APO Time-resolved Color Photometry of Highly Elongated Interstellar Object 1I/Oumuamua

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Received 2017 November 13; revised 2017 December 3; accepted 2017 December 6; published 2017 December 22

Abstract

We report on g-, r-, and i-band observations of the Interstellar Object 1I/Oumuamua (1I) taken on 2017 October 29 from 04:28 to 08:40 UTC by the Apache Point Observatory (APO) 3.5 m telescope’s ARCTIC camera. We find that 1I’s colors are $g - r = 0.41 \pm 0.24$ and $r - i = 0.23 \pm 0.25$, consistent with visible spectra and most comparable to the population of solar system C/D asteroids, Trojans, or comets. We find no evidence of any cometary activity at a heliocentric distance of 1.46 au, approximately 1.5 months after 1I’s closest approach distance to the Sun. Significant brightness variability was seen in the r observations, with the object becoming notably brighter toward the end of the run. By combining our APO photometric time series data with the Discovery Channel Telescope data of Knight et al., taken 20 hr later on 2017 October 30, we construct an almost complete lightcurve with a most probable single-peaked lightcurve period of $P \approx 4$ hr. Our results imply a double-peaked rotation period of $8.1 \pm 0.02$ hr, with a peak-to-trough amplitude of 1.5–2.1 mag. Assuming that 1I’s shape can be approximated by an ellipsoid, the amplitude constraint implies that 1I has an axial ratio of 3.5–10.3, which is strikingly elongated. Assuming that 1I is rotating above its critical break up limit, our results are compatible with 1I having modest cohesive strength and may have obtained its elongated shape during a tidal distortion event before being ejected from its home system.

Key words: local interstellar matter – minor planets, asteroids: individual (1I/2017 U1 (‘Oumuamua))

1. Introduction

The discovery and characterization of protoplanetary disks have provided ample observational evidence that icy comet belts and rocky asteroid belts exist in other planetary systems (e.g., and Lisse et al. 2007, 2017; Öberg et al. 2015; Nomura et al. 2016). However, these observations have consisted of distant collections of millions of objects spanning large ranges of temperature, astrocentric distance, and composition. Until now, it has been impossible to bring the level of detailed analysis possible for our own local small body populations to the large, but unresolved, groups of comets and asteroids in exoplanetary disks.

The observation and discovery of interstellar objects have been discussed before (Cook et al. 2016; Engelhardt et al. 2017), but the apparition of 1I/Oumuamua (hereafter “1I”) is the first opportunity to study up close an asteroid-like object that formed outside of the solar system. This provides a unique opportunity to measure the basic properties (size, shape, rotation rate, and color) of a small body originating in another planetary system, and compare it directly to the properties of cometary nuclei and asteroids in our own. Such measurements may shed light on how and where 1I formed within its planetary system, as well as provide a basis for comparison to potential solar system analogs.

In this work, we describe APO/ARCTIC imaging photometry in three bands, g, r, and i, taken to meet three scientific goals: (a) measure the color of the object’s surface, to compare with our own small body populations; (b) perform a deep search for cometary activity in the form of an extended coma; and (c) constrain the object’s rotation period to make an initial assessment of structural integrity.

2. Observations

Photometric imaging observations of 1I were acquired on 2017 October 29 (UTC) using the ARCTIC large format CCD camera (Huehnerhoff et al. 2016) on the Apache Point Observatory’s (APO’s) 3.5 m telescope. 1I was at that time at a 0.53 au geocentric distance, 1.46 au from the Sun and at a phase angle of 23°8. The camera was used in full frame, quad amplifier readout, $2 \times 2$ binning mode with rotating SDSS g, r, and i filters, and a pixel scale of 0′′.22. The integration time for each target was 180 s, and 71 frames were acquired between 58055.1875 MJD (04:30 UT) and 58055.3611 MJD (08:40 UT). Bias frames were taken immediately before observing the target, and instrument flat fields were obtained on the sky at the end of the night. Absolute calibration was obtained using nearby SDSS flux calibrators in the 1I field. A similar observing strategy was used over the last 8 years for our SEPPCON distant cometary nucleus survey (Fernandez et al. 2016).

The weather was photometric throughout the night, and the seeing remained between $1''3$ and $1''5$. Owing to 1I’s hyperbolic orbit, the object was fading rapidly in brightness after its discovery on 2017 October 18 and was observed as...
soon as possible with APO Director’s Discretionary time, while 1I was within ~0.5 au of the Earth. The observing circumstances were not ideal (air mass = 1.1 to 2.0, 60% illuminated moon within 75° of 1I), but good measurements of 1I could still be obtained. For the first 36 exposures, images were obtained with filters in the following sequence: 2 r, 2 g, and 1 i and repeated 6 times. Two additional r and one g exposure were taken at the end of the 30 exposure g, r, and i observing sequence. At the end of the main observing sequence, 15 g, 15 r, and 6 i were obtained for a total of 36 exposures. The air mass during the first 36 exposures was between 1.15 and 1.3.

