A Journal Club Presentation

the interstellar visitor ‘Oumuamua

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Could Solar Radiation Pressure Explain 'Oumuamua's Peculiar Acceleration?

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Abstract

'Oumuamua (1I/2017 U1) is the first object of interstellar origin observed in the solar system. Recently, Micheli et al. reported that 'Oumuamua showed deviations from a Keplerian orbit at a high statistical significance. The observed trajectory is best explained by an excess radial acceleration $\Delta a \propto r^{-2}$, where r is the distance of 'Oumuamua from the Sun. Such an acceleration is naturally expected for comets, driven by the evaporating material. However, recent observational and theoretical studies imply that 'Oumuamua is not an active comet. We explore the possibility that the excess acceleration results from solar radiation pressure. The required mass-to-area ratio is $(m/A) \approx 0.1$ g cm^{-2}. For a thin sheet this requires a thickness of ≈0.3–0.9 mm. We find that although extremely thin, such an object would survive interstellar travel over Galactic distances of ∼5 kpc, withstanding collisions with gas and dust grains as well as stresses from rotation and tidal forces. We discuss the possible origins of such an object. Our general results apply to any light probes designed for interstellar travel.

Key words: extraterrestrial intelligence – ISM: individual objects (1I/2017 U1) – minor planets, asteroids: general – minor planets, asteroids: individual (1I/2017 U1)

Time-Domain Astronomy

Panoramic Survey Telescope And Rapid Response System (Pan-STARRS) 泛星

PS1 + PS2

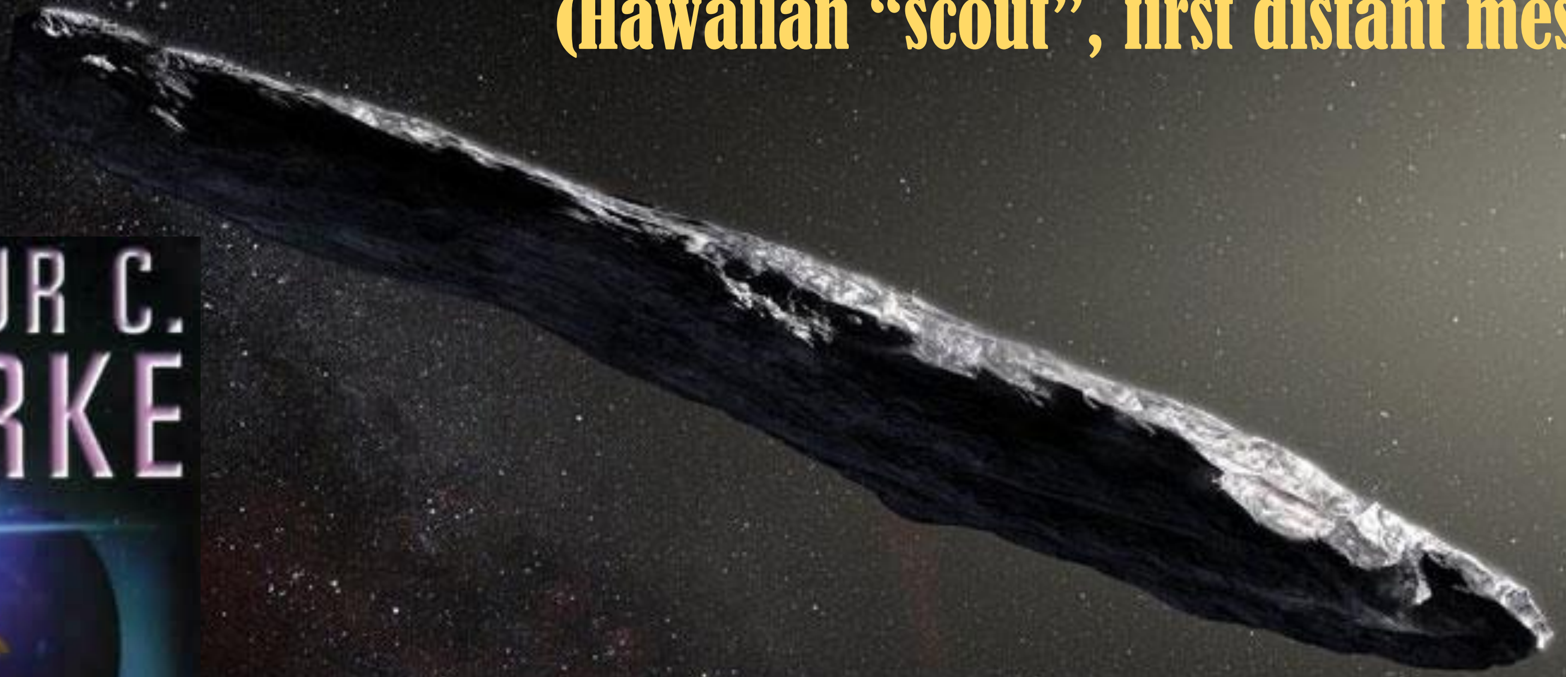
Maui, Hawai'i, USA

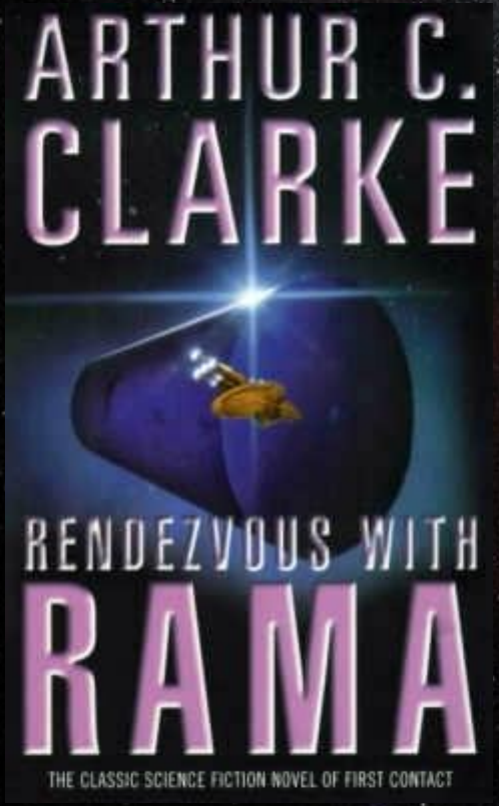
A 1.8 m telescope with a 1.4 Gpix camera

