Spin state of Apophis – predicting its orientation during and after the 2029 flyby

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Shape and spin reconstruction with light curve inversion

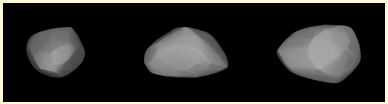
Aim: Predict the orientation of Apophis during its encounter with the Earth in 2029 and compute the change of the spin state due to gravitational torques

- **Excited** (tumbling) **rotation state** with eight parameters
  - direction of the angular momentum λ, β
  - precession and rotation periods P_ϕ, P_ψ
  - principal moments of the inertia tensor I_1, I_2
  - initial orientation ϕ_0, ψ_0
- Orientation in the space is given by **Euler angles** $\boldsymbol{\phi}$, $\boldsymbol{\theta}$, $\boldsymbol{\psi}$, their evolution has to be numerically integrated
- By applying the **light curve inversion** technique of *Kaasalainen (2001)* – fitting photometric light curves – we can determine the spin parameters and reconstruct a convex shape model

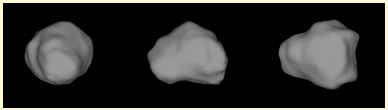
Already available models

Two favorable apparitions in **2012-13** and **2020–21** – extensive set of photometric data

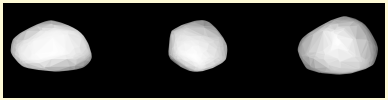
Pravec at al. (2014)
convex model
light curves 2012–13



Brozovic at al. (2018)
nonconvex model
radar observations 2012–13



Lee at al. (2022)
convex model from
light curves 2012–13, 2020–21



The precision of rotation parameters is **not sufficient to predict the orientation for 2029**

Creating a new model

Data

- 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 photometric data from 2021 compiled in Lee et al. (2022) – hundreds of individual light curves, $\sim$7500 photometric points
- Photometry from 2012-13 from Pravec et al. (2014)

Method

- Light curve inversion method of Kaasalainen (2001), convex shape, Hapke scattering model
- Trying different data set, a wide range of spin parameters, resolution of the shape model, etc.

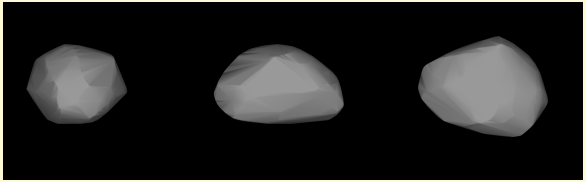
Results

- The photometric data set is not sufficient – several possible combinations of spin parameters, **spin solution is not unique**
- However, the orientation for 2029 fly-by is about the same for all acceptable models

Example of two possible models of Apophis

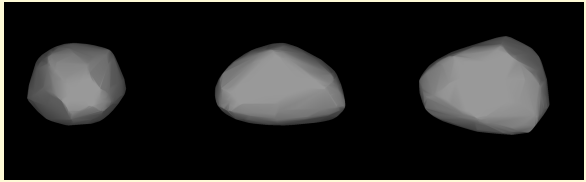
model A

$\lambda = 243.3°$, $\beta = -84.5°$
$I_1 = 0.572$, $I_2 = 0.972$
$P_\phi = 27.374\,\mathrm{h}$, $P_\psi = 262.1\,\mathrm{h}$
$p_V = 0.21$