We used non-sidereal guiding matched to the rate of 1I’s motion to maximize our sensitivity to the target, which caused the background stars to trail by ~10″ in each image (Figure 1). The motion of 1I on the sky fortuitously avoided significant overlap with the star trails, and its position within the frame was arranged to avoid cosmetic defects on the chip. The ARCTIC fields centered on the sky position of 1I contained a sufficient number of bright SDSS standard stars to enable accurate absolute calibration, despite the trailing of the stars.

3. The Colors of 1I/ʻOumuamua

The position of 1I/ʻOumuamua in our field, and the input rates used to track the object, were nearly spot-on, despite its very high apparent angular rate of motion (3′/hr⁻¹) implying that the ephemeris solution we used was accurate. We did report astrometric details of our observations to the Minor Planet Center to help refine the orbit further (Weaver et al. 2017).

To measure colors, individual frames in our data set were bias subtracted and flat-fielded before being stacked in a robust average. Statistical outlier pixels were removed at the 2σ level from the average stack of frames. The frames were stacked in two sets with one set centered on the motion of 1I and the other set stacked sidereally. All 15 g frames were stacked to create combined 1I and star centered images with an equivalent exposure time of 2700 s. All 6 i frames were stacked into a single exposure with the equivalent of a 1080 s exposure time. Only the first 15 r frames taken at the same time as the g and i frames were stacked for the purpose of comparing the photometry of the r-band 1I detection with the g- and i-band detections. The 15 g, 15 r, and 6 i frames were taken between 4.6 and 6.5 UTC, so they should have covered the same part of the rotation phase of 1I eliminating any differences in brightness between the color detections due to rotational change in brightness. Between 6.5 UTC and 8.6 UTC, only r exposures were taken. 1I was brighter compared to earlier in the night during this time, so frames were stacked in shorter sequences of 2-6, as appropriate to reach a signal-to-noise ratio (S/N) > 10.

Aperture photometry was applied to the detections in the g, r, and i frames. An aperture radius of 1″1 with a sky annulus between 3″3 and 4″4 was used to measure the flux. An aperture radius of 6″6 and a sky annulus between 8″8 and 10″0 was used for the standard stars. The median sky background in the sky annulus was subtracted from the aperture flux in both the non-sidereally and sidereally stacked frames to minimize the potential effect of artifacts on the photometry.

The SDSS solar analog star located at R.A. 23:48:32.355, δ +05:11:37.45 with g = 16.86, r = 16.41, and i = 16.22 was used to calibrate the photometry in the g and i average stacks, and the average stack corresponding to the first 36 r frames. The difference in air mass between frames in the g, r, and i average stacks used to calculate colors was only ~10%. Following the 36th r frame, additional SDSS catalog standard stars were used as the telescope’s tracking of 1I took it out of the frame of the imager. g, r, and i magnitudes were measured...
at S/N $\gtrsim 5$ level:

\[
g = 23.51 \pm 0.22 \\
r = 23.10 \pm 0.09 \\
i = 22.87 \pm 0.23.
\]

A complete list of our photometric measurements are available in Table 1. The photometric uncertainties are dominated by statistical photon noise because the effect of changing rotational brightness should have been averaged out as the exposures in the different bands were taken at the same time. The catalog magnitude uncertainty for the magnitude of the rocky small bodies in our solar system is less than 0.1 magnitudes are shown in the background contours; the illustrated contour intervals enclose 80%, 90%, and 95% of the objects in each class. Trans-Neptunian objects (TNOs) generally move too slowly to be identified in the MOC; however, Ofek (2012) cross-matched orbits of known (at the time) TNOs with reported photometry from SDSS Data Release 7. Colors of these objects are shown, with photometric errors, as red triangles. Comets also do not show up in the SDSS MOC, but Solontoi et al. (2012) searched for comets in SDSS catalogs using cuts on the catalogs directly and by cross-matching against known objects. Colors and photometric error bars of the resulting sample are shown with blue circles; note that these points likely refer to the color of the coma dust, not the nuclei. Our measured colors of 1I are shown, with photometric errors, as red triangles. Colors of these objects are shown, with photometric errors, as red triangles. Colors of these objects are shown, with photometric errors, as red triangles.

