Reconstruction of the shape and spin state of asteroid (99942) Apophis from its photometric light curves

Josef Ďurech[1], David Vokrouhlický[1], Petr Pravec[2], Kamil Hornoch[2], Peter Kušnirák[2], Petr Fatka[2], and Hana Kučaková[2]

[1]Charles University, Prague, Czech Republic
[2]Astronomical Institute, Academy of Sciences, Czech Republic

durech@sirrah.troja.mff.cuni.cz

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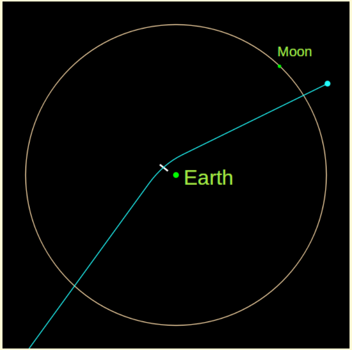
Asteroid (99942) Apophis

- near-Earth potentially hazardous asteroid
- size about 400 m
- close approaches with the Earth in 2029, 2036, 2066...
- excited rotation – tumbling rotation state described by precession and rotation periods: $P_\phi = 27.4\,\mathrm{h}$, $P_\psi = 263\,\mathrm{h}$ – mean periodicity of ~ 30 hr in light curves
- orbit influenced by nongravitational Yarkovsky force (detected by Tholen and Farnocchia, 2020), depends on the spin state

Close encounter with the Earth in 2029

- Close approach to Earth in 2029; the minimum geocentric distance $\sim 38,000\,\mathrm{km}$.
- During the approach, the spin state of Apophis is expected to be altered by Earth's gravitation torque. The exact change depends on the orientation of Apophis during the close approach.
- To predict the post-encounter orbit and impact probabilities in 2036, 2066, Yarkovsky effect has to be taken into account. It depends on the spin state that will be altered during the fly-by. The way it is altered depends on the Apophis' orientation during the fly-by.
- Although the shape and spin-state model of Apophis was reconstructed from 2012/13 photometric observations by Pravec et al. (2014) and from radar observations by Brozovic et al. (2018), the precision of rotation parameters they derived was not sufficient to predict the orientation for 2029.

13.4.2029



New photometric observations

- The long interval of observations 2012-2021 should enable us to precisely determine the rotation and precession periods and thus reliably predict the orientation of Apophis during its 2029 flyby, calculate the change of its spin state, and predict how the Yarkovsky effect will influence the post-encounter orbit of Apophis, which is crucial for its post-2029 impact predictions.
- We carried out photometric observations of Apophis from 2020-11-16 to 2021-05-06 (171 days) with the 1.54-m Danish telescope at La Silla.
- It total, we covered 67 individual nights, 1280 photometric points calibrated in R Cousins filter, 24–100 deg in phase angle.

- Other data photometric data from 2021 compiled in Lee et al. (2022).

Shape and spin reconstruction with light curve inversion

- By applying the light curve inversion technique of Kaasalainen (2001), we reconstructed the spin state and shape of Apophis.
- New model agrees with the one reconstructed by Pravec et al. (2014) and with an updated model published by Lee et al. (2022)
- We aimed to invert both the 2012-2013 and 2020-2021 data together and reconstruct the Apophis spin state with high precision. However – fitting the data sets separately provides a significantly better fit than joined fit, slightly different parameters.

The time evolution of the Euler angles ϕ, θ, ψ is easy to derive from the basic kinematic equations (see, e.g., Goldstein 1980) that can be written as

$$\begin{aligned} \frac{L_1}{I_1} &= \dot\phi \sin\theta \sin\psi + \dot\theta \cos\psi, \\ \frac{L_2}{I_2} &= \dot\phi \sin\theta \cos\psi - \dot\theta \sin\psi, \\ \frac{L_3}{I_3} &= \dot\phi \cos\theta + \dot\psi, \end{aligned} \tag{A.1}$$

where L_i are the projections of the angular momentum vector $\boldsymbol{L}$ onto the principal axes of the tumbling inertia ellipsoid; $\boldsymbol{L}$ is constant in an inertial frame in torque-free precession. The components L_i are, by the definition of the Euler angles,

$$(L_1, L_2, L_3) = (L \sin\theta \sin\psi, L \sin\theta \cos\psi, L \cos\theta). \tag{A.2}$$

