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Spectroscopy and thermal modelling of the first interstellar object 1I/2017 U1 ‘Oumuamua

Alan Fitzsimmons*, Colin Snodgrass, Ben Rozitis, Bin Yang, Méabh Hyland, Tom Secull, Michele T. Bannister, Wesley C. Fraser, Robert Jedicke and Pedro Lacerda

During the formation and evolution of the Solar System, significant numbers of cometary and asteroidal bodies were ejected into interstellar space. It is reasonable to expect that the same happened for planetary systems other than our own. Detection of such interstellar objects would allow us to probe the planetesimal formation processes around other stars, possibly together with the effects of long-term exposure to the interstellar medium. 1I/2017 U1 ‘Oumuamua is the first known interstellar object, discovered by the Pan-STARRS1 telescope in October 2017 (ref. 1). The discovery epoch photometry implies a highly elongated body with radii of ~200 × 20 m when a comet-like geometric albedo of 0.04 is assumed. The observable interstellar object population is expected to be dominated by comet-like bodies in agreement with our spectra, yet the reported inactivity of ‘Oumuamua implies a lack of surface ice. Here, we report spectroscopic characterization of ‘Oumuamua, finding it to be variable with time but similar to organically rich surfaces found in the outer Solar System. We show that this is consistent with predictions of an insulating mantle produced by long-term cosmic ray exposure. An internal icy composition cannot therefore be ruled out by the lack of activity, even though ‘Oumuamua passed within 0.25 au of the Sun.

Following the announcement of the discovery, we performed spectroscopic observations at two facilities. The 4.2 m William Herschel Telescope (WHT) on La Palma was used with the ACAM auxiliary port imager and spectrograph on 25 October 21:45 UT–22:03 UT. An initial analysis of this spectrum revealed an optically red body. Spectra were also obtained using the X-shooter spectrograph on the European Southern Observatory 8.2 m Very Large Telescope (VLT) on 27 October 00:21 UT–00:53 UT, covering 0.3–2.5 μm. Observation circumstances are given in Table 1 and the resulting binned reflectance spectra at optical wavelengths are shown in Fig. 1.

Active comets possess strong molecular emission bands via electronic transitions within the vibrational ground state due to fluorescence of CN at 0.38 μm and C2 at 0.52 μm. Although our spectra are noisy, no such emission is seen, in concordance with imaging reports of an apparently inert body1–4. Asteroid spectra can show significant solid-state absorption features in this region depending on their mineralogy, notably a wide shallowness absorption centred at ~0.7 μm due to phyllosilicates (aqueously altered silicates)5. Mafic minerals seen in asteroids (typically pyroxines and olivines) exhibit an absorption band starting at ~0.75 μm and centred at ~0.95 μm. Again, no such diagnostic features are observed.

Over the range 0.4 μm ≤ λ ≤ 0.9 μm, the reflectance gradients are 17.0 ± 2.3%/100 nm (one standard deviation) and 9.3 ± 0.6%/100 nm for the ACAM and X-shooter data, respectively. Additional measurements of the spectral slope have been reported from the Palomar Observatory as 30 ± 15%/100 nm over 0.52 μm ≤ λ ≤ 0.95 μm on October 25.3 UT4, and 10 ± 6%/100 nm over 0.4 μm ≤ λ ≤ 0.9 μm on October 26.2 UT4. The published photometric colours range from somewhat neutral to moderately red5,6. While most of these measurements are similar within their uncertainties, the reported (g − r) = 0.47 ± 0.04 is relatively neutral, while we have a significant red slope in this region. Within our own data, our spectra differ in slope by >3σ. This is due to the ACAM spectrum being redder than the X-shooter spectrum at 0.7 μm ≤ λ ≤ 0.9 μm, with the mean reflectance increasing to 42% and 21% relative to 0.55 μm, respectively.

The measured rotation period is probably in the 7–8 h range based on photometry from different observers4,5,7. The most complete reported lightcurve is consistent with a rotation period of 7.34 h and an extremely elongated shape with an axial ratio of ~10:1 and a 20% change in minimum brightness, possibly due to hemispherically averaged albedo differences. Using this rotation period, our spectra are separated by 0.66 in rotational phase and near opposing minima in the lightcurve. This implies that our spectra viewed different extrema of the body and supports the existence of compositional differences across the surface. We note the October 25 Palomar spectrum would have been obtained during lightcurve maximum, while the October 26 Palomar spectrum would have been near the same rotational phase as our WHT spectrum. Comparable spectral slope variations with rotation have been detected in ground-based data on a few S-type asteroids and trans-Neptunian objects (TNOs), although these objects are significantly larger than 1I/2017 U1.

