Icarus 233 (2014) 48–60

Contents lists available at ScienceDirect

Icarus

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

The tumbling spin state of (99942) Apophis

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ARTICLE INFO

Article history:
Received 26 November 2013
Revised 23 January 2014
Accepted 24 January 2014
Available online 1 February 2014

Keywords:
Photometry
Asteroids, rotation
Asteroids, dynamics

ABSTRACT

Our photometric observations of Asteroid (99942) Apophis from December 2012 to April 2013 revealed it to be in a state of non-principal axis rotation (tumbling). We constructed its spin and shape model and found that it is in a moderately excited Short Axis Mode (SAM) state with a ratio of the rotational kinetic energy to the basic spin state energy $E/E_0 = 1.024 \pm 0.013$. (All quoted uncertainties correspond to 3σ.) The greatest and intermediate principal moments of inertia are nearly the same with $I_2/I_3 = 0.965^{+0.009}_{-0.015}$, but the smallest principal moment of inertia is substantially lower with $I_1/I_3 = 0.61^{+0.11}_{-0.08}$; the asteroid's dynamically equivalent ellipsoid is close to a prolate ellipsoid. The precession and rotation periods are $P_\phi = 27.38 \pm 0.07$ h and $P_\psi = 263 \pm 6$ h, respectively; the strongest observed lightcurve amplitude for the SAM case is in the 2nd harmonic of $P_1 = \left(P_\phi^{-1} - P_\psi^{-1}\right)^{-1} = 30.56 \pm 0.01$ h. The rotation is retrograde with the angular momentum vector's ecliptic longitude and latitude of 250° and −75° (the uncertainty area is approximately an ellipse with the major and minor semiaxes of 27° and 14°, respectively). An implication of the retrograde rotation is a somewhat increased probability of the Apophis' impact in 2068, but it is still very small with the risk level on the Palermo Scale remaining well below zero. Apophis is a member of the population of slowly tumbling asteroids. Applying the theory of asteroid nutational damping by Breiter et al. (Breiter, S., Rożek, A., Vokrouhlický, D. [2012]. Mon. Not. R. Astron. Soc. 427, 755–769), we found that slowly tumbling asteroids predominate in the spin rate–size range where their estimated damping times are greater than about 0.2 Gyr. The appearance that the PA/NPA rotators transition line seems to follow a line of constant damping time may be because there are two or more asteroid spin evolution mechanisms in play, or the factor of μQ (the elastic modulus times the quality factor) is not constant but it may decrease with decreasing asteroid size, which would oppose the trend due to decreasing collisional age or excitation time.

1. Introduction

Aten-type Asteroid (99942) Apophis was discovered by R.A. Tucker, D.J. Tholen and F. Bernardi at Kitt Peak, Arizona on June 19, 2004. After rediscovery by G.J. Garradd at Siding Springs, Australia in December 2004 it was recognized as a potentially hazardous asteroid with a significant Earth impact probability in April 2029. Arecibo radar observations in January 2005, August 2005 and May 2006 significantly reduced Apophis' orbital uncertainty and ruled out the 2029 impact (the minimum nominal distance from the geocenter in 2029 was computed to be 6 Earth radii), but other potential impacts in following decades were revealed. As the very close approach distance in 2029 turns a well determined pre-2029 orbit to a poorly estimated post-2029 orbit, even small perturbations prior to 2029 play a significant role. (See Farnocchia et al., 2013, for details and references on the progress in astrometric observations and orbit computations during 2004–2006.)

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http://dx.doi.org/10.1016/j.icarus.2014.01.026
0019-1035/

Chesley (2006), Giorgini et al. (2008) and Chesley et al. (2009) showed that the Yarkovsky effect (Bottke et al., 2006) significantly affects post-2029 predictions and they took it into account for Apophis impact predictions. Farnocchia et al. (2013) did a careful orbital analysis using selected best astrometric and radar data covering the interval 2004 March 15 to 2012 December 29 and quantified a sensitivity of predictions of the Earth impacts between 2060 and 2105 on physical parameters of the asteroid (diameter, albedo, density, thermal inertia, rotation period, and obliquity) that determine the rate of Yarkovsky drift of Apophis' semimajor axis. They estimated an impact probability greater than 10^{-6} for an impact in 2068. They also showed that further optical astrometric and radar observations will likely significantly constrain the Yarkovsky drift in late 2020 or 2021.

To put this formal detection in its true context, one must model the Yarkovsky accelerations as accurately as possible. A starting, and presently the most fundamental, step toward this analysis is to understand the rotation state of Apophis. This is because the sense of Apophis' rotation has been shown to be a critical element in predicting its possible future impacts. It would also allow to obtain an estimate of the asteroid's bulk density, which is a very important parameter as far as the potential impact hazard is concerned.

Raoul Behrend and his collaborators[1] took lightcurve observations during 2005 January 5 to February 1 and, assuming a principal axis (PA) rotation, estimated its spin period of 30.4 h. Their formal error of 0.014 h is underestimated as they did not account for all uncertainty sources, and especially not for a possible systematic error due to the assumption of PA rotation. The data blocks from different nights were on different (relative) magnitude scales and Behrend et al. applied offsets in their zero points for the fit; this approach would not allow them to reveal a potential non-principal axis rotation unless it had a high amplitude in other than the main period.