Figure 2. Measured $g - r$ vs. $r - i$ colors of 1I/Oumuamua in context with moving objects observed with SDSS (Ivezic et al. 2001; Juric et al. 2002). Some data point’s error bars are smaller than the plotting symbol. Colors derived from detections in the SDSS Moving Object Catalog (MOC; Ivezic et al. 2002) with a corresponding D or P, S, or C Bus-DeMeo taxonomic classification (DeMeo & Carry 2013) and $g - r$ and $r - i$ photometric errors smaller than 0.1 magnitudes are shown in the background contours; the illustrated contour intervals enclose 80%, 90%, and 95% of the objects in each class. Trans-Neptunian objects (TNOs) generally move too slowly to be identified in the MOC; however, Ofek (2012) cross-matched orbits of known (at the time) TNOs with reported photometry from SDSS Data Release 7. Colors of these objects are shown, with photometric errors, as red triangles. Comets also do not show up in the SDSS MOC, but Solontoi et al. (2012) searched for comets in SDSS catalogs using cuts on the catalogs directly and by cross-matching against known objects. Colors and photometric error bars of the resulting sample are shown with blue circles; note that these points likely refer to the color of the coma dust, not the nuclei. Our measured colors of 1I are shown, with photometric errors, as red triangles. Colors of these objects are shown, with photometric errors, as red triangles. Colors of these objects are shown, with photometric errors, as red triangles.

Our measured colors,

\[
g - r = 0.41 \pm 0.24 \\
r - i = 0.23 \pm 0.25
\]

are consistent with reported colors and Palomar and William Herschel Telescope optical spectra from Masiero (2017), Fitzsimmons et al. (2017), and Ye et al. (2017). When compared to the visible light colors of known objects in our solar system (see Figure 2), 1I’s colors are consistent with those of the rocky small bodies in our solar system (including solar colors), and are significantly less red than most trans-Neptunian objects (TNOs), especially the cold classical TNOs and highly processed JFC comet nuclei.

The majority of $r$ band detections in image stacks used in the lightcurve have an uncertainty of $<0.1$, as seen in the top left panel of Figure 3.

4. The Lightcurve of 1I/Oumuamua

The data obtained in this paper do not allow for an unambiguous measurement of 1I’s lightcurve amplitude and periodicity. We therefore added to our data set the measurements reported by Knight et al. (2017; henceforth referred to as the “Discovery Channel Telescope (DCT) data set”). Expected secular changes in the magnitude were removed prior to fitting the data by assuming an inverse-square distance from the Earth and Sun, and assuming a linear phase function with slope 0.02 mag deg$^{-1}$. A phase slope of the combined data set is shown in Figure 3.

Table 1

| MJD   | Filter | Total Time (s) | $m_{\text{apparent}}$ |
|-------|--------|----------------|------------------------|
| 58055.23427 | $g$   | 2700           | 23.51 ± 0.22           |
| 58055.23436 | $r$   | 2700           | 23.12 ± 0.09           |
| 58055.23432 | $i$   | 2700           | 22.88 ± 0.23           |
| 58055.28729 | $r$   | 2700           | 22.37 ± 0.11           |
| 58055.29892 | $r$   | 2700           | 21.18 ± 0.11           |
| 58055.30778 | $r$   | 720            | 22.22 ± 0.11           |
| 58055.31447 | $r$   | 360            | 22.37 ± 0.07           |
| 58055.31923 | $r$   | 360            | 22.64 ± 0.08           |
| 58055.32369 | $r$   | 360            | 22.66 ± 0.09           |
| 58055.32852 | $r$   | 360            | 22.44 ± 0.07           |
| 58055.33295 | $r$   | 360            | 22.55 ± 0.07           |
| 58055.33737 | $r$   | 360            | 22.73 ± 0.07           |
| 58055.34395 | $r$   | 720            | 23.12 ± 0.08           |
| 58055.35438 | $r$   | 900            | 23.46 ± 0.11           |

Even with the extended data set, estimating the lightcurve period using the Lomb–Scargle (LS) periodogram (Lomb 1976; Scargle 1982) was inconclusive due to the sparse sampling pattern and the short time baseline of observations. This motivated us to apply more sophisticated methods—a direct Bayesian approach to model the observed lightcurve and estimate the period and amplitude of the periodic variation.

4.1. Simple Sinusoidal Model

We begin by modeling the lightcurve with a simple sinusoidal signal of the form

\[
\lambda_i = A \sin(2\pi t_i / P + \phi) + b,
\]

where $\lambda_i$ is the model magnitude at time step $t_i$, $A$, $P$, and $\phi$ are the amplitude, period, and phase of the sinusoid, respectively, and $b$ denotes the constant mean of the lightcurve. This sinusoidal model is equivalent in concept to the generalized LS periodogram (Lomb 1976; Scargle 1982), but the difference is that the LS periodogram assumes a well-sampled lightcurve, which cannot be guaranteed here (for more details, see Ivezic...
et al. 2014). We model the data using a Gaussian likelihood and choose a flat prior on the period between 1 and 24 hr, consistent with periods observed from similar sources known in the solar system (Pravec et al. 2002). We assume a simple sinusoidal model with the expectation that the actual rotation period of asteroids with significant elongation as will be discussed for II in Section 5 are assumed to have a double-peaked rotation curve (Harris et al. 2014) and double the period of a simple sinusoidal model.