C/2017 U1 → A/2017 U1

1I/2017 U1 (’Oumuamua)

(Hawaiian “scout”, first distant messenger)





2017/10/19 found by PS1, at first classified as a comet, then, with a hyperbolic trajectory, as an interstellar object, the first of its kind

Illustration : ESO/ M. Kornmesser

‘Oumuamua

- Found by PS1 on 2017 October 19; $H = 22.1$ mag
- The first IS object in the solar system (1I/2017 U1)
- Highly hyperbolic, eccentricity $e = 1.1956 \pm 0.0006$
- Pre-entry speed $v_\infty \approx 26$ km s^{-1}
- Size $\sim 102 \pm 4$ m

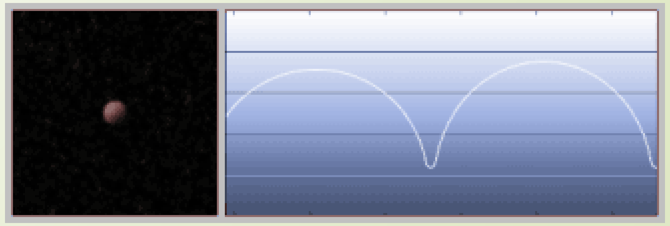
(Meech et al. 2017, Natur, 552, 378)

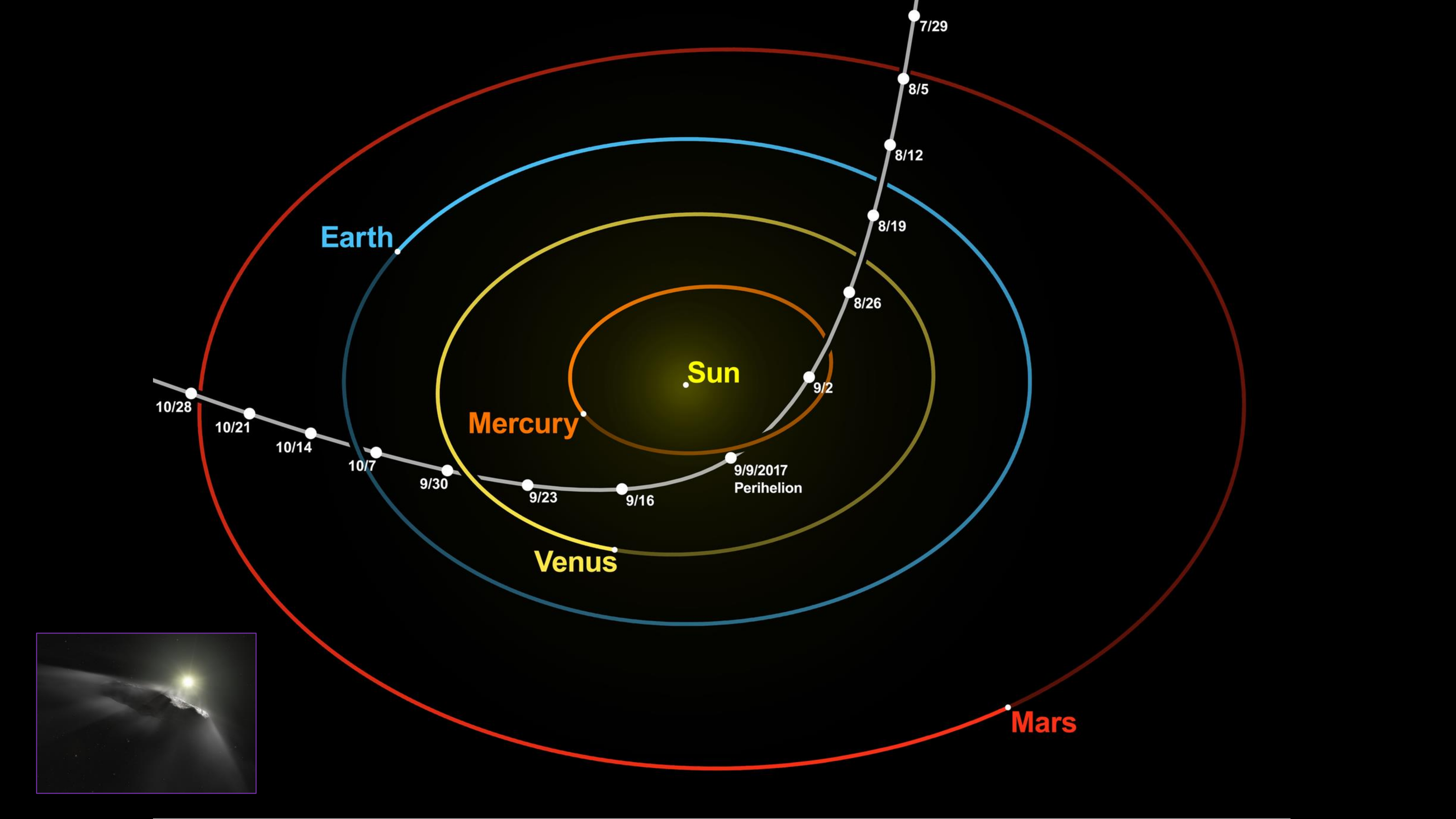
✓ May be numerous, 0.2 au^{-3} or $n \approx 2 \times 10^{15}$ pc^{-3}, 2-8 orders higher than expected previously