Asteroids of sizes and spin rates similar to Apophis are often found to be in non-principal axis ("tumbling") rotation states. This is not surprising, considering their estimated damping times are comparable to or longer than the age of the solar system (Burns and Safronov, 1973; Harris, 1994; Pravec et al., 2005). After excitation (e.g., by a sub-catastrophic collision; Henych and Pravec, 2013), their rotation would not be damped down to pure spin due to the energy dissipation from a stress–strain cycling within the tumbling body, as long as the rotation remains slow.

The spin state of Apophis can be described with the technique of lightcurve photometry. However, a huge amount of telescopic observing time is needed to get photometric data necessary to describe the spin state of a slow tumbling asteroid. To accomplish the task, it is needed to cover the long period multiple times (though the sampling rate may be relatively sparse). The large volume of photometric observations required could only realistically be obtained using small telescopes, thus requiring a favorable apparition with the asteroid bright enough and at sufficient elongation from the Sun. Apophis had such a favorable apparition from December 2012 to April 2013 when it could be observed with telescopes with sizes as small as 0.35–1.5 m. An additional requirement for description of tumbling was that the observations must be calibrated in a consistent magnitude system throughout the apparition. We collected such data through a collaborative campaign described in Section 2. Our analysis of the photometric data revealed that Apophis is indeed in a non-principal axis (NPA) rotation state (Section 3). We performed a physical modeling of the NPA rotation that we present in Section 4. In Section 5, we put Apophis in the context of the population of slowly tumbling asteroids.

[1] http://obswww.unige.ch/~behrend/page_cou.html.

2. Photometric observations

We took photometric observations of Apophis with the 1.54-m Danish telescope on La Silla (35 nights), the 0.41-m PROMPT 1 telescope on Cerro Tololo (30 nights), the 0.6-m TRAPPIST telescope on La Silla (4 nights), the 1-m telescope on Pic du Midi (3 nights), the 0.35-m telescope on Leura (3 nights), and the 0.65-m telescope in Ondřejov (1 night). Only good quality data that were calibrated in a consistent magnitude system were included in the dataset. The individual runs and their observational circumstances are listed in Table 1. The mid-time (UTC) of the run, rounded to the nearest tenths of day, is given in the first column. The asteroid's apparent right ascension and declination (equinox J2000.0) are given in the 2nd and 3rd column. In the next three columns, its geo- and heliocentric distances and solar phase angle are given. The telescope used is given in the last column.

The observations with the 1.54-m Danish telescope were taken with the Bessell R filter, with supplementary observations in the V filter on 2013 January 9, and they were calibrated in the Johnson–Cousins system using Landolt (1992) standard stars. Integration times were between 30 and 120 s and the telescope was tracked at half-apparent rate of the asteroid, providing star and asteroid images of the same profile in one frame. For the Apophis' long period, we did not need to take continuous observations but we took a short series of typically five images once per hour or so, depending also on scheduling constraints of our other asteroid observations we ran on the nights; we worked Apophis as a secondary target on most of the 35 nights. We processed and reduced the data with our photometric reduction software package *Aphot32*.

The University of North Carolina at Chapel Hill's PROMPT observatory (Panchromatic Robotic Optical Monitoring and Polarimetry Telescopes) on Cerro Tololo consists of six 0.41-m telescopes outfitted with Alta U47 + cameras by Apogee, which make use of E2V CCDs. The field of view is $10' \times 10'$ with 0.59 arcsec/pixel. All raw image frames were processed (master dark, master flat, bad pixel correction) using the software package MIRA. Aperture photometry was then performed on the asteroid and three comparison stars. A master image frame was created to identify any faint stars in the path of the asteroid. Data from images with background contamination stars in the asteroid's path were then eliminated. The observations were done with Lum (IR block) filter and they were mutually linked in an instrumental magnitude system with an internal consistency of 0.02–0.03 mag.

The robotic 0.6-m telescope TRAPPIST (TRAnsiting Planets and PlanetesImals Small Telescope; Jehin et al., 2011) is located at ESO La Silla Observatory. Several image series with duration between 10 and 30 min were acquired each night. The camera is a FLI ProLine PL3041-BB with 2 k $\times$ 2 k pixels of 15 μm. It was used with a special exoplanet filter (blue cut at 450 nm) and in the binning 2 mode, resulting in a pixel scale of 1.3 arcsec and a field of view of 22 arcmin. The telescope was tracking the asteroid. All the fields crossed by the asteroid were observed again on a photometric night in order to provide the best calibration. The obtained internal consistency is around 0.02 mag. The Exo magnitudes were converted to R band magnitude using TRAPPIST internal calibration system based on the regular observations of standard fields.

The observations with the 1-m telescope on Pic du Midi were performed with a sloan DSS, r' filter and a CCD 2 V 2 k $\times$ 2 k.

The observations with the 0.35-m telescope on Leura Observatory were taken and reduced using procedures described in Oey (2010). They were done in Clear filter and calibrated using solar colored comparison stars and Rc magnitudes derived from 2MASS catalog with internal consistency of 0.02–0.03 mag (Warner, 2007).

The Ondřejov 0.65-m observations were taken and reduced using procedures described in Pravec et al. (2006).