We choose a flat prior for $b$ between 20 and 25 magnitudes, and an exponential prior for the logarithm of the amplitude between $-20$ and 20. For the phase $\phi$, we use a Von Mises distribution as appropriate for angles in order to incorporate the phase-wrapping in the parameters correctly, with a scale parameter $\kappa = 0.1$ and a mean of $\mu = 0$, corresponding to a fairly weak prior.

We sampled the posterior distribution of the parameters using Markov chain Monte Carlo (MCMC), as implemented in the Python package emcee (Foreman-Mackey et al. 2013).

This analysis reveals well-constrained, nearly Gaussian distributions for all relevant parameters. We summarize the marginalized posterior distributions in terms of their posterior means, as well as the 0.16 and 0.84 percentiles, corresponding to 1σ credible intervals. These are given by

$$P_{\text{sin model}} = 4.07 \pm 0.01 \text{ hr}$$

$$A_{\text{sin model}} = 0.64 \pm 0.05 \text{ mag}$$

for the period and the amplitude, respectively.

In Figure 3, we show the observed lightcurve along with models drawn from the posterior distribution of the parameters. In particular, we show that the sinusoidal model slightly underestimates the minimum brightness in the DCT data set as seen in the right panel of Figure 3. This is likely due to deviations from the sinusoidal shape, which compels the model to adequately fit the wings rather than the peak.

4.2. Gaussian Process Model

Figure 3 indicates that the strictly sinusoidal model is too simplistic to adequately model the more complex lightcurve shape of the object. We therefore turn to a more complex model that, while still periodic, allows for non-sinusoidal as well as double-peaked lightcurve shapes. In short, instead of modeling the lightcurve directly as above, we model the covariance between data points, a method commonly referred to as Gaussian Processes (see Rasmussen & Williams 2006 for a pedagogical introduction). This approach has recently been successfully deployed in a range of astronomical applications (e.g., Angus et al. 2017; Jones et al. 2017). The covariance matrix between data points is modeled by a so-called covariance function or kernel. Different choices are appropriate for different applications, and we choose a strictly periodic kernel of the following form (MacKay 1998) here:

$$k(t_i, t_j) = C \exp \left( \frac{\sin^2(\pi|t_i - t_j|/P)}{d^2} \right)$$

for time stamps $t_i$ and $t_j$. In this framework, the amplitude $C$ corresponds to the amplitude of the covariance between data points and is thus not comparable to the amplitude in the sinusoidal model above. The period $P$ on the other hand retains exactly the same meaning. The model also gains an additional parameter $d$ describing the length scale of variations within a single period. It is defined with respect to the period, with $d \gg P$ leading to sinusoidal variations, whereas increasingly smaller values result in an increasingly complex harmonic content within each period.

We use a Gaussian process, such as that implemented in the Python package george (Ambikasaran et al. 2014), with the covariance function defined above, to model the combined DCT and APO data sets. For the period, we use the same prior as for the sinusoidal model, but we assume uniform priors on the logarithms of amplitude ($-100 < \log(C) < 100$) and the length scale of within-period variations, $\Gamma = 1/d^2$ ($-20 < \log(\Gamma) < 20$). As before, we use emcee to draw MCMC samples from the posterior probability. In Figure 4, we show the posterior distributions for the period, amplitude and $\Gamma$ parameter. The marginalized posterior probability distribution for the period is in broad agreement with the sinusoidal model at $P = 4.07$ hr.

We inferred what the expected lightcurve profile would look like if the period were twice that inferred by both the sinusoidal and Gaussian process models in order to guide additional observations of II, either with improved photometry from existing observations or future observations before the object becomes too faint as it leaves the solar system. We took the parameters with the highest posterior probability, doubled its period, and computed the 1σ credible intervals for the model lightcurve admitted by this particular Gaussian process with these parameters (Figure 4, lower panel). This figure shows that if a double-peaked profile were present, roughly half of it would be well-constrained by current observations (indicated by narrow credible intervals). The second peak of the profile, however, is considerably less well constrained due to the lack of data points. Observations in that part of the phase space, in particular, near the minimum and maximum of that second peak, could help pin down the exact lightcurve shape.