(Do et al. 2018, ApJ)

- Lightcurves → tumbling spin and a 5:1 aspect ratio

(Drahus et al. 2018; Fraser et al. 2018)





7/29
8/5
8/12
8/19
8/26
9/2
9/9/2017
Perihelion
9/16
9/23
9/30
10/7
10/14
10/21
10/28
Earth
Sun
Mercury
Venus
Mars

LETTER

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Non-gravitational acceleration in the trajectory of 1I/2017 U1 (‘Oumuamua)

Marco Micheli[1,2*], Davide Farnocchia[3], Karen J. Meech[4], Marc W. Buie[5], Olivier R. Hainaut[6], Dina Prialnik[7], Norbert Schörghofer[8], Harold A. Weaver[9], Paul W. Chodas[3], Jan T. Kleyna[4], Robert Weryk[4], Richard J. Wainscoat[4], Harald Ebeling[4], Jacqueline V. Keane[4], Kenneth C. Chambers[4], Detlef Koschny[1,10,11] & Anastassios E. Petropoulos[3]

‘Oumuamua (1I/2017 U1) is the first known object of interstellar origin to have entered the Solar System on an unbound and hyperbolic trajectory with respect to the Sun1. Various physical observations collected during its visit to the Solar System showed that it has an unusually elongated shape and a tumbling rotation state1–4 and that the physical properties of its surface resemble those of cometary nuclei5,6, even though it showed no evidence of cometary activity1,5,7. The motion of all celestial bodies is governed mostly by gravity, but the trajectories of comets can also be affected by non-gravitational forces due to cometary outgassing8. Because non-gravitational accelerations are at least three to four orders of magnitude weaker than gravitational acceleration, the detection of any deviation from a purely gravity-driven trajectory requires high-quality astrometry over a long arc. As a result, non-gravitational effects have been measured on only a limited subset of the small-body population9. Here we report the detection, at 30 σ significance, of non-gravitational acceleration in the motion of ‘Oumuamua. We analyse imaging data from extensive observations by ground-based and orbiting facilities. This analysis rules out systematic biases and shows that all astrometric data can be described once a non-gravitational component representing a heliocentric radial acceleration proportional to r−2 or r−1 (where r is the heliocentric distance) is included in the model. After ruling out solar-radiation pressure, drag- and friction-like forces, interaction with solar wind for a highly magnetized object, and geometric effects originating from ‘Oumuamua potentially being composed of several spatially separated bodies or having a pronounced offset between its photocentre and centre of mass, we find comet-like outgassing to be a physically viable explanation, provided that ‘Oumuamua has thermal properties similar to comets.