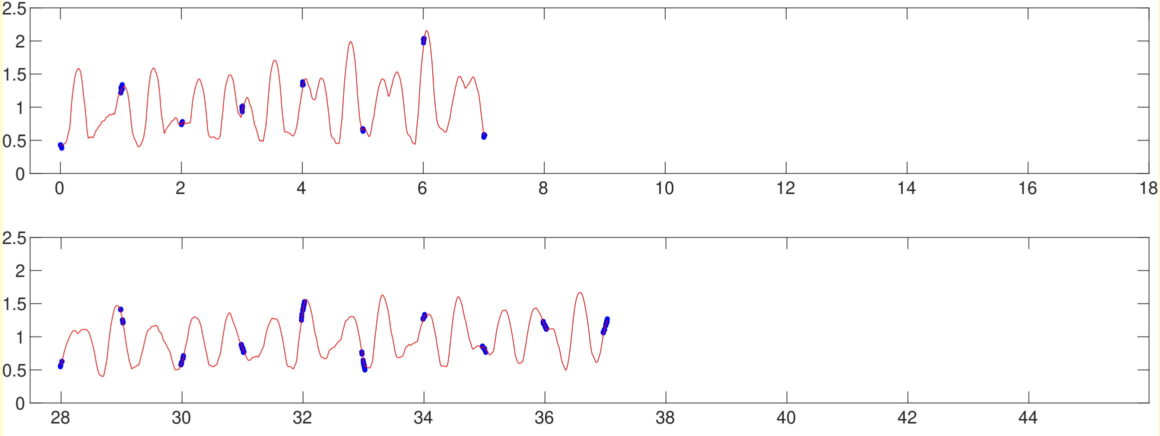
Combining the two sets of equations, we get

$$\begin{aligned} \dot\phi &= L(I_+ - I_- \cos 2\psi), \\ \dot\theta &= L\, I_- \sin\theta \sin 2\psi, \\ \dot\psi &= \cos\theta \left(\frac{L}{I_3} - \dot\phi \right), \end{aligned} \tag{A.3}$$

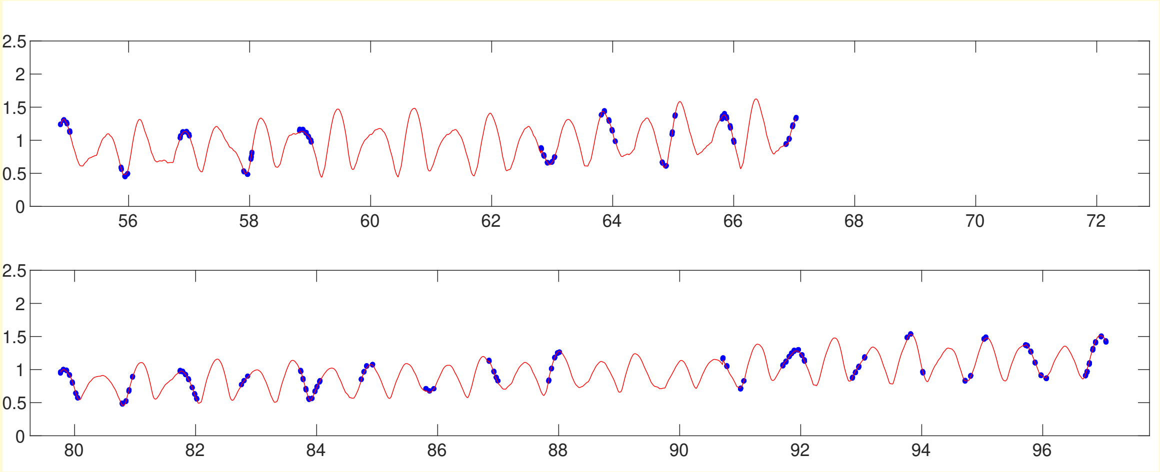
where $I_+ = \frac{1}{2}(I_1^{-1} + I_2^{-1})$ and $I_- = \frac{1}{2}(I_1^{-1} - I_2^{-1})$. The