We have made our data and analysis tool used to arrive at our results online.8
5. Results and Discussion

1I was challenging to characterize with the APO due to its faintness. At first, it was impossible to locate 1I by eye in our single 180 s integrations, but as the night progressed it became distinct, indicating a significant brightening in less than 4 hr. A similar behavior was reported by Knight et al. (2017) in observations from the DCT 4 m on the next night (Figure 2). Combining the two data sets, we find a most likely lightcurve period of 4.07 hr as described in Section 4; phasing the data to this period produces a well structured, near-sinusoidal lightcurve, such as that seen in the bottom panel of Figure 3. The peak-to-trough amplitude of the lightcurve, almost 2 magnitudes, is unusual compared to the population of asteroids in the solar system, which usually have peak-to-trough amplitudes of <0.75 (Warner et al. 2009).

We estimate the size of 1I from a clean set of 4 r-band photometric images taken in the middle of our run at around 07:53, when the telescope pointing and focus had stabilized. Using the \( r = 15.23 \) magnitude reference star UCAC4 ID 477-131394 with \( 4.08 \times 10^3 \text{DN} \) sky-subtracted counts, we find our \( 2.42 \times 10^3 \text{DN} \) sky-subtracted counts from 1I in 180 s translates into a 22.44 r magnitude object at a heliocentric distance of 1.458 au and geocentric distance of 0.534 au. Assuming the \( r \) band zero-point to be \( 3.631 \times 10^3 \text{Jy} \), this yields an in-band flux density of \( 3.03 \times 10^{-17} \text{W m}^{-2} \mu \text{m}^{-1} \). Using a solar flux density of \( 1.90 \times 10^3 \text{W m}^{-2} \mu \text{m}^{-1} \) at the \( r \)-band central wavelength of 0.624 \( \mu \text{m} \), we find an effective radius of 0.130 km for a comet-like surface albedo of 0.03 (referring to an albedo value at a solar phase angle of \( 0^\circ \)). This size estimate is likely an upper limit because it is based on data taken near 1I’s peak in brightness.

The size and shape of 1I’s image was consistent with a point source throughout the observing run, with no evidence for an extended source even in a stacked image of all the APO r-band data. This is unlike many of our distant comet program targets (Fernandez et al. 2016), which we have over 10 years worth of experience observing for size, rotation rate, and signs of activity. The object was well-detected in multiple 180 s r-band images, but it took all of our 15 g-band 180 s exposures and all 6 of our i band 180 s exposures to obtain a detection at S/N \( \sim 5 \). As discussed above and shown in Figure 2, the colors of 1I are consistent with having origins in the inner part of its solar system compared to the outer part of its solar system where comets come from. We used the 1I ephemeris from the JPL Horizons system (reference solution #4) to drive the APO telescope pointing and tracking, the latter at the relatively high rate of \( \sim 3^\prime \text{hr}^{-1} \). The location of 1I in our field, and the essentially point-source appearance of 1I even after stacking multiple images, provided strong evidence that 1I’s orbital elements were accurate and thus consistent with an interstellar origin for the object. We reported astrometric details of our observations to the Minor Planet Center to help refine the orbit further (Weaver et al. 2017).

The peak-to-trough amplitude of our lightcurve, determined by the difference between the minimum and maximum brightness (Barucci & Pulchignoni 1982) of 1I, is \( A_{\text{peak.difference}} = 2.05 \pm 0.53 \) as seen in Figure 3. \( A_{\text{peak.sin model}} = 2A_{\sin model} = 1.28 \pm 0.1 \text{mag} \).

The angle between the observer and the Sun from the point of view of the asteroid, or the phase angle, \( \alpha \), can affect the measured lightcurve peak-to-trough amplitude. Zappala et al. (1990) found that the peak-to-trough amplitudes increase with the phase angle, \( \alpha \) according to

\[
\Delta m(\alpha = 0^\circ) = \frac{\Delta m(\alpha)}{1 + s \alpha^2},
\]

where \( s \) is the slope of the increase in peak-to-trough magnitude with \( \alpha \). Zappala et al. (1990) and Gutierrez et al. (2006) found that \( s \) varies with taxonomic type and with asteroid surface topography. We adopt a value of 0.015 mag deg\(^{-1}\) as a value of \( s \) for primitive asteroids as described in Zappala et al. (1990) as expected for 1I, but note that a different value of \( s \) would result in a different value of the peak-to-trough magnitude. \( \alpha \) at the time of the APO and DCT observations 1I was 24\(^\circ\) which according to Equation 3 corrects \( A_{\text{peak.difference}} \) and \( A_{\text{peak.sin model}} \) by a factor of 0.73, so that \( A_{\text{peak.difference}} \approx 1.51 \text{ and } A_{\text{peak.sin model}} \approx 0.94 \).