The X-shooter spectrum contained a weak but measurable signal at 1.0 μm ≤ λ ≤ 1.8 μm. Beyond 1.8 μm, the sky background is much brighter than the object. We therefore excluded this spectral region at longer wavelengths from further analysis. In Fig. 2, we show the ACAM and X-shooter spectra, binned to a spectral resolution of 0.02 μm at λ > 1 μm. Although the signal-to-noise is low, it is apparent that the reflectance is relatively neutral in this spectral region; a weighted least-squares fit gives a slope of −1.8 ± 5.3%/100 nm at these near-infrared (NIR) wavelengths. There is a suggestion of decreasing reflectance beyond 1.4 μm, but the uncertainties are large due to the very weak flux from the object. There is no apparent strong absorption band due to water ice at 1.5 μm, as observed on some large TNOs. The only other reported NIR data are J-band

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Methods. The spectral reflectance ranges of D-, L- and C-type asteroids are denoted by solid colours. Uncertainties shown were calculated as explained in the wavelength. 1

σ

μ

0.55 μm. Uncertainties come from errors on the median reflectance within μλ bins at μm and 0.02 μm. Both spectra have been averaged over 0.01 μm wavelength asteroids. ACAM (red data points) and VL T

WHT

X-shooter (grey data

WHT 2017 /10/25 21:45 UT–22:03 UT

VLT 2017 /10/27 00:21 22.5 1.43 0.50 22.9 1.33-1.24

ut-00:53 UT

Table 1 | Observation circumstances

<table>
<thead>
<tr>
<th>Telescope</th>
<th>ut date</th>
<th>r’</th>
<th>rₜ</th>
<th>Δ</th>
<th>α</th>
<th>Airmass</th>
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</thead>
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<tr>
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<td>2017/10/25</td>
<td>21.7</td>
<td>1.38</td>
<td>0.42</td>
<td>20.5</td>
<td>1.16-1.13</td>
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<td>VLT</td>
<td>2017/10/27 00:21</td>
<td>22.5</td>
<td>1.43</td>
<td>0.50</td>
<td>22.9</td>
<td>1.33-1.24</td>
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r’ is the 1I/2017 U1 magnitude measured from flux calibrated spectra, rₜ and Δ are heliocentric and geocentric distances, and α is the phase angle.

Fig. 1 | Optical reflectance spectra of 1I/2017 U1 obtained with the WHT + ACAM and VLT + X-shooter. Both spectra have been averaged over 0.01μm bins in wavelength and normalized at a wavelength of 0.55μm. Uncertainties come from errors on the median reflectance within individual spectral bins and do not include possible systematic effects from atmospheric extinction corrections or the different solar analogues observed. See Methods for further details.

Fig. 2 | WHT + ACAM (red data points) and VLT + X-shooter (grey data points) spectra of 1I/2017 U1 compared with reflectances of main-belt asteroids. Both spectra have been averaged over 0.01μm wavelength bins at λ < 1μm and 0.02μm bins at λ > 1μm and normalized at 0.55μm wavelength. To uncertainties shown were calculated as explained in the Methods. The spectral reflectance ranges of D-, L- and C-type asteroids are denoted by solid colours.

Fig. 3 | Comparison of our X-shooter 1I/2017 U1 spectrum from Fig. 2 with ranges of reflectance spectra of outer Solar System bodies. The purple line shows an X-shooter spectrum of (60558) Echeclus. 1I/2017 U1 lies between cometary nuclei and centaurs possessing ultra-red material. We define the red centaur, trojan and comet spectral reflectance zones based on observed spectra of extreme examples of those populations (see Methods for details).

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heating at significant depth. As shown in Fig. 4, the heat wave passes only slowly into the interior and, while the surface reached peak temperatures of ~600 K, H$_2$O ice buried >20 cm deep would only commence sublimation weeks after perihelion. Layers 30 cm deep or more would never experience temperatures high enough to sublimate H$_2$O ice. Taking the unphysical extreme of a surface continuously exposed to the Sun during the orbit only increases the depth of the ice sublation layer by ~10 cm. Therefore, we conclude that if there is no ice within ~40 cm of the surface, we would expect to see no activity at all, even if the interior has an ice-rich composition. Simple thermal approximations give a similar surface temperature and thermal skin depth.\footnote{Were we actually to observe heating at important depth, we might expect the heat wave to pass into the interior and, while the surface reached peak temperatures of ~600 K, H$_2$O ice buried >20 cm deep would only commence sublimation weeks after perihelion. Layers 30 cm deep or more would never experience temperatures high enough to sublimate H$_2$O ice. Taking the unphysical extreme of a surface continuously exposed to the Sun during the orbit only increases the depth of the ice sublation layer by ~10 cm. Therefore, we conclude that if there is no ice within ~40 cm of the surface, we would expect to see no activity at all, even if the interior has an ice-rich composition. Simple thermal approximations give a similar surface temperature and thermal skin depth.\footnote{More likely, 1I/2017 U1 dates from the more recent generations of comet-like ISOs such as 1I/2017 U1.}