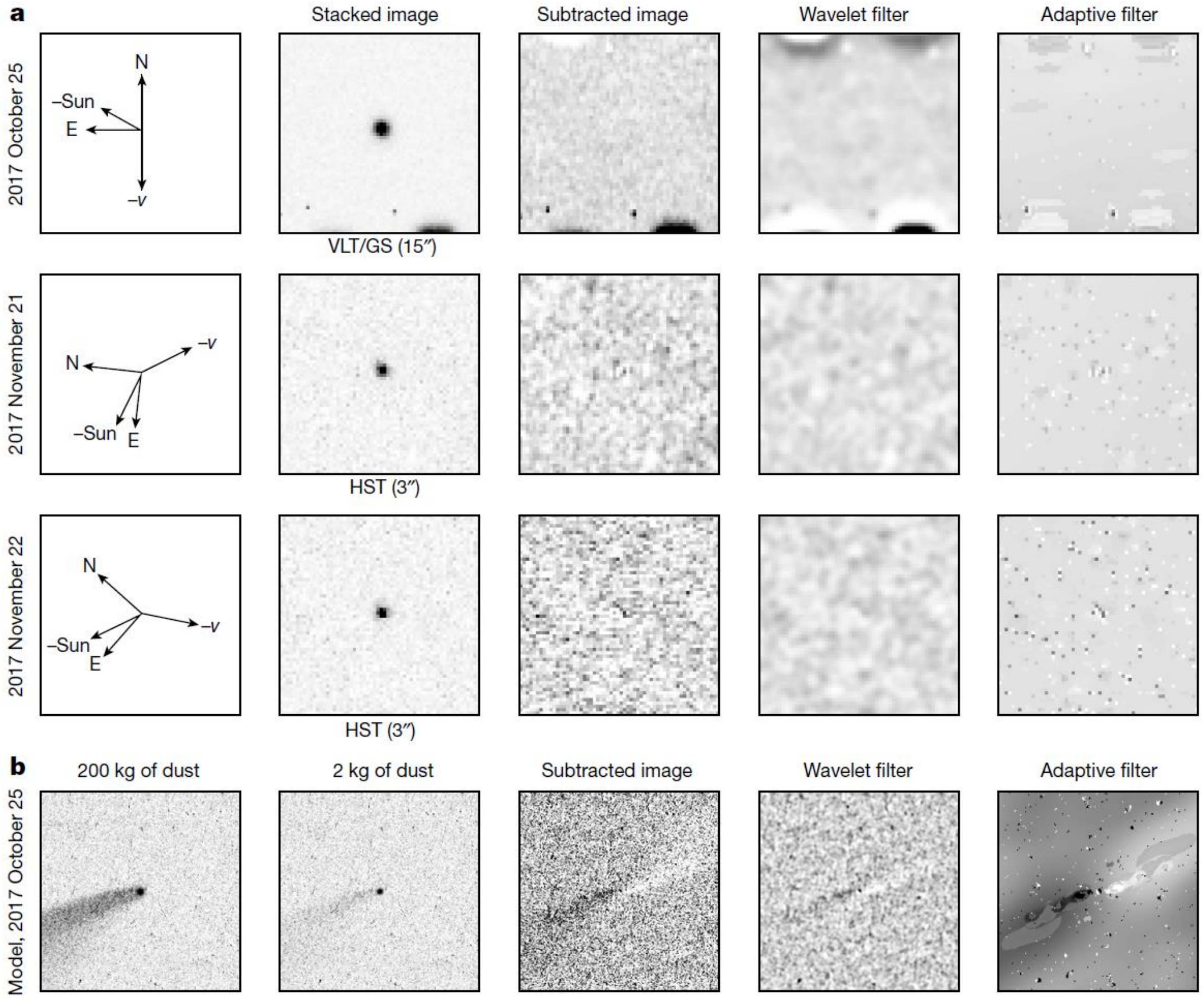

Fig. 1 | Deep stacked images for dust detection. a, For each date we show the image orientation (−Sun, anti-solar direction; −*v*, anti-motion direction), the stacked image (telescope and size of the image are listed below the image), a self-subtracted image (see Methods), and the image after application of a wavelet or adaptive filter to enhance low-surface-brightness features. No dust is visible. **b**, Images from a model with an artificial cometary feature that matches the October geometry demonstrate the sensitivity of the image enhancement: a very strong dust feature is evident when 200 kg of dust is used in the point spread function (PSF) region (left-most panel); the other panels show the same feature scaled to 2 kg of dust in the PSF region (twice the observed ʻOumuamua limit) and the image processed in the same manner as the real data.

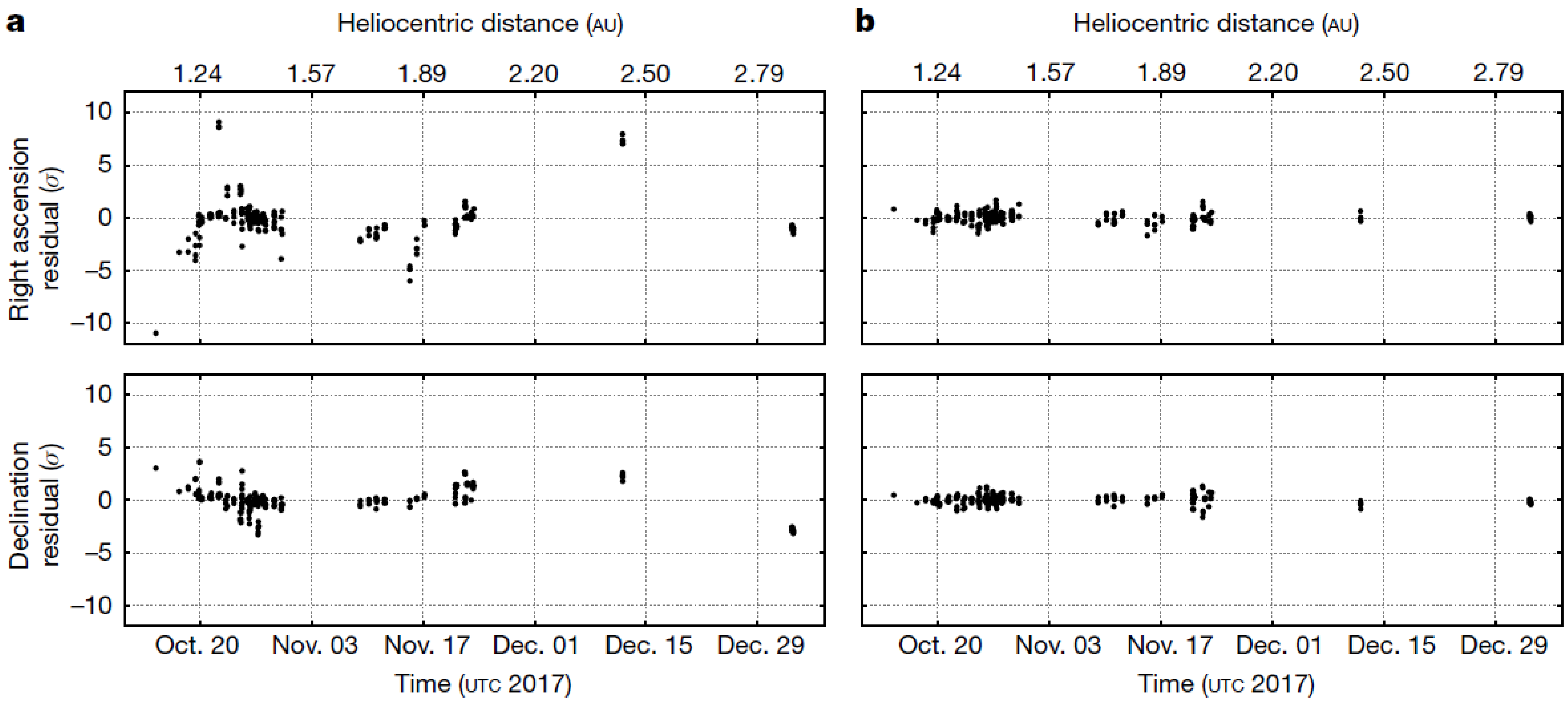

Fig. 2 | Astrometric residuals of ʻOumuamua observations. a, **b**, Normalized residuals for right ascension and declination compared to a gravity-only solution (**a**) and a solution that includes a non-gravitational radial acceleration of A_1r^{-2} (**b**). Because each residual is normalized to its formal uncertainty, each data point has a 1σ error bar (not shown) equal to 1 on this scale.