Asteroids are assumed in the general case to have a simplistic triaxial prolate shape with an axial ratio, \( a:b:c \), where \( b \geq a \geq c \) (Binzel et al. 1989). As a result, the aspect angle between the observer’s line of sight and the rotational pole of the asteroid, \( \theta \), can modify the measured peak-to-trough amplitude as the rotational cross section with respect to the observer increases or decreases for different \( \theta, a, b, \text{ and } c \).
We consider the possibility that we are observing 1I at some average angle of \( \theta \) and can estimate the peak-to-trough magnitude if observing 1I from an angle of \( \theta = 90^\circ \). From Thirouin et al. (2016), the difference in peak-to-trough magnitude observed at angle \( \theta \) and peak-to-trough magnitude observed at angle \( \theta = 90^\circ \), \( \Delta m_{\text{diff}} = \Delta m(\theta) - \Delta m(\theta = 90^\circ) \) as a function of \( a, b, c \) is

\[
\Delta m_{\text{diff}} = 1.25 \log \left( \frac{b^2 \cos^2 \theta + c^2 \sin^2 \theta}{a^2 \cos^2 \theta + c^2 \sin^2 \theta} \right). \tag{4}
\]

Assuming \( a = c \), Equation (4) implies that \(\Delta m\) will be at least \( \sim 0.6 \) magnitudes fainter on average compared \( \Delta m(\theta = 90^\circ) \) with the assumptions that \( b/a > 3 \) and \( a = c \). We can estimate upper limits for the peak-to-trough magnitudes at \( \theta = 90^\circ \) by recalculating \( A_{\text{peak,difference}} \) and \( A_{\text{peak,sin model}} \) with the assumption that the data used for their calculations are representative of the average aspect angle and have \( b/a > 3 \) and \( a = c \) by using Equation (4)

\[
A_{\text{max,difference}} = A_{\text{peak,difference}} - \Delta m_{\text{diff}}
\]

\[
A_{\text{max,sin model}} = A_{\text{peak,sin model}} - \Delta m_{\text{diff}}
\]

results in \( A_{\text{max,difference}} = 2.11 \pm 0.53 \) and \( A_{\text{max,sin model}} = 1.54 \pm 0.1 \). We note our measurements of \( A_{\text{max,difference}} = 2.11 \pm 0.53 \) and \( A_{\text{max,sin model}} = 1.54 \pm 0.1 \) for the peak-to-trough magnitude of 1I are lower than the peak-to-trough magnitude of 2.5 described by Meech et al. (2017). The difference our peak-to-trough magnitude measurements and those of Meech et al. (2017) is possibly due to the fact that the S/N of the faintest measurements of the brightness of 1I from Knight et al. (2017) may be substantially lower than the S/N of the faintest measurements of the brightness of 1I from Meech et al. (2017). Additionally, our conservative estimates of the contribution of the phase angle to the peak-to-trough amplitude and the aspect angle on our measured peak-to-trough amplitude via Equations (3) and (4) may also result in differences between our measurements and those of Meech et al. (2017).

Assuming 1I is a prolate triaxial body with an axial ratio \( a:b:c \), where \( b \geq a \geq c \) and that the lightcurve variation in magnitude is wholly due to the changing projected surface area (consistent with the sinusoidal shape of our phased lightcurve), we obtain an upper limit of \( b/a = 6.91 \pm 3.41 \) from \( b/a = 10^{0.43 \Delta M} \) (Binzel et al. 1989), where \( \Delta M = A_{\text{max,difference}} \). A more conservative estimate of the upper limit on the peak-to-trough amplitude is given by using \( A_{\text{max,sin model}} \) for \( \Delta M \) resulting in \( b/a = 4.13 \pm 0.48 \). The uncertainty in the \( b/a = 6.91 \pm 3.41 \) using \( \Delta M = A_{\text{peak,difference}} \) is dominated by uncertainty on magnitude measurement compared to \( A_{\text{max,sin model}} \). The uncertainties of \( A_{\text{max,sin model}} \) are determined by the spread of compatible values for the amplitude within the uncertainties of all data points in the lightcurve and are probably more statistically robust than using the difference between the minimum and maximum brightness data points in the lightcurve. However, this fact must be tempered by the fact that the true peak-to-trough amplitude may be underestimated due to the sparseness of data points as described in Section 4. Therefore, we assume that the true axial ratio \( b/a \) lies between 3.5 \( \leq b/a \leq 10.3 \). These limits are based on generalized assumptions and more accurately determining the true value of \( b/a \) would require additional observations at different \( \theta \) and at times in which the object’s rotation are not covered by our observations as discussed in Section 4.2.

