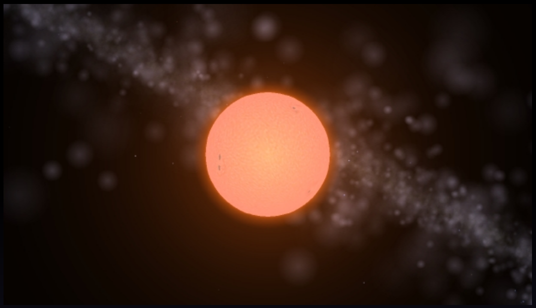
Param	Value	Param	Value
k [w/m/K]	0.7	Porosity	60%
Radius, p	102, 0.04	Depth to H2O/CO ice	18 cm, 3.6 m
Ice/dust	3	QH2O @ 1.4 au	4.9E25
CO/H2O	0.25	QCO @ 1.4 au	4.5E25

A Variety of formation Theories

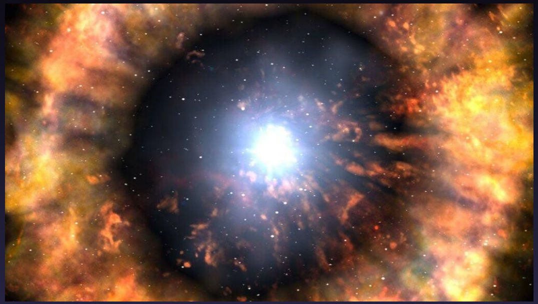


Tidal disruption, giant planets, volatile stripping with close solar passages (Raymond 2018)

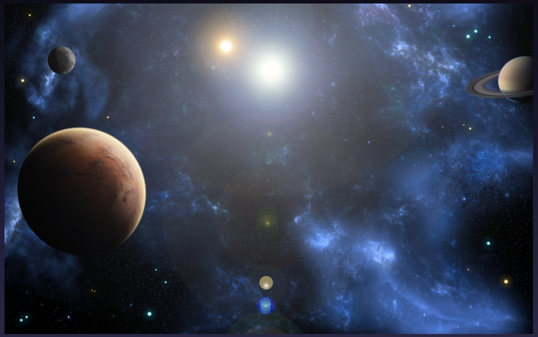
Tidal disruption, in WD system, (Rafikov 2017)



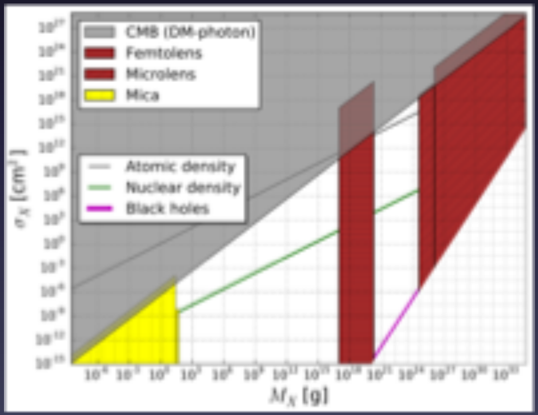
Heating during supergiant phase – loss of volatiles → fluidized to Jacobi ellipsoid shape, (Katz 2018)



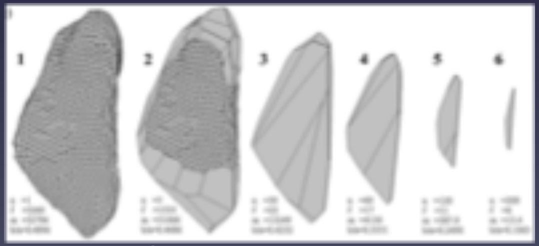
Planetesimal shredding during SN explosion (Tucker 2018)



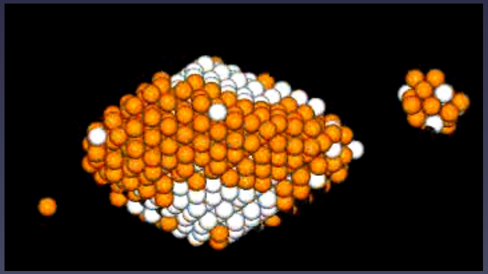
Tidal disruption, in binary system, (Cuk 2017)



Macroscopic dark matter, (Cyncynates 2017)



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



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

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

Date	V wrt Sun	V wrt Earth	Energy [Mton]	x Hiro-shima	x KT impact
Sep 9, 2017	87 km/s	68.3 km/s	17,900	1.2 million	0.0007
Oct 14, 2017	48 km/s	60 km/s	14,000	1 million	0.0006

Art by: Dana Berry

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

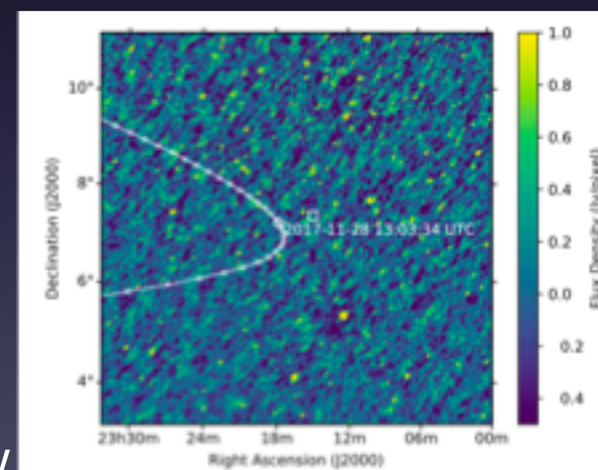
Where did it come from?

- 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)

Lead Author	Galactic $v_{\infty}(U, V, W)$ km/s	Comments
Meech	-11.2, -22.4, -7.6	Similar to stars in solar neighborhood, from a younger system?
Mamajek (31 Oct)	-11.3, -22.4 -7.6	Not from α Cen Oort cloud
Gaidos (3 Nov)	-11.3, -22.4, -7.6	Possible origin in proto planetary disk from Carina/Columba association
Zwart (13 Nov)		Passed by 5 stars with somewhat close encounters
Feng (27 Nov)	-11.4, -22.4, -7.7	Integrate orbit back 100 Myr – 109 stars with "close" encounters; young

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)