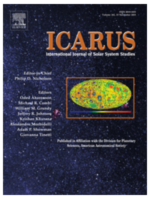
Icarus 297 (2017) 126–133

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus



The fast spin of near-Earth asteroid (455213) 2001 OE84, revisited after 14 years: Constraints on internal structure

D. Polishook[a,*], N. Moskovitz[b], A. Thirouin[b], A. Bosh[c], S. Levine[b], C. Zuluaga[c], S.C. Tegler[d], O. Aharonson[a]

[a] *Department of Earth and Planetary Sciences, Weizmann Institute of Science, Rehovot 0076100, Israel*
[b] *Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001, USA*
[c] *Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA*
[d] *Department of Physics and Astronomy, Northern Arizona University, Flagstaff, AZ, 86011, USA*

ARTICLE INFO

Article history:
Received 6 February 2017
Revised 22 June 2017
Accepted 29 June 2017
Available online 30 June 2017

Keywords:
Asteroids
Near-Earth asteroids
Asteroids rotation
Rotational dynamics
Photometry

ABSTRACT

At a mean diameter of ~650 m, the near-Earth asteroid (455213) *2001 OE84* (*OE84* for short) has a rapid rotation period of 0.486542 ± 0.000002 h, which is uncommon for asteroids larger than ~200 m. We revisited *OE84* 14 years after it was first, and last, observed by Pravec et al. (2002) in order to measure again its spin rate and to search for changes. We have confirmed the rapid rotation and, by fitting the photometric data from 2001 and 2016 using the lightcurve inversion technique, we determined a retrograde sense of rotation, with the spin axis close to the ecliptic south pole; an oblate shape model of $a/b = 1.32 \pm 0.04$ and $b/c = 1.8 \pm 0.2$; and no change in spin rate between 2001 and 2016. Using these parameters we constrained the body's internal strength, and found that current estimations of asteroid cohesion (up to ~80 Pa) are insufficient to maintain an intact rubble pile at the measured spin rate of *OE84*. Therefore, we argue that a monolithic asteroid, that can rotate at the rate of *OE84* without shedding mass and without slowing down its spin rate, is the most plausible for *OE84*, and we give constraints on its age, since the time it was liberated from its parent body, between 2 – 10 million years.

1. Introduction

The near-Earth asteroid (NEA) (455213) *2001 OE84* (*OE84* for short) has been known for more than fifteen years as a unique object that "defies" the spin rate barrier - the threshold at which asteroids larger than ~200 m are not observed to rotate faster (Fig. 1). This spin barrier suggests that most, if not all, asteroids larger than ~200 m and up to tens of kilometers, are rubble piles - conglomerates of rocks held together only by the weak force of their self gravity (*e.g.*, Harris, 1996; Richardson et al., 1998). In this paradigm, small asteroids ($D \lesssim 200$ m) with spin rates faster than the spin barrier have strong internal structures with significant internal tensile strength.

Even though a few large asteroids (with $D > 200$ m) have been found to rotate faster than the spin barrier at ~2 h (Chang et al., 2014; Chang et al., 2015; Chang et al., 2017; Naidu, 2015; Polishook et al., 2016), none is as fast as the 0.5 h rotation period of *OE84*. Pravec et al. (2002) measured its lightcurve in October through December of 2001 with sufficiently high signal to noise to unambiguously determine the anomalously high rotation rate. Furthermore, a 4-peaked lightcurve with twice the period is impossible due to a high measured amplitude of ~0.6 mag (Harris et al., 2014). Pravec et al. (2002) measured *OE84*'s reflectance spectrum and found it matches an S-type taxonomy. Therefore, they estimated an albedo of 0.18, which combined with an absolute magnitude $H_v = 18.31 \pm 0.16$, suggest an effective diameter of 0.7 km.

The unique position of *OE84* on the diameter-spin plane (Fig. 1), can be explained by one of the two following physical models:

1. *OE84* could have a rubble pile structure with sufficient internal cohesion between its components to resist centrifugal disruption. A leading theory (Scheeres et al., 2010) suggests that sub-millimeter-sized gravel has enough cohesion due to week van der Waals forces to act as a glue between meter-sized and larger boulders. Holsapple (2007) used the Drucker-Prager yield criterion, a pressure-dependent metric for determining whether a material has failed or deformed, to show that with enough cohesion, objects smaller than ~200 m can rotate rapidly without being considered monolithic, while larger bodies ($D \gtrsim 10$ km) will still break up at the *rubble pile spin barrier*, regardless of their cohesion. Since this yield criterion is size dependent, objects in an intermediate size range (~200 m to ~10 km) can rotate faster, in principal, than

---

[*] Corresponding author.
E-mail address: david.polishook@weizmann.ac.il (D. Polishook).

