# Apophis Observational Opportunities from Now till the 2029 April 13 Close Approach, to Improve Solution for Its Spin State

Petr Pravec[1] and Josef Ďurech[2]

[1] Astronomical Institute AS CR, Ondřejov, Czech Republic
[2] Astronomical Institute of the Charles University, Prague, Czech Republic

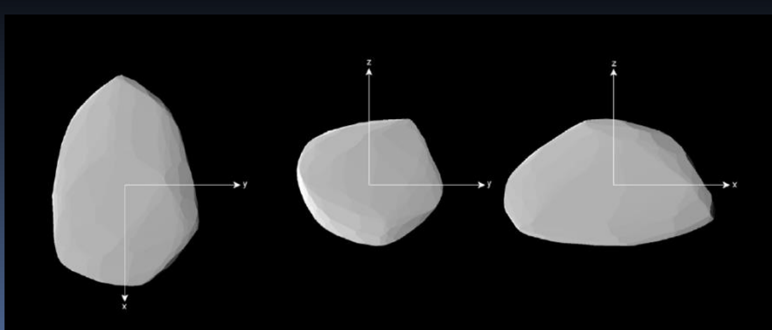
*Apophis T-5 Years meeting*
*ESTEC, Noordwijk, Netherlands*
*2024 April 22*

# Apophis spin and shape modeling

Apophis – a slow rotating asteroid in non-principal axis spin state.

Its rotation and precession frequencies, and some their linear combinations are low – data spanning long intervals (many nights) needed to construct its spin and shape model.

The lightcurve data taken from 2012-12-23 to 2013-04-15 (55 nights) → the first spin and convex-shape model (Pravec et al. 2014). The radar data taken from 2012-12-22 to 2013-02-20 (11 nights) → a similar shape model, and suggested possible bifurcation (Brozovic et al. 2018).



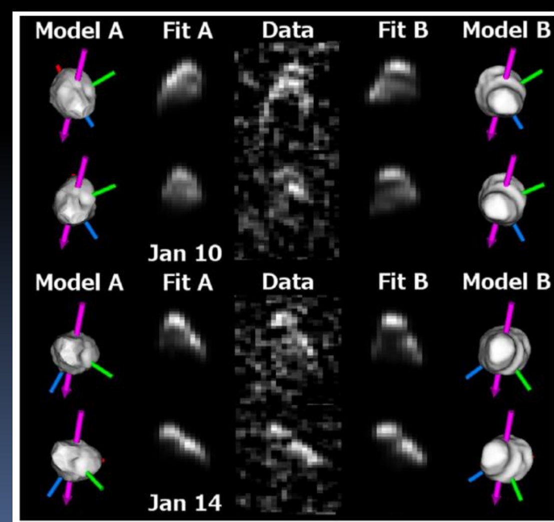
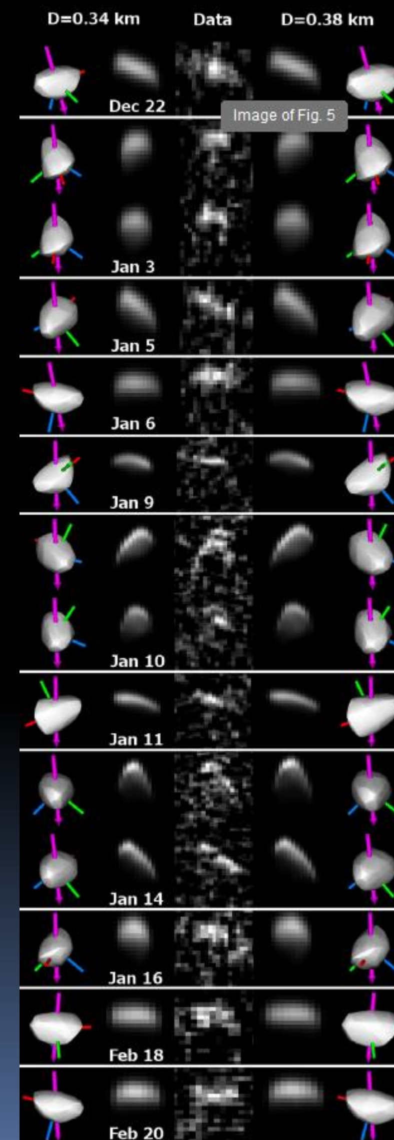



**Fig. 6.** Data, fits, and 3D models for two vertex models that are bifurcated. Collage




References: Pravec et al. (2014) Icarus 233, 48-60; Brozovic et al. (2018) Icarus 300, 115-128

# Apophis lightcurve characteristics (1)

Three main frequencies:

$27.38^{-1}$, $30.56^{-1}$ and $263^{-1}$ $h^{-1}$.