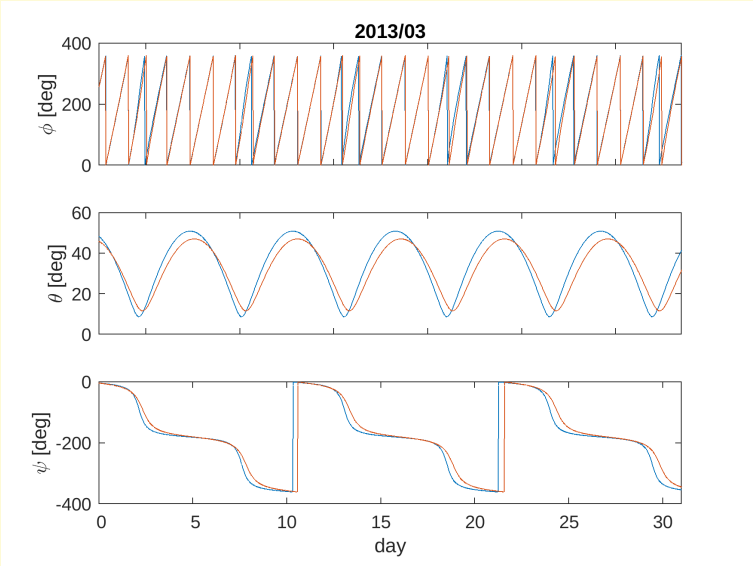


model B

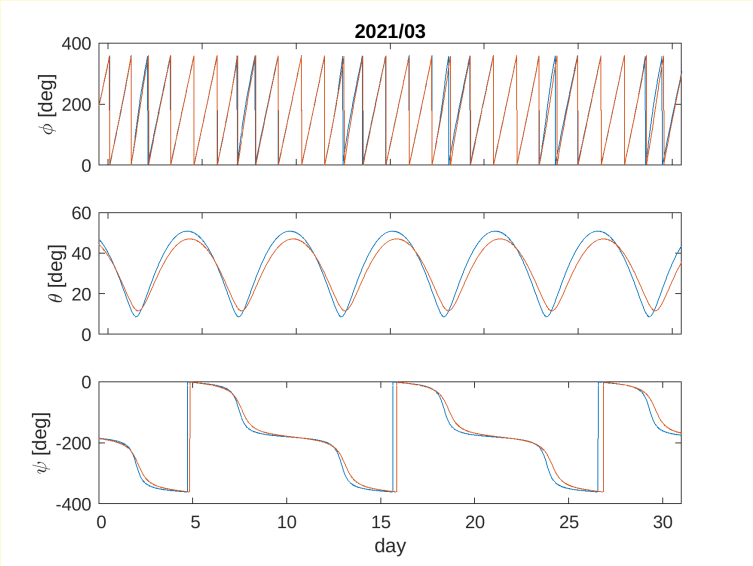
$\lambda = 245.6°$, $\beta = -82.7°$
$I_1 = 0.660$, $I_2 = 0.962$
$P_\phi = 27.395\,\mathrm{h}$, $P_\psi = 264.1\,\mathrm{h}$
$p_V = 0.22$



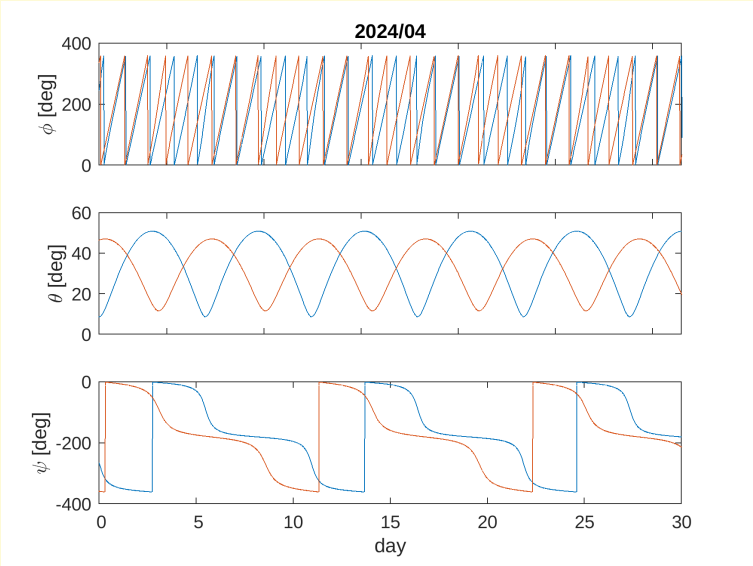
Euler angles for two models in March 2013



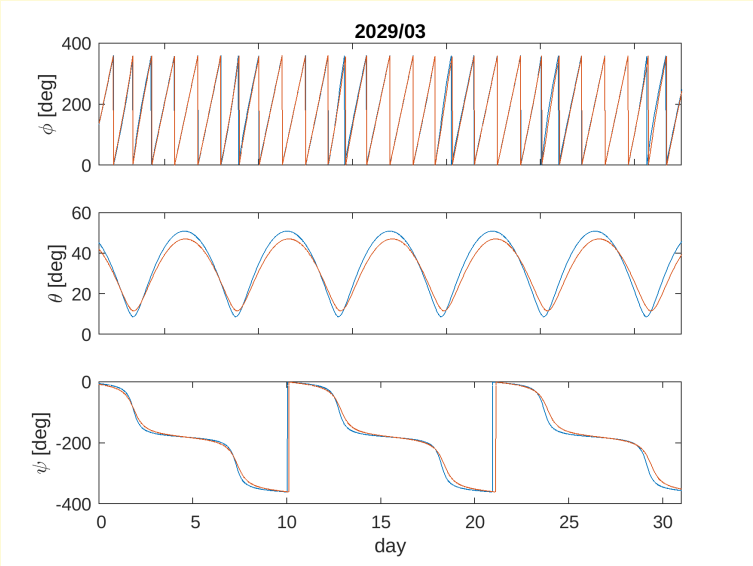
Euler angles for two models in March 2021