This large value for \( A_{\text{peak,difference}} \) or \( A_{\text{peak,sin model}} \) suggests that the modulation seen in the lightcurve is due to the rotation of an elongated triaxial body dominated by the second harmonic resulting in a bimodal, double-peak lightcurve (Harris et al. 2014; Butkiewicz-Beak et al. 2017). Thus, we obtain a double-peak amplitude of \( P_{\text{rotation}} = 2P_{\text{sin model}} \) or \( 8.14 \pm 0.02 \) hr. Non-triaxial asteroid shapes can result in lightcurves exceeding two peaks per rotation period, but this case is ruled out as unlikely because the large amplitude of the lightcurve strongly favors an elongated object (Harris et al. 2014). Another alternative explanation of the rotation period is that the lightcurve variation is due to surface variations in the reflectivity of the asteroid. Surface variations result in single-peak lightcurves (Barucci et al. 1989), but the similarity of the colors and spectra of 1I obtained in observations taken at different times (Fitzsimmons et al. 2017; Masiero 2017; Ye et al. 2017) does not suggest significant variation on the object’s surface.

Asteroid elongations with \( 3.5 \leq b/a \leq 10.3 \) are uncommon for asteroids in the solar system where the majority have \( b/a < 2.0 \) (Cibulková et al. 2016, 2017). Only a few known solar system asteroids have \( b/a > 4 \) (e.g., the asteroid Elachi with \( b/a \sim 4 \)), comparable to our lower limit on \( b/a \) for 1I (Warner & Harris 2011). Smaller asteroids have been observed to have statistically higher elongations than larger asteroids (Pravec et al. 2008; Cibulková et al. 2016). Smaller asteroids and comets have weaker surface gravity and may be under large structural stress imposed by their rotation resulting in plasticity of their structure (Harris et al. 2009; Hirabayashi & Scheeres 2014; Hirabayashi 2015) or may become reconfigured after fracturing due to rotational stress (Hirabayashi et al. 2016).

To examine the possibility that rotational stress might be an explanation for the large elongation of 1I, we examine the existing evidence for the rotational breakup of asteroids in the solar system. Asteroids in the solar system have been observed to undergo rotational break up into fragments such as active asteroids spin-up by thermal recoil forces (Rubincam 2000; Jewitt et al. 2015b). Additionally, active comets and asteroids can become spun up due to the sublimation of volatiles (Samarasinha & Mueller 2013; Steckloff & Jacobson 2016).

The critical breakup period for a strengthless rotating ellipsoid with an axial ratio is given by Jewitt et al. (2017b) and Bannister et al. (2017)

\[
P_{\text{critical period}} = (b/a) \left( \frac{3\pi}{G\rho} \right)^{1/2}, \tag{5}
\]

where \( \rho \) is the asteroid density and \( G \) is the gravitational constant. Figure 5 shows the value of \( P_{\text{critical period}} \) in hours for values of \( a/b \) allowable by our results and \( \rho \) for different solar system asteroid taxonomic types from comets, D types with \( 0.5-1.0 \) g cm\(^{-3} \), B and C types with \( 1.2-1.4 \) g cm\(^{-3} \), S types with \( 2.3 \) g cm\(^{-3} \), X types with \( 2.7 \) g cm\(^{-3} \), rubble piles with \( 3.3 \) g cm\(^{-3} \), and \( 4 \) g cm\(^{-3} \) for M types (Lisse et al. 1999; Britt et al. 2002; A’Hearn et al. 2005; Fujiwara et al. 2006; Carry 2012).

As seen in Figure 5, the observed \( \sim 8 \) hr rotational period of 1I is shorter than the critical breakup period described by most of the \( b/a \) versus \( \rho \) phase space covering typical asteroid
There are no valid natural text elements.
It has been shown that tidal forces can completely disrupt the structure of comets and asteroids such as in the complete disruption of Comet Shoemaker-Levy 9 during its close encounter with Jupiter (Shoemaker 1995; Asphaug & Benz 1996) and the shape distortion of the asteroid Geographos during close encounters with the Earth (Bottke et al. 1999; Durouch et al. 2008; Rozitis & Green 2014). Modeling of asteroids and comets under the stress of tidal forces reveals that that one result of tidal shape distortion is that their structures become elongated due to the stress of tidal forces (Solem & Hills 1996; Richardson et al. 1998; Walsh & Jacobson 2015). Furthermore, in the complete disruption case of an asteroid or comet by tidal disruption, the fragmentation of the parent body can result in fragments having elongated shapes (Walsh & Richardson 2006; Richardson et al. 2009). Therefore, 1I could have attained its elongated structure while experiencing tidal distortion itself, or while being produced as a fragment from a larger body undergoing complete tidal disruption.