We analysed the full observational dataset, which includes 177 ground-based and 30 HST-based astrometric positions (for a total of 414 scalar measurements), applying the procedures and assumptions discussed in Methods. Our analysis shows that the observed orbital arc cannot be fitted in its entirety by a trajectory governed solely by gravitational forces due to the Sun, the eight planets, the Moon, Pluto, the 16 largest bodies in the asteroid main belt and relativistic effects[14].

Alternative explanations for the observed acceleration include (1) solar-radiation pressure, (2) the Yarkovsky effect, (3) friction-like effects aligned with the velocity vector, (4) an impulsive change in velocity, (5) a binary or fragmented object, (6) a photocentre offset or (7) a magnetized object. However, as outlined in the following, these explanation are all either physically unrealistic or insufficient to explain the observed behaviour. ➔ comet-like outgasing

Table 1 | Fits for different non-gravitational models

Model	Number of parameters	χ^2	χ_ν^2
Gravity-only	6	1.031×10^3	2.53
(1) Impulsive change in velocity	10	117	0.29
(2) Pure radial acceleration, $A_1 g(r) \propto r^{-k}, k \in \{0, 1, 2, 3\}$	7	99, 80, 81, 98	0.24, 0.20, 0.20, 0.24
(3) RTN decomposition, $[A_1, A_2, A_3]g(r) \propto r^{-k}, k \in \{0, 1, 2, 3\}$	9	90, 80, 78, 87	0.22, 0.20, 0.19, 0.21
(4) ACN decomposition, $[A_A, A_C, A_N]g(r) \propto r^{-k}, k \in \{0, 1, 2, 3\}$	9	104, 85, 77, 83	0.26, 0.21, 0.19, 0.21
(5) Pure along-track acceleration, $A_A g(r) \propto r^{-k}, k \in \{0, 1, 2, 3\}$	7	1.031×10^3, 1.025×10^3, 1.002×10^3, 963	2.53, 2.52, 2.46, 2.37
(6) Constant, inertially fixed acceleration vector	9	116	0.29
(7a) Pure radial acceleration, $A_1 g_{CO}(r)$	7	84	0.21
(7b) Pure radial acceleration, $A_1 g_{H2O}(r)$	7	111	0.27
(7c) RTN decomposition, $[A_1, A_2, A_3]$ $g_{CO}(r)$	9	79	0.19
(7d) RTN decomposition, $[A_1, A_2, A_3]g_{H2O}(r)$	9	89	0.22
(7e) RTN decomposition, $[A_1, A_2, A_3]g_{H2O}(r)$, ΔT	10	86	0.21

For reference, we list the values for a gravity-only model of the trajectory in addition to those for the different non-gravitational models. In addition to a model involving an impulsive change in velocity, we consider continuous non-gravitational accelerations $g(r)$ with a dependence on the heliocentric distance r that is either a power law or, for H_2O or CO volatiles (g_{H2O} or g_{CO}), based on cometary outgassing models[8,30]. The acceleration vector can be inertially fixed or decomposed in either the radial, transverse, normal (RTN; components indicated as $A_1g(r)$, $A_2g(r)$ and $A_3g(r)$, respectively) or the along-track, cross-track, normal (ACN; components indicated as $A_Ag(r)$, $A_Cg(r)$ and $A_Ng(r)$, respectively) frame. We also test the possibility of a time delay ΔT with respect to perihelion for the peak of the outgassing activity. The numbering of the models refers to the discussion in Methods.

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Key words: extraterrestrial intelligence – ISM: individual objects (1I/2017 U1) – minor planets, asteroids: general – minor planets, asteroids: individual (1I/2017 U1)

Recently, Micheli et al. (2018) reported the detection of non-gravitational acceleration in the motion of ‘Oumuamua, at a statistical significance of 30σ. Their best fit to the data is obtained for a model with a non-constant excess acceleration that scales with distance from the Sun, r, as $\Delta a \propto r^{-2}$, but other power-law index values are also possible. They concluded that the observed acceleration is most likely the result of cometary activity. Yet, despite its close solar approach of $r = 0.25$ au, ‘Oumuamua shows no signs of any cometary activity, no cometary tail, and no gas emission/absorption lines were observed (Fitzsimmons et al. 2017; Jewitt et al. 2017; Knight et al. 2017; Meech et al. 2017; Ye et al. 2017). From a theoretical point of view, Rafikov (2018) has shown that if outgassing was responsible for the acceleration (as originally proposed by Micheli et al. 2018), then the associated outgassing torques would have driven a rapid evolution in ‘Oumuamua’s spin, incompatible with observations.

a~100 m (1000 m x 35-167 m x 35-167 m)

Acceleration by solar radiation pressure

$$P = C_R \frac{L_\odot}{4\pi r^2 c}$$

[force/area] [cm/s] = [energy]/[area] [s]

$C_R \approx 1; \leftrightarrow$ geometry and composition

$$\Delta a = (4.92 \pm 0.16) \times 10^{-4} \left(\frac{r}{\text{au}}\right)^{-2} = \frac{PA}{m} = C_R \left(\frac{L_\odot}{4\pi r^2 c}\right)\left(\frac{A}{m}\right)$$

$$\Rightarrow \left(\frac{m}{A}\right) = (9.3 \pm 0.3) \times 10^{-2} C_R \text{ [g cm}^{-2}\text{] [mass-to-area]}$$

$$\Rightarrow \; w = \frac{m}{A\rho} \approx 0.3 - 0.9 \text{ [mm] [thickness]}; \rho \approx 1 - 3 \text{ g cm}^{-3}$$

An object with a cross section of *A*

Accumulating ISM gas → slow-down (?)