Would a body with interior ice have significant strength to resist rotational disruption? Assuming a low density of $\lesssim$1,000 kg m$^{-3}$, the required strength is estimated to be in the range 0.5–3 Pa.\footnote{Weak materials like talcum powder have a strength of ~10 Pa, sufficient to maintain the body structure. The inactive surface of comet 67P had a tensile strength ranging from 3–15 Pa. Therefore, the unusual shape of 1I/2017 U1 does not rule out an internal ice-rich comet-like composition.} We recognize one obvious problem with this model—that Oort cloud comets should have undergone similar mantling due to cosmic-ray exposure over 4.6 Gyr, yet many show significant activity via sublimation of near-surface ice during their first perihelion passage.\footnote{More likely, 1I/2017 U1 dates from the more recent generations of comet-like ISOs such as 1I/2017 U1.} 1I/2017 U1 cannot have had a significantly longer exposure to cosmic rays; even if it was formed around one of the earliest stars, it will not be more than ~3 times the age of our Solar System. More likely, 1I/2017 U1 dates from the more recent generations of stars as it could not be formed before the Universe had created enough heavy elements to, in turn, form planetesimals.\footnote{It may have become desiccated through sublimation of surface ices during close passages to its parent star before being ejected from its natal system. Damocloid objects in our own Solar System are thought to be similar cometary bodies that have developed thick insulating mantles preventing sublimation.\footnote{Alternatively, the cause could be the relatively small size of 1I/2017 U1 compared with active Oort cloud nuclei with radii of \(\geq \)1 km. The possible minimum radius of only \(\sim 20 \text{ m}\) may have allowed most of the interior ice to escape over its unknown history. In this case, we should expect that the Large Synoptic Survey Telescope will find many small devolatized ‘comets’ from our own Oort cloud, in addition to more ISOs like 1I/2017 U1.}}

Methods

Observations. The apparent magnitude and position of 1I/2017 U1 relative to the Earth and Sun at the time of the two sets of observations are given in Table 1. Details of the instrument setup for each observation are given below. At both telescopes, the observations were performed by observatory staff in service mode. Each set of data was subsequently independently reduced by two of the authors; intercomparison of the resulting spectra showed no significant differences for the individual instruments.

For WHT, two 900 s exposures were obtained with AGAM\footnote{AGAM is an acronym for Asteroid Global Area Mapping.} in spectroscopic mode using a slit width of 2 arcsec at the parallactic angle. Subsequent inspection of the data showed that the second spectrum was contaminated by a late-type star passing through the slit; hence only the first spectrum was usable. The reflectance spectrum was obtained through division by a spectrum of the fundamental solar analogue 16 Cyg B taken directly afterwards with the same instrumental setup.

Flux calibration was performed via a spectrum of the spectrophotometric standard BD +4 25455 obtained through a 10-arcsec-wide slit.

For VLT, X-shooter contains three arms covering the ultraviolet/blue (UVB), visible and NIR spectral regions, separated by dichroic beam-splitters to enable simultaneous observation over the 0.3–2.5 µm range.\footnote{Four consecutive exposures were obtained, with both 900 s exposures in the UVB and NIR arms and 855 s exposure in the visible arm (as the UVB and visible arms share readout electronics, this allows the most efficient use of the telescope while maximizing the flux in the low-signal ultraviolet region). It was found that the signal in the last two exposures was very poor and these were not used in the analysis. Subsequent matching with published photometry shows we were near lightcurve minimum at that time.}

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analogue star HD 1368 were obtained with the same setup to allow calculation of reflectance spectra. Flux calibration was performed via observations of the spectrophotometric standard LTT 7987 obtained through a 4-arcsec-wide slit.

For the spectra from both facilities, the reflectance spectra were calculated from the median reflectance in spectral bins. There was enough flux at λ < 1 μm to allow binning over 0.01 μm bins in wavelength, but in the NIR the detected flux was so low bins had to be increased to 0.02 μm to obtain a reasonable spectrum. A robust estimation of the dispersion of the original spectral reflectance elements in each wavelength bin was performed using the ROBUST_SIGMA routine in IDL or equivalent code in Python. The reflectance uncertainty in each bin was then calculated by dividing by the square root of the number of original spectral elements in the bin.

