The role of the Yarkovsky effect in the long-term dynamics of asteroid (469219) Kamo'oalewa

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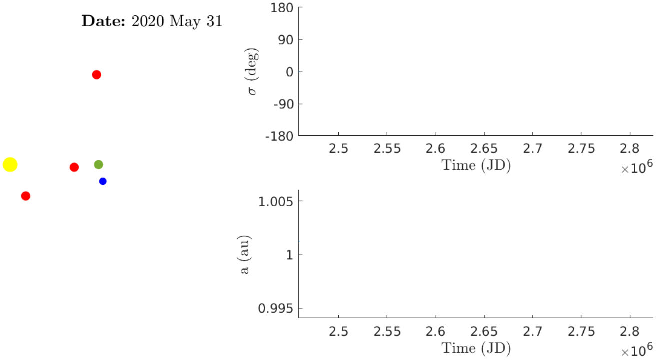
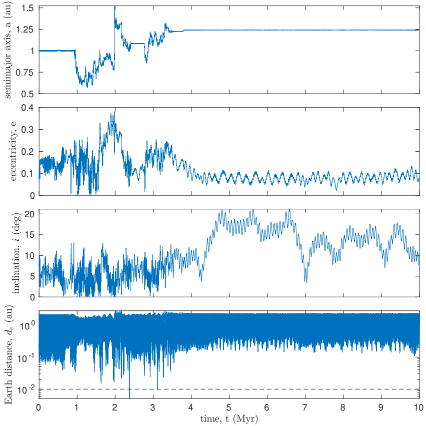
About (469219) Kamo'oalewa: short-term motion

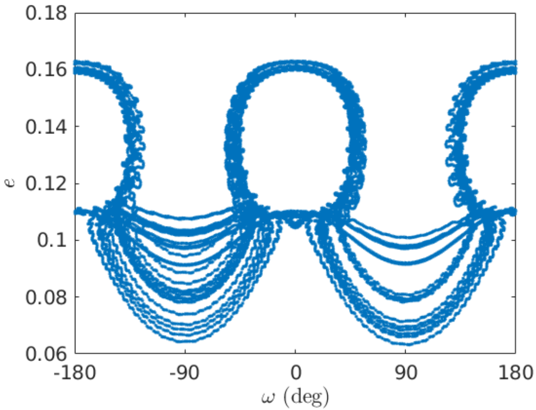
Discovered: 2016 April 27^{th}



Resonant angle: $\sigma = \lambda - \lambda_E$, where $\lambda = \ell + \omega + \Omega$

About (469219) Kamo'oalewa: long-term motion



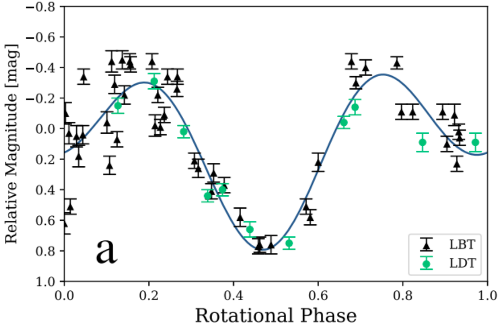


- Kamo'oalewa remains in the 1:1 MMR region for ∼1 Myr
- The long-term motion is **chaotic**!

See also: de La Fuente Marcos & de La Fuente Marcos (2016). MNRAS 462, 3441-3456.

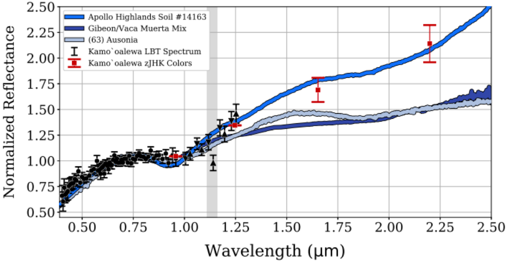
About (469219) Kamo'oalewa: physical characteristics*

Lightcurve



$P = 28.3 \pm 1.5$ m

VIS + NIR Spectra and zJHK colors



*B. Sharkley, et al. (2021). Comm. Earth & Environment 2, 231.