“ ’Oumuamua can travel Galactic distances before encountering appreciable slow-down.”

Collisions with dust grains → melting and evaporation (?)

“ ’Oumuamua can travel through the entire Galaxy before a significant mass is evaporated.”

Lightcurve shows 6 to 8 hours modulation → torn-apart (?)

“ ’Oumuamua can easily withstand its centrifugal force.”

Close encounters with stars → tidally stripped (?)

“ ’Unless … an extremely close … unlikely …”

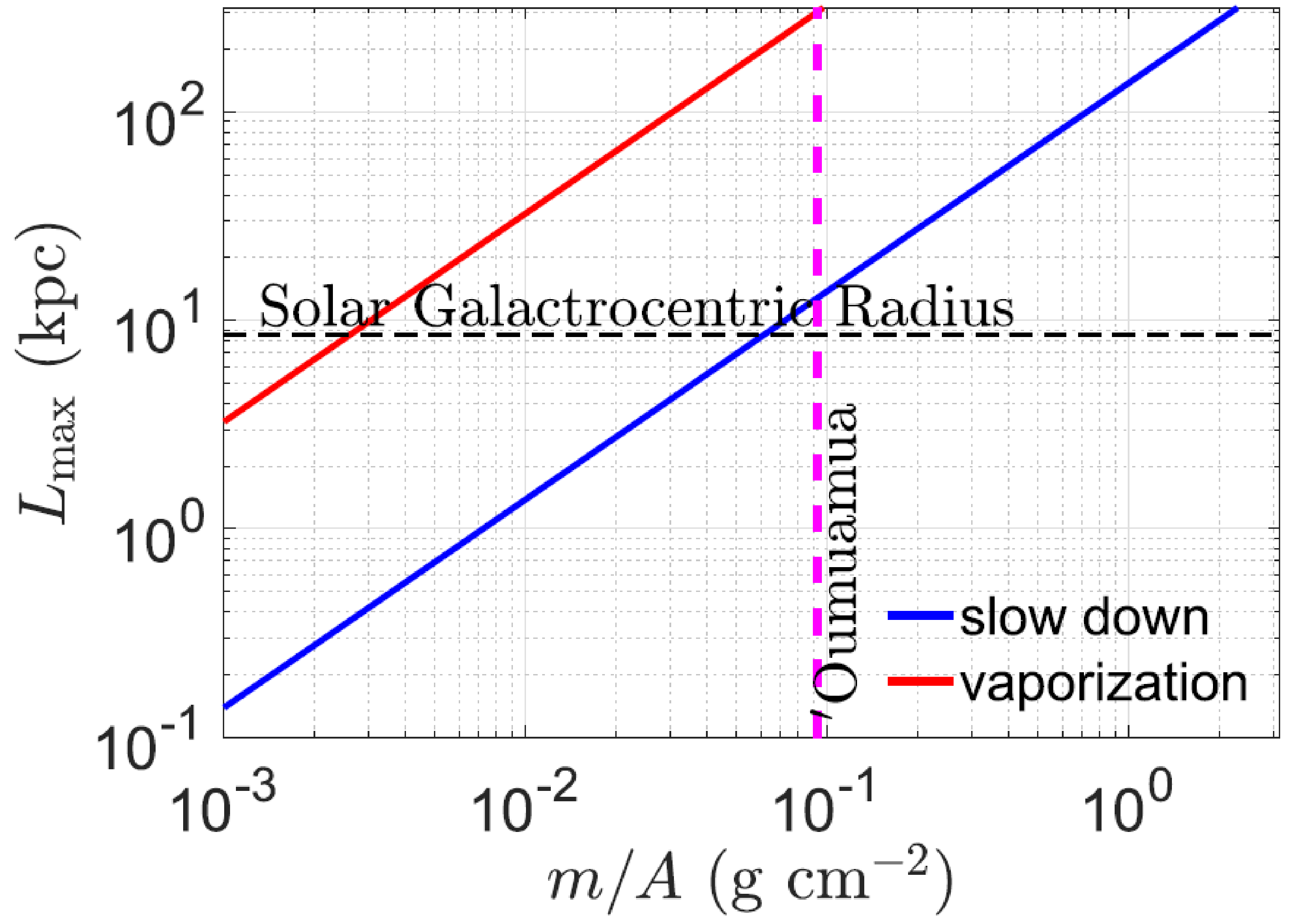


Figure 1. Maximum allowed travel distance through the ISM, as a function of (m/A). The blue and red lines are limitations obtained by slow-down due to gas accumulation, and vaporization by dust collisions, respectively. The plotted results are for a mean ISM proton density of $\langle n \rangle \sim 1$ cm^{-3}. All lines scale as $1/\langle n \rangle$. The dashed magenta line is our constraint on 'Oumuamua based on its excess acceleration. The Solar Galactrocentric distance is also indicated.

With this spin, the associated tensile stress is

$$P_{\rm rot} \approx \mathcal{O}(0.25)\ \text{dyne cm}^{-2}$$

TABLE 1
TENSILE STRENGTHS

material	tensile strength (dyne cm^{-2})
67P/Churyumov-Gerasimenko[1]	10-50
Meteorites[2]	$(1-5)\times 10^{7}$
Iron	3×10^{7}
Diamond	2×10^{10}
Silicon (monocrystalline)	7×10^{10}

[1] Attree et al. (2018)

[2] Petrovic (2001)

estimate for ‘Oumuamua. If radiation pressure is the accelerating force, then ‘Oumuamua represents a new class of thin interstellar material, either produced naturally,through a yet unknown process in the ISM or in proto-planetary disks, or of an artificial origin.