http://dx.doi.org/10.1016/j.icarus.2017.06.036
0019-1035/

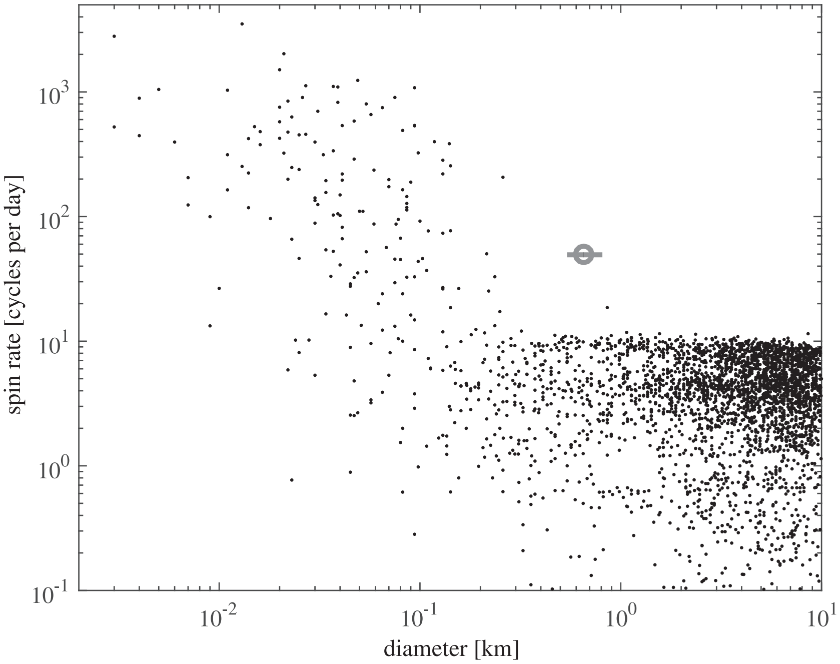


Fig. 1. Asteroid diameters *vs*. spin rates (black dots). *OE84* is marked with a grey circle. The uncertainty on the diameter is marked by the grey horizontal line. The uncertainty of the spin rate is too small to see on this scale. The asteroid data is from the lightcurve database (Warner et al., 2009). The *spin rate barrier* at about 10 cycles per day for asteroids larger than ~200 m is easily noticed.

the currently observed spin barrier ($P \lesssim 2$ h). However, this cohesion model cannot explain why there are so few intermediate-sized asteroids beyond the spin barrier (Fig. 1). Since the uniqueness of *OE84* could arise from unusual internal cohesion, we derived the asteroid shape model to constrain the three physical axis of the geoid, A, B and C (where $A \geq B \geq C$), and thus inform the minimal cohesion needed to keep *OE84* bound.

2. *OE84* could be a large monolithic body with non-zero tensile strength (Pravec et al., 2002). In this case, *OE84* is at least 10–30 times larger in volume than any other presumed monolithic body. Such a scenario would be possible if *OE84* were a fragment of a much larger, intact body ($>$ 100 km) that was destroyed by a catastrophic collision. However this requires an explanation of how such a structure has remained intact while presumably other similarly sized collisional fragments have been further disrupted into smaller pieces.

Below we discuss our observations, performed 14 years and 3 months after the observations presented by Pravec et al. (2002). This is followed by analysis of the spin state and a discussion regarding the internal structure of *OE84*.

2. Observations and measurements

Observations were conducted over four nights on Lowell Observatory's 4.3 m Discovery Channel Telescope (DCT) between January 19, and March 12, 2016, in excellent photometric conditions. Data from one additional night (Feb 22, 2016) was omitted from our analysis due to low signal-to-noise in the resulting photometry, primarily due to proximity of the full moon. We employed the Large Monolithic Imager (LMI, 6k × 6k pixels) with 3× 3 binning and a field of view of $12.5' \times 12.5'$ (Levine et al., 2012). In order to maximize the signal to noise we used a wide-band *VR* filter, roughly equivalent to the combined *Johnson V* and *Cousins R* filters. Guiding the telescope at sidereal rates allowed the asteroid to stay within a single field for each observing night. Over our two months of observations, the visible magnitude of *OE84* ranged from 20.5 to 21.2. Observational circumstances are summarized in Table 1.

Reduction followed standard procedures such as subtracting bias and dividing by a normalized and combined image of dome and twilight flat fields. Aperture photometry was performed with an aperture radius equal to 4 times the measured seeing (typically $\sim 1''$) and calibration of differential magnitude was achieved using hundreds of local comparison stars. Only comparison stars with $<$ 0.02 mag variation were used for calibration. The photometry was corrected to unity of geo- and heliocentric distances and the data were corrected by light-travel time using values for the orbital geometry from the JPL Horizons website.[1] This reduction procedure is described in more detail in Polishook and Brosch (2009). In addition, we calibrated the instrumental magnitudes of field stars against the PanSTARRS catalog (Flewelling et al., 2016) assuming we were using the *SDSS r* filter. This calibration generally included ~100 field stars per image and was achieved using an automated photometry pipeline (Mommert, 2017). The net precision of this calibration (combined uncertainty in zero point and photon noise in the source photometry) was generally $<$ 0.05 magnitudes. This precision does not reflect uncertainty in the transform from our *VR* filter to *SDSS r*. However, this calibration did allow us to place the measured photometry on a single magnitude scale.

3. Albedo and size estimation

The decrease in brightness as a function of the phase angle correlates with the asteroid's taxonomy and albedo (Belskaya and Shevchenko, 2000). We used the mid-peak value of the lightcurves in each night, corrected to unity of geo- and heliocentric distances, to derive the phase curve and to match a linear fit to it. The fit has a slope of 0.026 ± 0.004 mag/deg, consistent with the S-type taxonomy (Fig. 4 at Belskaya and Shevchenko (2000)). Since there is nothing suggesting *OE84* is any different from a typical S-type we adopt an albedo of 0.197 ± 0.051 which is statistically derived from WISE spacecraft data (Pravec et al., 2012). New data would be required to know the actual albedo value.

---

[1] http://ssd.jpl.nasa.gov/horizons.cgi.