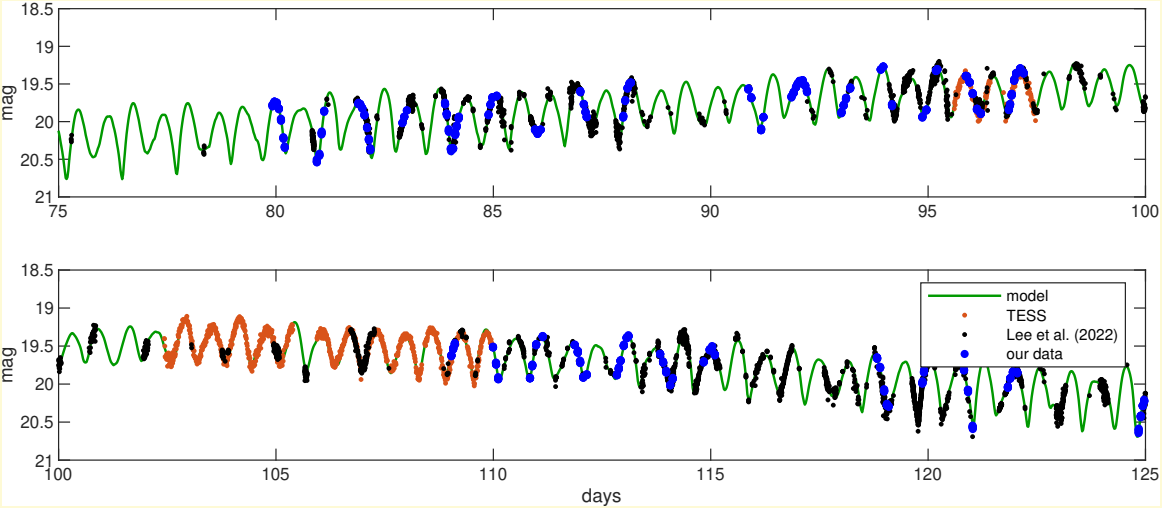
Euler angles for two models in April 2024



Euler angles for two models in March 2029

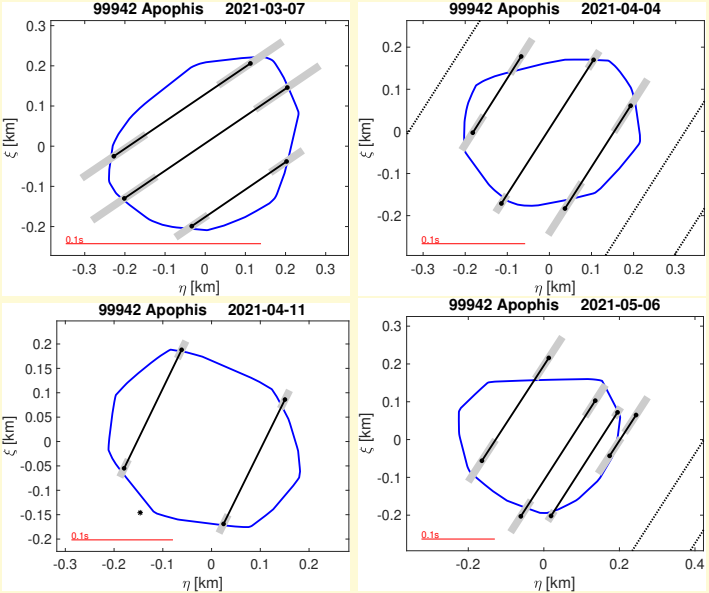


An example of light curve fit for data from 2021



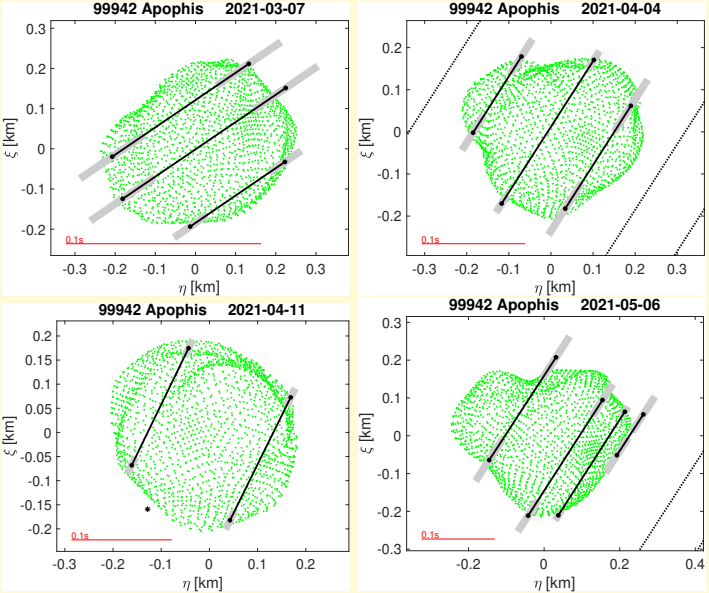
Occultations – convex shape model from light curves