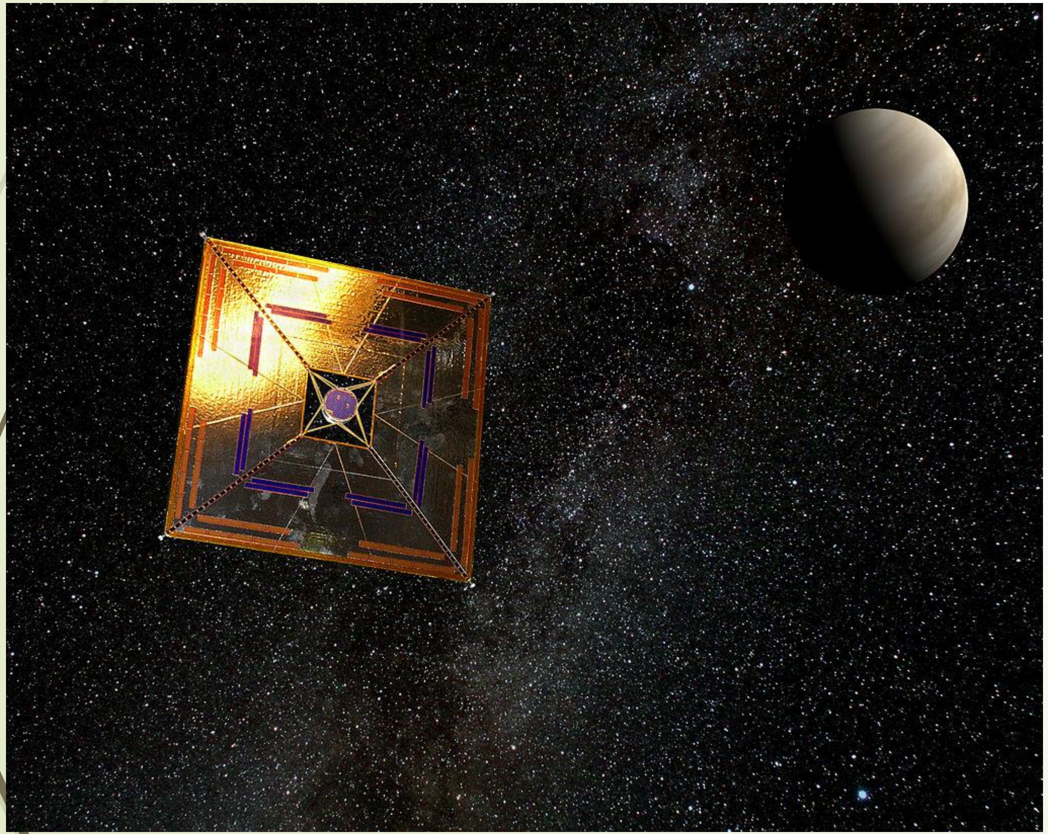
Considering an artificial origin, one possibility is that ‘Oumuamua is a lightsail, floating in interstellar space as a debris from an advanced technological equipment (Loeb 2018). Lightsails with similar dimensions have been designed and constructed by our own civilization, including the IKAROS project and the Starshot Initiative[2]. The lightsail technology might be abundantly used for transportation of cargo between planets (Guillochon & Loeb 2015) or between stars (Lingam & Loeb 2017). In the former case, dynamical ejec-

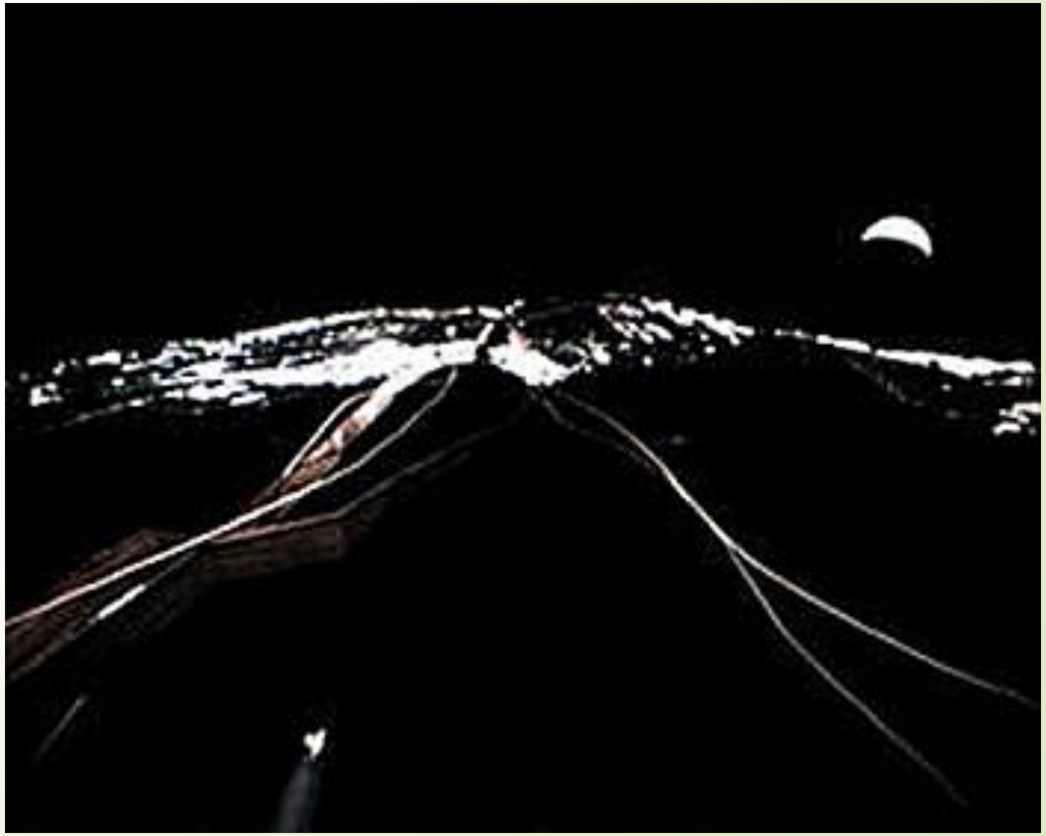
A fragment from a tidally disrupted planet?