Kaasalainen (2001)

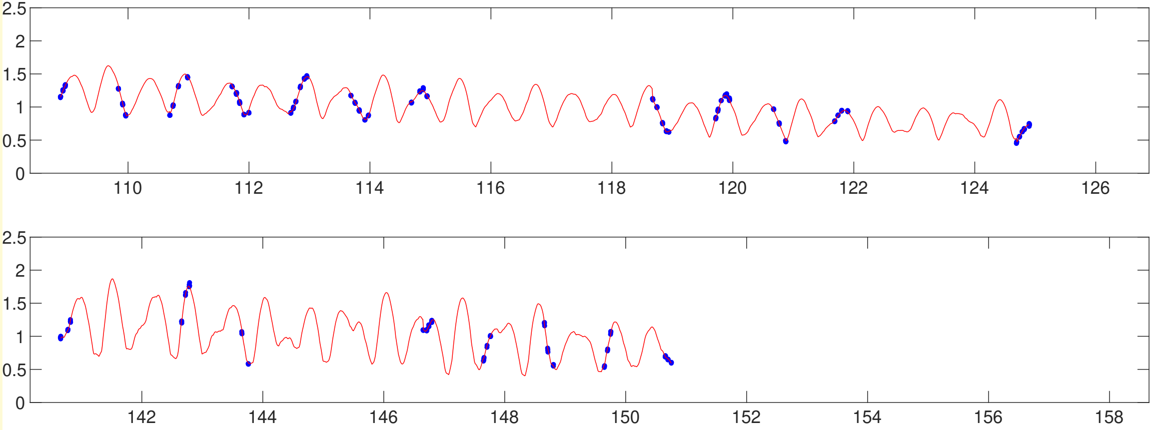
Our 2020/21 data



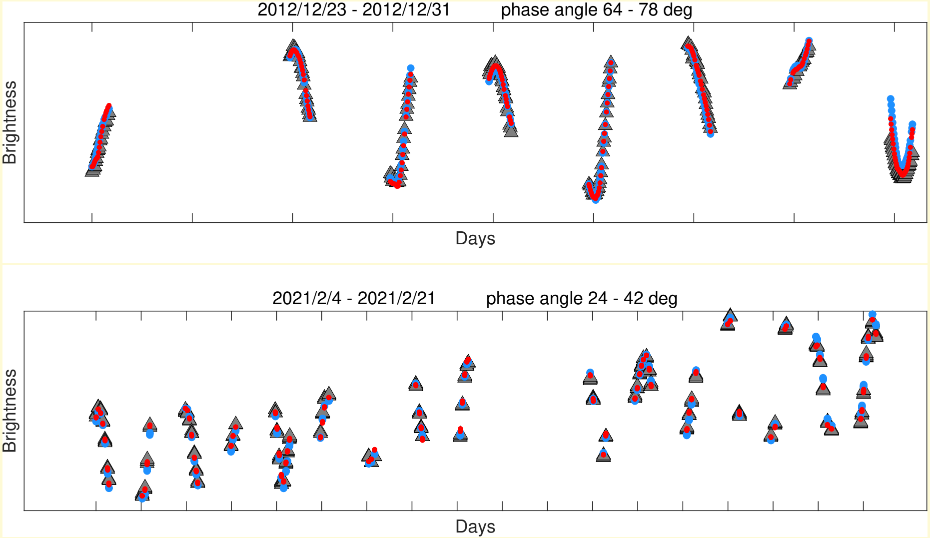
Our 2020/21 data



Our 2020/21 data



The best fit to our 2012/13 + 2020/21 data



separate 2012/13 and 2020/21 fit vs. join 2012–2021 fit

Conclusions

- Rotation state not known precisely to predict the orientation for 2029.
- Model published by Lee et al. (2022) has underestimated uncertainties (Lee, pers. comm.), there are other models outside the uncertainty intervals that fit the data with the same (or slightly smaller) residuals.
- Why is the inversion of data from both apparitions problematic?
  - Parameter space not searched densely enough?
  - Problems with the model assumptions? – convex shape, Hapke scattering,...
  - Change of the rotation state from 2012/13 to 2020/21?
- Work in progress...