Motivations to our study*

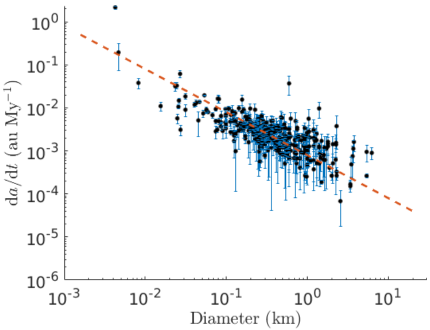
Motivations:

- Kamo'oalewa is the most stable quasi-satellite known
- Yarkovsky effect was discarded
- Yarkovsky effect could be large for small asteroids

Goals:

- Model the Yarkovsky effect of Kamo'oalewa
- Study the long-term dynamics including non-gravitational effects

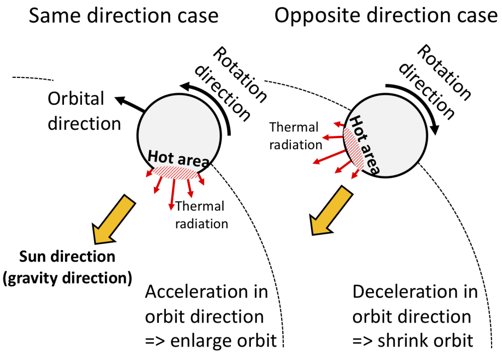
Measurements of Yarkovsky drift



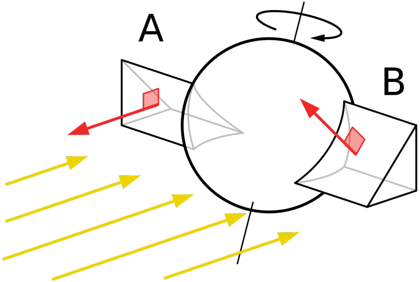
*M. Fenucci & B. Novaković (2021). AJ, Vol. 162, Is. 6, 227.

The Yarkovsky/YORP effects

Yarkovsky effect



YORP effect



Modeling the Yarkovsky drift

$$\left(\frac{\mathrm{d}a}{\mathrm{d}t}\right) = \left(\frac{\mathrm{d}a}{\mathrm{d}t}\right)(a, D, \rho, K, C, \gamma, P, \alpha, \varepsilon)$$

Measured parameters:

- a: semi-major axis
- P: rotation period

Assumed parameters:

- K: thermal conductivity
  $K \in \{0.001,\ 0.01,\ 0.1,\ 1,\ 5\}$ W/m/K
- C: heat capacity
  $C = 800$ J/kg/K
- α: absorption coefficient
- ε: emissivity

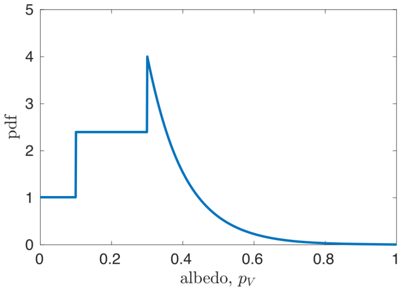
Modeled parameters:

- D: diameter
- ρ: density
- γ: obliquity

Modeled parameters: albedo

Three albedo categories:

- **c1:** $p_V \leq 0.1$
- **c2:** $0.1 < p_V \leq 0.3$
- **c3:** $0.3 < p_V$



Refs:

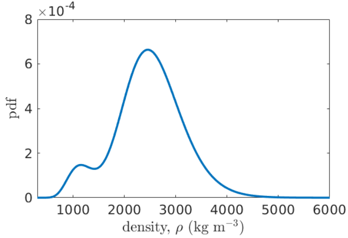
NEOs orbital distribution, Granvik et al. (2018)

NEOs albedo distribution, Morbidelli et al. (2020)

Modeled parameters: density, diameter, obliquity

Density

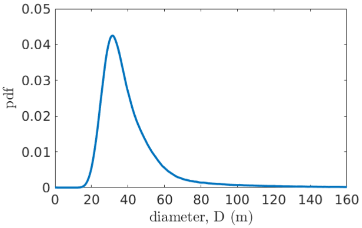
Complex	ρ (kg/m^3)
C	1200±200
S	2720±540
X	2350±520