(The first and the last are $P_\phi^{-1}$ and $P_\psi^{-1}$ in the Kaasalainen 2001 convention.)

The long $P_\psi$ is because Apophis is dynamically not far from a prolate spheroid: $b_{dyn}/c_{dyn}$ = 1.06

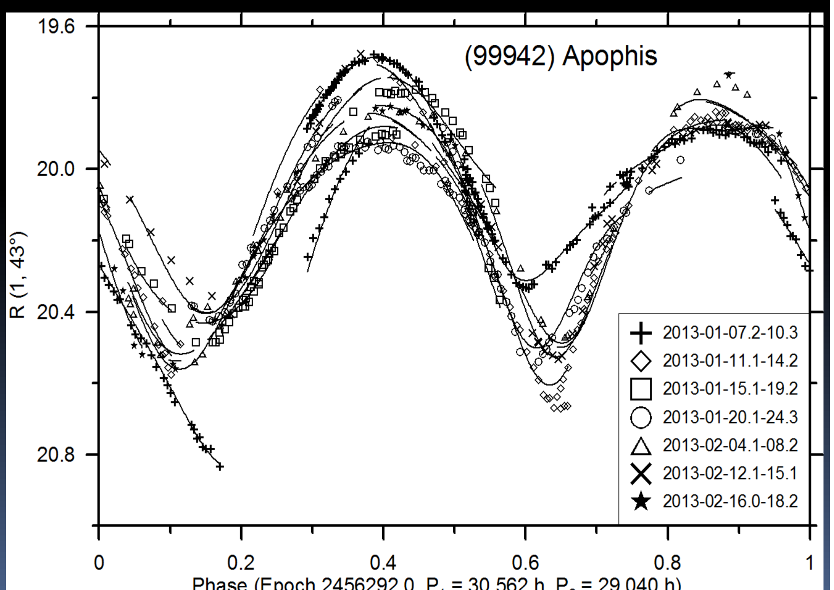



**Table 2**
Parameters of the Apophis model with their estimated admissible uncertainties (corresponding to $3\sigma$ confidence level).

| | |
|---|---|
| *Fitted parameters* | |
| $\lambda_L$ (°) | $250$[a] |
| $\beta_L$ (°) | $-75$ |
| $\phi_0$ (°) | $152^{+173}_{-64}$ |
| $\psi_0$ (°) | $14^{+44}_{-11}$ |
| $P_\psi$ (h) | $263 \pm 6$ |
| $P_\phi$ (h) | $27.38 \pm 0.07$ |
| $I_a \equiv I_1/I_3$ | $0.61^{+0.11}_{-0.08}$ |
| $I_b \equiv I_2/I_3$ | $0.965^{+0.009}_{-0.015}$ |
| *Derived parameters* | |
| $\left(P_\phi^{-1} - P_\psi^{-1}\right)^{-1} = P_1$ (h) | $30.56 \pm 0.01$ |
| $\theta_{min}$ (°) | $12 \pm 4$ |
| $\theta_{max}$ (°) | $55^{+9}_{-20}$ |
| $\theta_{aver}$ (°) | $37^{+6}_{-14}$ |
| $a_{dyn}/c_{dyn}$ | $1.51 \pm 0.18$ |
| $b_{dyn}/c_{dyn}$ | $1.06 \pm 0.02$ |
| $a_{shp}/c_{shp}$ | $1.64 \pm 0.09$ |
| $b_{shp}/c_{shp}$ | $1.14^{+0.04}_{-0.08}$ |
| $E/E_0$ | $1.024 \pm 0.013$ |

The angles $\phi_0$ and $\psi_0$ are for the epoch JD 2456284.676388 (=2012 December 23.176388 UT), light-travel time corrected (i.e., asterocentric).
$E/E_0$ is a ratio of the rotational kinetic energy and the lowest energy for given angular momentum, defined as $E_0 = L^2/(2I_3)$.
[a] The major and minor semiaxes of the uncertainty area of the direction of $\vec{L}$ are 27° and 14°, respectively, see Fig. 4.

Reference: Pravec et al. (2014) Icarus 233, 48-60

# Apophis lightcurve characteristics (2)

Significant harmonics in Apophis's lightcurve up to the 3rd order.

The highest frequency: (3*27.38$^{-1}$ + 3*30.56$^{-1}$) = 4.81$^{-1}$ h$^{-1}$.