D = 400 m

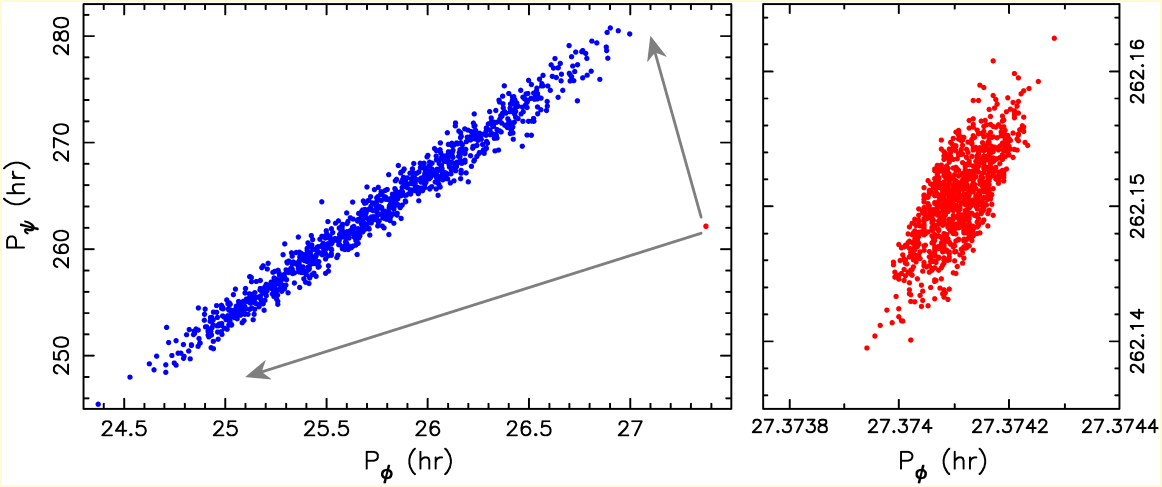


Occultations – nonconvex shape model from radar

D = 400 m

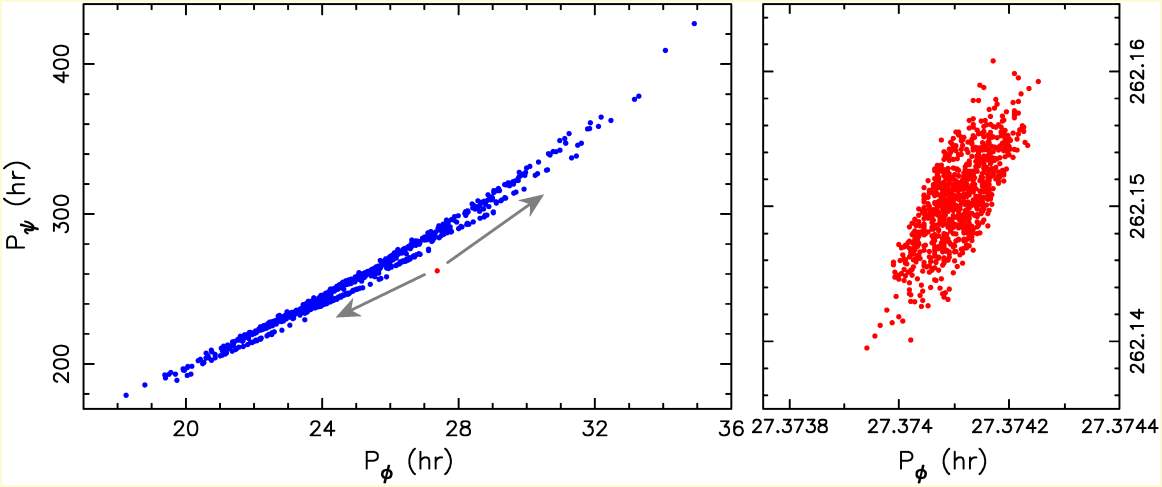


Period change during the encounter



Pre-encounter vs. post-encounter precession period P_ϕ and rotation period P_ψ.

Period change during the encounter – YORP effect included



Pre-encounter vs. post-encounter precession period P_ϕ and rotation period P_ψ.

Conclusions

- Spin state of Apophis cannot be reconstruct uniquely from available data, there are more acceptable solutions
- Still, it is possible to predict the orientation for 2029 with some level of confidence because all acceptabe models have similar orientation in 2029
- However, the post-encounter spin state is so sensitive to exact fly-by attitude (affected by YORP and model uncertainties) that it **is not possible to determine the post-encounter spin state quantitatively**
- To solve the spin state ambiguity, photometric observation in 2029 will not help – **observations in 2027 and 2028 are crucial**