We can examine the possibility that the highly elongated shape as of 1I with cohesive strength could have been shaped by tidal forces during a close encounter with a gas giant planet. The scaling for tidal disruption distance of a comet-like body with an assumed cohesive strength <65 Pa consistent with the range of possible cohesive strengths for a body with 4 < b/a < 7 and 0.7 g cm⁻³ < ρ < 7.0 g cm⁻³ as seen in Figure 6, from Asphaug & Benz (1996) is

\[
1 < \frac{d}{R} < \left(\frac{\rho_{\text{1I}}}{\rho_{\text{planet}}}\right)^{-1/3},
\]

where d and R are the close passage distance and planet radius. We can predict how close 1I would have had to have passed by a gas giant to be tidally disrupted. Using the above limit and assuming ρ_{planet} = 1.33 g cm⁻³, the density of Jupiter (Simon et al. 1994), 1I would have to have a ρ < 1.3 g cm⁻³ to enable a close enough encounter distance to the gas giant planet to be tidally disrupted, while d/R > 1. A ρ ≈ 1.0 to 1.4 g cm⁻³ is possible for C- and D-type asteroids in the solar system (Carr 2012) and a cohesive strength <65 Pa is allowable by the range of b/a described by our data, therefore, we conclude that tidal disruption as a mechanism for the formation of the 1I’s shape is possible.

6. Conclusion

We observed interstellar asteroidal object 1I/ʻOumuamua from the APO on 2017 October 29 from 04:28 to 08:40 UTC. Three-color photometry and time domain observations were obtained in the g, r, and i bands when the object was as bright as 22 and as faint as 23 mag. An unresolved object with solar, or slightly reddish, color and variable brightness was found. The results from our observations are consistent with the point-source nature and slightly reddish color found by other observers (Fitzsimmons et al. 2017; Masiero 2017; Ye et al. 2017). The asteroidal-like appearance and nearly solar-like color of 1I suggests formation in a volatile-poor region near its parent star, rather than in an icy-rich exoplanetary region. Combining APO and DCT time domain photometry, we found that 1I was rotating with a period of ~8.14 hr, which is consistent with the rotational periods of many solar system asteroids (Warner et al. 2009). We also found that 1I’s lightcurve amplitude was ~1.5–2 mag, suggesting an axial ratio of b/a ~ 4:1–10:1. Our results on the lightcurve period and amplitude are compatible with 1I having a density >2.0 g cm⁻³, or having modest cohesive strength. Our modeling of the lightcurve data with Gaussian processing shows that, during 1I’s rotation phase, additional observations can be used to improve constraints on the period and axial ratio. We conclude that the high elongation of 1I is possibly the result of tidal disruption or structural plasticity due to rotational stress.

We would like to thank the reviewer of our manuscript, Matthew Knight, for providing a thorough review and helpful suggestions for improving the quality of the manuscript. Our work is based on observations obtained with the Apache Point Observatory 3.5 m telescope, which is owned and operated by the Astrophysical Research Consortium. We thank the Director (Nancy Chanover) and Deputy Director (Ben Williams) of the Astrophysical Research Consortium (ARC) 3.5 m telescope at Apache Point Observatory for their enthusiastic and timely support of our Director’s Discretionary Time (DDT) proposals. We also thank Russet McMillan and the rest of the APO technical staff for their assistance in performing the observations just two days after our DDT proposals were submitted. We thank Ed Lu, Sarah Tuttle, and Ben Weaver for fruitful discussions and advice that made this paper possible. B.T.B. would like to acknowledge the generous support of the B612 Foundation and its Asteroid Institute program. M.J. and C.T.S. wish to acknowledge the support of the Washington Research Foundation Data Science Term Chair fund and the University of Washington Provost’s Initiative in Data-Intensive Discovery. B.T.B., D.H., R.L.J., M.J., M.L.G., C.T.S., E.C.B., and A.J.C. wish to acknowledge the support of DIRAC (Data Intensive Research in Astronomy and Cosmology), Institute at the University of Washington. J.M. thanks the LSSTC Data Science Fellowship Program, his time as a Fellow has benefited this work. We would also like to thank Marco Delbó Alan Fitzsimmons, Robert Jedicke, and Alessandro Morbelli for constructive feedback and discussion when planning this project.

Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the U.S. Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS website is http://www.sdss.org/.

The SDSS is managed by the Astrophysical Research Consortium (ARC) for the Participating Institutions. The Participating Institutions are The University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Korean Scientist Group, Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

Funding for the Asteroid Institute program is provided by B612 Foundation, the W.K. Bowes Jr. Foundation, the P. Rawls Family Fund, and two anonymous donors in addition to general support from the B612 Founding Circle (K. Algeri-Wong, B. Anders, G. Baehr, B. Burton, A. Carlson, D. Carlson, Bolin et al.
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