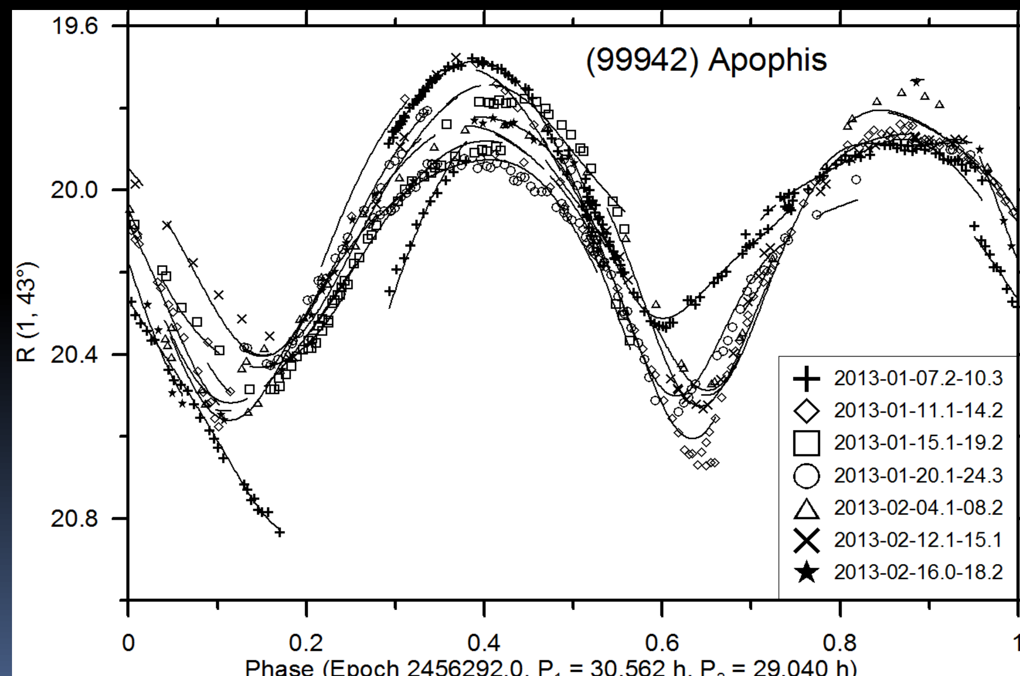
Need to observe Apophis's lightcurve with a sampling of ~2 hours. A denser sampling does not provide a significant additional information.

$$F(\psi,\phi) = C_0 + \sum_{j=1}^{\infty}[C_{j0}\cos j\psi + S_{j0}\sin j\psi]$$
$$+ \sum_{k=1}^{\infty}\sum_{j=-\infty}^{\infty}[C_{jk}\cos(j\psi + k\phi)$$
$$+ S_{jk}\sin(j\psi + k\phi)],$$

where

$$C_0 = a_{00}, \qquad C_{j0} = a_{j0}, \qquad S_{j0} = b_{j0},$$
$$C_{0k} = a_{0k}, \qquad S_{0k} = c_{0k},$$
$$C_{\pm j,k} = \frac{a_{jk} \pm d_{jk}}{2}, \qquad S_{\pm j,k} = \frac{c_{jk} \pm b_{jk}}{2},$$

for $j, k > 0$.




References: Pravec et al. (2005) Icarus 173, 108-131; Pravec et al. (2014) Icarus 233, 48-60

# Apophis LC observations – requirements

To construct a good model for Apophis's spin and shape (in one apparition), we need lightcurve observations with

- Coverage: Tens of nights over an interval of several weeks (a few times $P_\psi$)
- Cadence: One (normal) photometric data point per 2 hours
- Photometric accuracy of each normal photometric data point: 0.03 mag

Limited data sets, covering shorter time intervals, will be useful in combination with data from other years (in a joint modeling using data from many years).

To get the needed long coverage, a collaboration of several telescopes needed.

Key for the success: Consistent calibrations of the data taken from different telescopes on many nights (to get an internally consistent, homogeneous dataset).

The relatively sparse sampling (1 data point per 2 hours) makes the Apophis observations suitable as a supplementary program to other (semi/quasi-continuous) observing programs at suitable telescopes.

# Apophis observational windows

Photometric observations possible in three observational windows (before the 2029 April 13 close approach):

- 2027 February-April
- 2027 December-2028 June
- 2028 October-2029 April 13

Taking data in each of the three observational windows will be probably needed to get a unique model for Apophis over all the years 2012-2029. (See the previous talk by J. Ďurech.)