Diameter

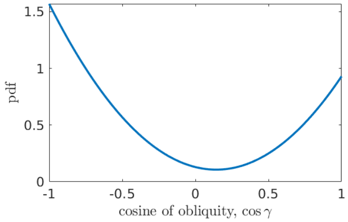
$$H = 24.3 \pm 0.3$$

$$D = \frac{1329 \text{ km}}{\sqrt{p_V}} 10^{-H/5}$$



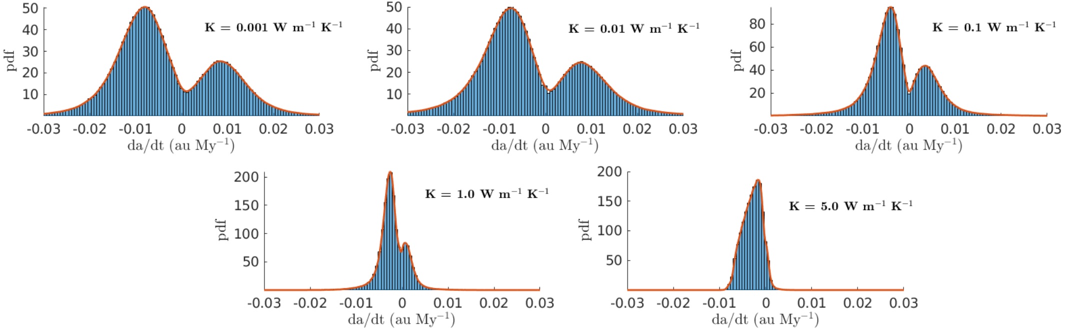
Obliquity

NEO population obliquity distribution (Tardioli et al. 2017)



Yarkovsky drift estimation

Method: Monte Carlo sampling of parameters and evalutation of the drift



Orbital clones

From orbit determination:

$\boldsymbol{x} \in \mathbb{R}^6$ nominal orbit

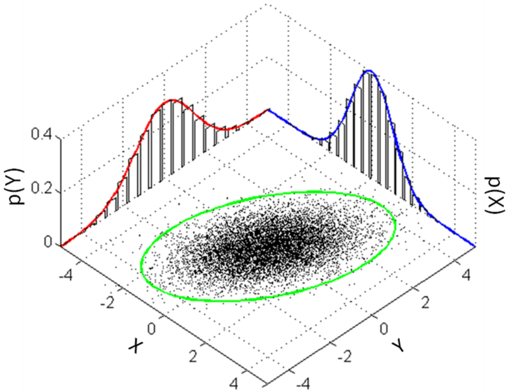
$\Gamma \in \mathbb{R}^{6\times 6}$ covariance matrix

For sampling:

If $\boldsymbol{u} \sim \mathcal{N}(\mathbf{0}, I)$, then

$$A\boldsymbol{u} + \boldsymbol{x} \sim \mathcal{N}(\boldsymbol{x}, \Gamma)$$

where $\Gamma = AA^T$ is the *Cholesky* decomposition.



Note: we assign each clone a different da/dt.

Dynamical model and simulation settings

Dynamical model:

- Sun + 8 planets + Moon
- Sun + 8 planets + Moon + Yarkovsky
- Sun + 8 planets + Moon + Yarkovsky + statistical model of YORP

Numerical integrations:

- Modified `mercury` integrator[1]
- Bulirsch-Stoer method
- 10 Myr integration time

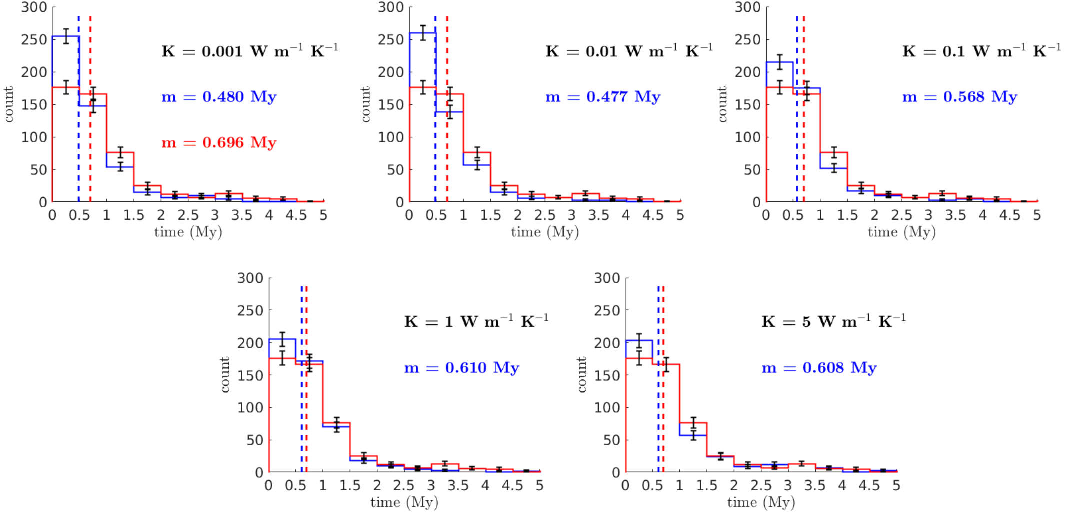
Output:

- Keplerian elements every 10 yr
- Collisions with Sun and planets
- Time spent in the Earth 1:1 MMR region

$$0.994 \text{ au} \leq a \leq 1.006 \text{ au}$$

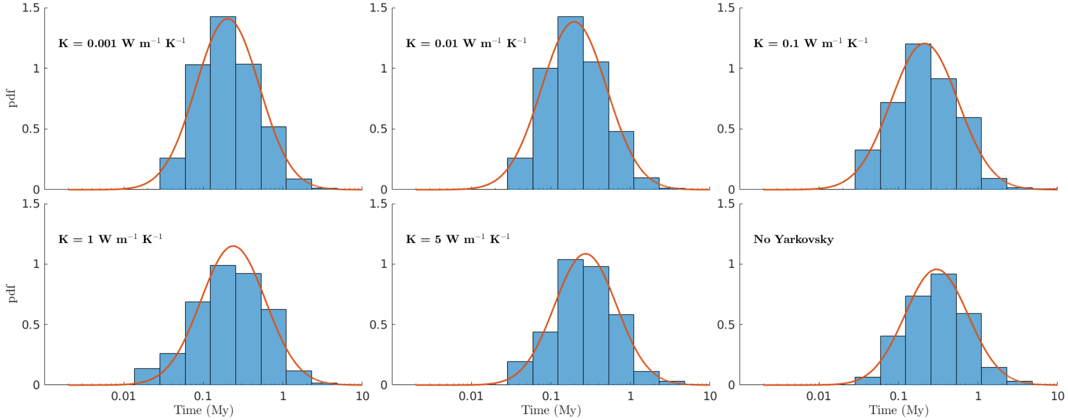
[1] Fenucci & Novaković (2022). *Mercury and OrbFit packages for the numerical integration of planetary systems: implementation of the Yarkovsky and YORP effects. ArXiv: 2202.13656*

Results: co-orbital stability

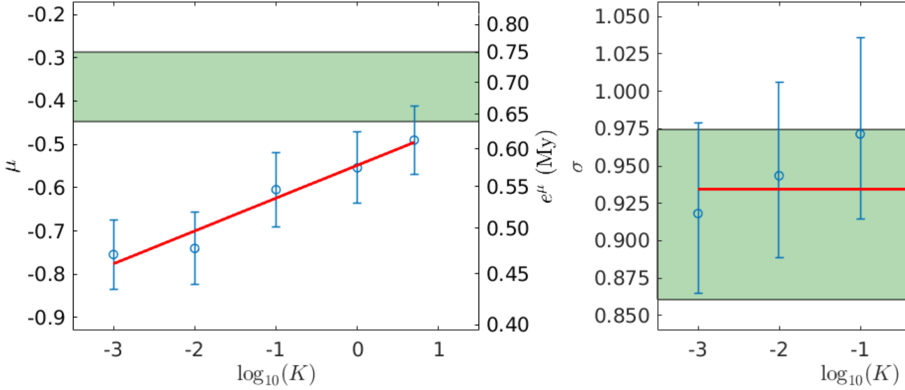


Results: co-orbital stability

Note: the distribution can be fitted with $\ln \mathcal{N}(\mu, \sigma)$



Results: co-orbital stability



Other results and conclusions

Other results:

- Statistics of collisions was not changed with different models
- Adding YORP effect did not change results for low K

Conclusions:

- Many clones are removed from the co-orbital zone within 0.5 Myr
- About 80% of clones are removed from the co-orbital zone within 1 Myr
- The Yarkovsky effect causes significant statistical changes, especially for low and moderate K