Spectrum comparison. In Figs. 2 and 3, we compare our observed spectra of 1I/2017 U1 with various Solar System minor bodies. Spectral types for asteroids are taken from the Bus–DeMeo taxonomy definitions established in ref. 13 and available at http://ssmal.mit.edu/busdemeoclass.html. For outer Solar System bodies, we define the red centaur, trojan and comet zones based on observed spectra of extreme examples. The centaur zone upper limit is the Pholus spectrum taken from ref. 33, while the lower limit is (55576) Amorcyus16. The trojan spectra are also defined by previously published data35. The X-shooter spectrum of Echeclus was obtained by the authors (W.C.F. and T.S.) and reduced in the same manner as the 1I/2017 U1 data. This will be fully described in a forthcoming paper.

For comet nuclei, there are relatively few observations in the NIR, due to the fact that missions are often far from targets when far enough from the Sun to be inactive, but previous observations have shown the dust spectra of weakly active comets to match their nuclei (for example, 67P/Churyumov–Gerasimenko observed simultaneously with X-shooter and from Rosetta14). To define the comet zone, we take the upper limit from 19P/Borrelly from spacecraft data32 and the lower limit from C/2001 OG108 (ref. 13), as it covers a wide wavelength range.

Thermal modelling. To determine the surface and sub-surface temperature of 1I/2017 U1 as a function of time, we solve the one-dimensional heat conduction equation with a suitable surface boundary condition. For temperature T, time t, and depth z, one-dimensional heat conduction is described by

$$\frac{dT}{dt} = \frac{k}{\rho C} \frac{d^2T}{dz^2},$$

where k is the thermal conductivity, ρ is the material density and C is the heat capacity. For comet nuclei, these properties are assumed to be constant with temperature and depth. For surface element located on 1I/2017 U1, conservation of energy leads to the surface boundary condition

$$f(1-A_b) F_0(n_i)^3 + \left[ \frac{dT}{dz} \right]_{z=0} - \varepsilon T_{solar}^4 = 0,$$

where $A_b$ is the Bond albedo, $F_0$ is the integrated solar flux at 1 au (1.367 W m$^{-2}$), $n_i$ is the heliocentric distance in au of 1I/2017 U1 at time t, $r$ is the bolometric emissivity and $\sigma$ is the Stefan–Boltzmann constant. $f_s$ is a multiplying factor to take into account the different illumination scenarios we considered. For instance, $f_s$ has a value of 1 for the case when the rotation axis of 1I/2017 U1 is perpendicular to the Sun vector, 1/2 when the Sun vector and rotation axis are orthogonal, 0 for the case when the Sun vector and rotation axis are parallel, and 4/3 when the Sun vector and rotation axis are at an angle of 60°.

For the two illumination scenarios considered, the thermal model was propagated forwards from its initial starting point and run until 6,500 days after perihelion. The temperature at depths of 0, 10, 20, 30 and 40 cm was recorded at 1-day intervals in the model. As shown in Fig. 4, the most significant temperature changes occur during the 400 days centred on perihelion.

We note that as the thermal penetration depth is proportional to $\varepsilon / (k/\rho C)$, our results can be scaled to different thermal property values. Identical temperature profiles can be found at depths given by

$$z = \frac{d}{\sqrt{\varepsilon}} \left( \frac{k}{\rho C} \right)^{1/4}.$$

For example, if the thermal inertia was ~250 m$^2$ K$^{-1}$s$^{-1/2}$ (the 3σ upper limit determined for comet 103P/Hartley 2; ref. 33), the depth of the temperature profiles would be ten times higher if the difference in thermal inertia was solely due to a difference in thermal conductivity. However, the depth would be less if the increased thermal inertia was spread equally across its three components. Furthermore, if the geometric albedo of 1I/2017 U1 is very low, the temperatures are also relatively insensitive to factor of two changes in this parameter.

Data availability. The ACAM and X-shooter spectra that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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**Author contributions**

A.F. led the application and organization of the WHT observations, analysis of these data and writing of the paper. C.S. led the application for VLT observations, organized the observing plan and assisted with analysis and writing. B.R. performed the thermal modelling of 1I/2017 U1. B.Y. was co-investigator on the telescope proposals, assisted in writing the VLT proposal and reduced the X-shooter data. M.T.B. and W.C.F. assisted in interpretation of the spectra in terms of known TNO properties and helped with writing the paper. M.H. reduced the WHT data. T.S. reduced the VLT data and provided the comparison spectrum of Echeclus. R.J. was co-investigator on the telescope proposals and contributed to the analysis and interpretation, especially with respect to observational selection effects. P.L. assisted in interpretation of the variable spectra and helped with writing the paper.

**Competing interests**

The authors declare no competing financial interests.

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