Table 1: Observational windows for Apophis

| Date of Max.El. | Max.El. (°) | Sol.Ph. (°) | V (mag) | App.Dur. (days) |
|---|---|---|---|---|
| 2025-05-23 | 19 | 19 | 21.4 | 0 |
| 2026-04-18 | 39 | 38 | 21.6 | 0 |
| 2027-03-17 | 61 | 53-60 | 21.1-21.5 | -24/+27 |
| 2028-02-14 | 90 | 65-100 | 19.2-20.7 | -70/+137 |
| 2029-04-13 | 167 | 13-98 | 3.2-20.1 | -170/+0 |

Note: Apparition Duration and the ranges of Solar Phase and V magnitude (from MPC) are given for intervals with Solar Elongation > 60°.

# The 2027 February-April window

Apophis observable with large (4+m) northern-hemisphere telescopes in the evening sky.

Each telescope may take only 1 or 2 normal data points on one night → observations from a few telescopes spread in longitude on a number of nights (in evening hours) needed.

However sparse and limited the obtained data may be, it probably will be critical data for getting a unique spin and shape model for Apophis in a joint modeling of the whole data set 2012-2029.

Table 1: Observational windows for Apophis

| Date of Max.El. | Max.El. (º) | Sol.Ph. (º) | V (mag) | App.Dur. (days) |
|---|---|---|---|---|
| 2025-05-23 | 19 | 19 | 21.4 | 0 |
| 2026-04-18 | 39 | 38 | 21.6 | 0 |
| 2027-03-17 | 61 | 53-60 | 21.1-21.5 | -24/+27 |
| 2028-02-14 | 90 | 65-100 | 19.2-20.7 | -70/+137 |
| 2029-04-13 | 167 | 13-98 | 3.2-20.1 | -170/+0 |

Note: Apparition Duration and the ranges of Solar Phase and V magnitude (from MPC) are given for intervals with Solar Elongation > 60º.

# The 2027 December-2028 June window

Observations with medium sized (2-4m) telescopes in both hemispheres needed.

One telescope can observe Apophis for only a ~couple hours in the evening sky, but observations spread over the 7 months would provide data for checking stability of the spin and shape solution.

Though a single telescope may take only 1 or 2 normal data points on one night, a coordinated photometric campaign involving a few telescopes spread in longitude would provide sufficient coverage for solving Apophis's spin and shape model.

Taking data at the extremely high solar phases (100°) in December 2027 may be important for successful modeling (for the possible concavities of Apophis's figure).

Table 1: Observational windows for Apophis

| Date of Max.El. | Max.El. (º) | Sol.Ph. (º) | V (mag) | App.Dur. (days) |
|---|---|---|---|---|
| 2025-05-23 | 19 | 19 | 21.4 | 0 |
| 2026-04-18 | 39 | 38 | 21.6 | 0 |
| 2027-03-17 | 61 | 53-60 | 21.1-21.5 | -24/+27 |
| 2028-02-14 | 90 | 65-100 | 19.2-20.7 | -70/+137 |
| 2029-04-13 | 167 | 13-98 | 3.2-20.1 | -170/+0 |

Note: Apparition Duration and the ranges of Solar Phase and V magnitude (from MPC) are given for intervals with Solar Elongation > 60º.

# The 2028 October-2029 April 13 window

Medium sized (2-4m) northern hemisphere telescopes needed at the beginning of the apparition.

Since January 2029 Apophis will be bright enough for photometry with small (1-m class) telescopes (preferably in the southern hemisphere for the negative declinations of Apophis).

A thorough coordinated campaign will provide rich data for getting a final spin and shape model for Apophis.

Taking data at the extremely high solar phases (98°) in October 2028 may be important for successful modeling (for the possible concavities of Apophis's figure).

Table 1: Observational windows for Apophis

| Date of Max.El. | Max.El. (°) | Sol.Ph. (°) | V (mag) | App.Dur. (days) |
|---|---|---|---|---|
| 2025-05-23 | 19 | 19 | 21.4 | 0 |
| 2026-04-18 | 39 | 38 | 21.6 | 0 |
| 2027-03-17 | 61 | 53-60 | 21.1-21.5 | -24/+27 |
| 2028-02-14 | 90 | 65-100 | 19.2-20.7 | -70/+137 |
| 2029-04-13 | 167 | 13-98 | 3.2-20.1 | -170/+0 |

Note: Apparition Duration and the ranges of Solar Phase and V magnitude (from MPC) are given for intervals with Solar Elongation > 60°.

# Conclusions

A dedicated Apophis photometry campaign in the three observational windows in 2027-2029 needed to produce lightcurve data that we will use for a joint modeling with the 2012-2021 data.

There will be certain challenges: The need to use a number of telescopes of various sizes over many nights (but with a relatively low cadence, providing a relatively sparse sampling) and with consistent calibrations so that we get a homogeneous dataset.

With such data, we will get a unique spin and shape model for Apophis and check its long-term stability.