IKAROS **(Interplanetary Kite-craft Accelerated by Radiation Of the Sun)**

JAXA's space "kite"

launched on 20 May 2010, aboard an H-IIA rocket, together with the Akatsuki (Venus Climate Orbiter) probe and four other small spacecraft





Alternatively, a more exotic scenario is that ‘Oumuamua may be a fully operational probe sent *intentionally* to Earth vicinity by an alien civilization. Based on the PAN-STARRS1 survey characteristics, and assuming natural origins following *random* trajectories, Do et al. (2018) derived that the interstellar number density of ‘Oumuamua-like objects should be extremely high, $\sim 2 \times 10^{15}$ pc^{-3}, equivalent to $\sim 10^{15}$ ejected planetisimals per star, and a factor of 100 to 10^8 larger than predicted by theoretical models (Moro-Martin et al. 2009). This discrepancy is readily solved if ‘Oumuamua does not follow a random trajectory but is rather a targeted probe. Interestingly, ‘Oumuamua’s entry velocity is found to be extremely close to the velocity of the Local Standard of Rest, in a kinematic region that is occupied by less than 1 to 500 stars (Mamajek 2017).

A survey for lightsails as technosignatures in the solar system is warranted, irrespective of whether ‘Oumuamua is one of them.

Large Synoptic Survey Telescope (LSST)

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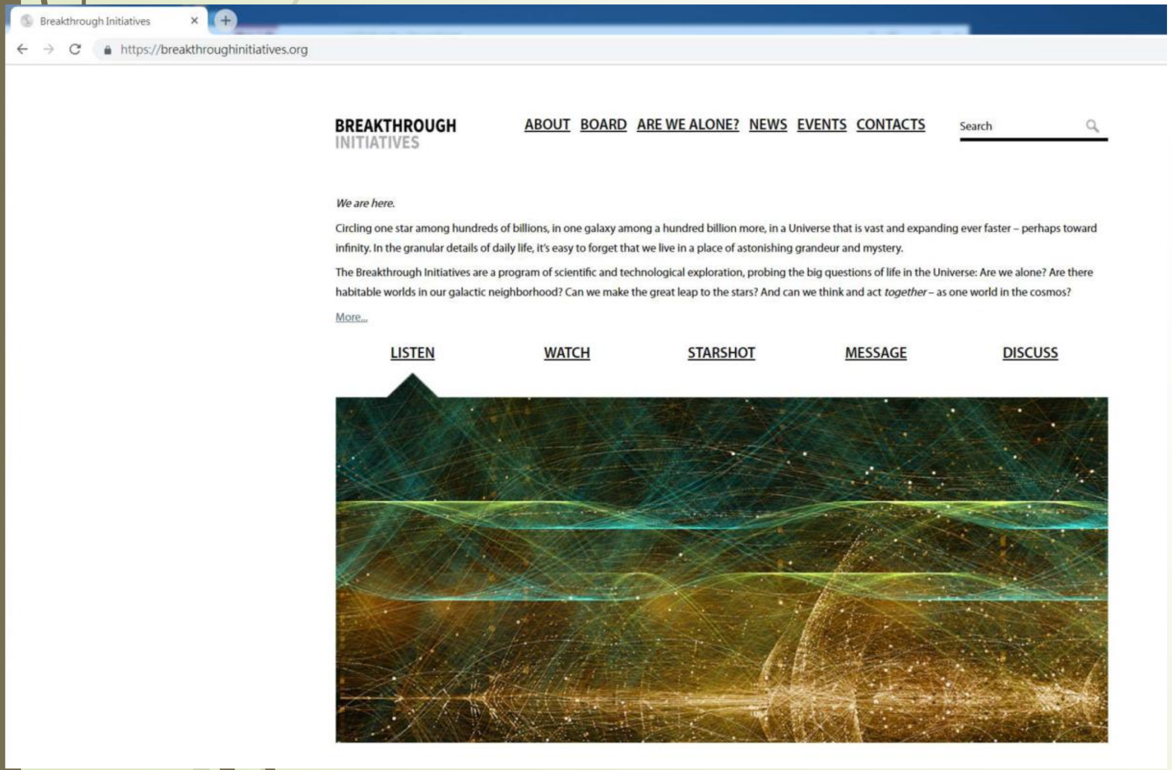

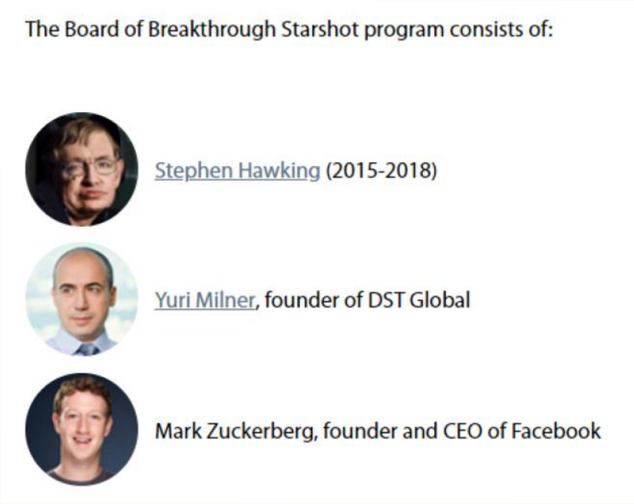

Starshot Initiative