Tidal Effects on the Shape and Structure of Apophis during the Earth Flyby in 2029

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Abstract

In this work, we perform simulations of Apophis' 2029 close encounter with the Earth and follow the evolution of the object. Previous studies (e.g. [1][2]) have done similar simulations. However, the internal structure of Apophis was modeled either by a rigid body or by a collection of spherical particles. We assume a gravitational aggregate (GA) internal structure for Apophis and we apply our internal structure model to the currently available shape model. The GA internal structure is modeled by means of multiple irregular shape components of different sizes using PKDGRAV. Each irregular component is obtained by grouping together particles forming irregular overall shapes, in which relative particle motion is inhibited (rigid-aggregates). We present the model outcome of possible changes in the shape and structure of Apophis as well as changes to its spin state. The outcome of the present model will be compared with previous studies.

1. Introduction

Over the past two decades, 99942 Apophis (2004 MN4) has been a well-known asteroid due to its high rating on the Torino impact hazard scale, reaching level 4 on December 27, 2004. With subsequent improved observations, the possibility of an impact on Earth was ruled out. As calculated by the JPL Center for NEO Studies (CNEOS) and by the ESA NEODyS-2, Apophis will have a non-threatening Earth close encounter (CE) at 5.96 Earth radii from the centre of Earth on April 13th, 2029. On the other hand, the tidal effect induced by such an extraordinarily close approach is not yet determined due to its unknown internal structure. Therefore, it becomes an excellent case study for understanding the behavior of asteroids closely approaching the Earth. DeMartini et al. (2019) [1] (hereafter DE19) tackled this problem with a SSDEM high-performance parallel gravitational N-body code, PKDGRAV [3][4][5]. They used mono-disperse hexagonal-close-packing configuration of spherical particles for the internal structure of Apophis. Further refinement included poly-disperse distributions of spherical particles mixed with some larger rigid-aggregate components. Nevertheless, asteroids larger than 200-300 m and smaller than some 100 km in diameter are most likely gravitational aggregates (GAs) [6][7]. The tidal effects on such internal structure are not determined by previous studies. This study is complementary to DE19.

2. Methods

We model the GA internal structure of Apophis using the ***SHEXSSPY*** (SHattering EXperiments to Synthetic Shapes through PhotogrammetrY) algorithm we developed to generate realistic shape components with the following process:

1. Customized mass distributions withdrawn from the fragments (**Fig. 1**) generated by 6 shot experiments on basalt targets at V~4-5 km/s performed at NASA-Ames Vertical Gun Range (July 2013) [8]
2. 27 realistic irregular shape models derived from fragments of the aforementioned shot experiments through *photogrammetry* method. (**Fig. 2**)
3. Greate any given number of components (usually around 100 to 10000) with their shapes randomly chosen from the 27 shape models and scale their sizes so that they follow the mass distribution.
4. Convert the Irregular shape components to PKDGRAV objects (each component is a rigid body made of many spherical particles).
5. Randomly distribute the initial locations of components in space to initiate the gravitationally reaccumulating process to form a GA.
6. Use the current shape model of Apophis [9] to select from the reaccumulated GA the particles inside Apophis' shape model.

In this way, we generated a model of Apophis made of 353 rigid irregular components with total number of 108191 particles (**Fig. 3**).

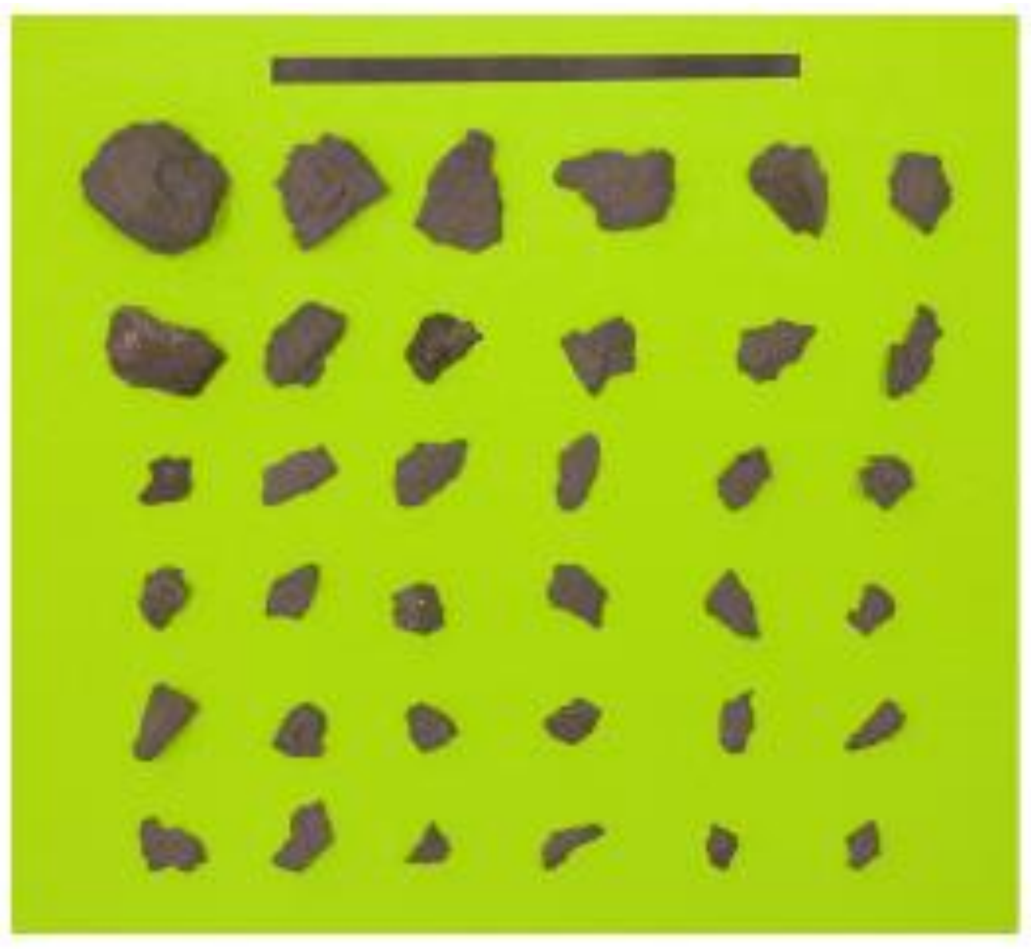

Fig. 1. Fragments generated by shot experiments at NASA-Ames Vertical Gun Range.

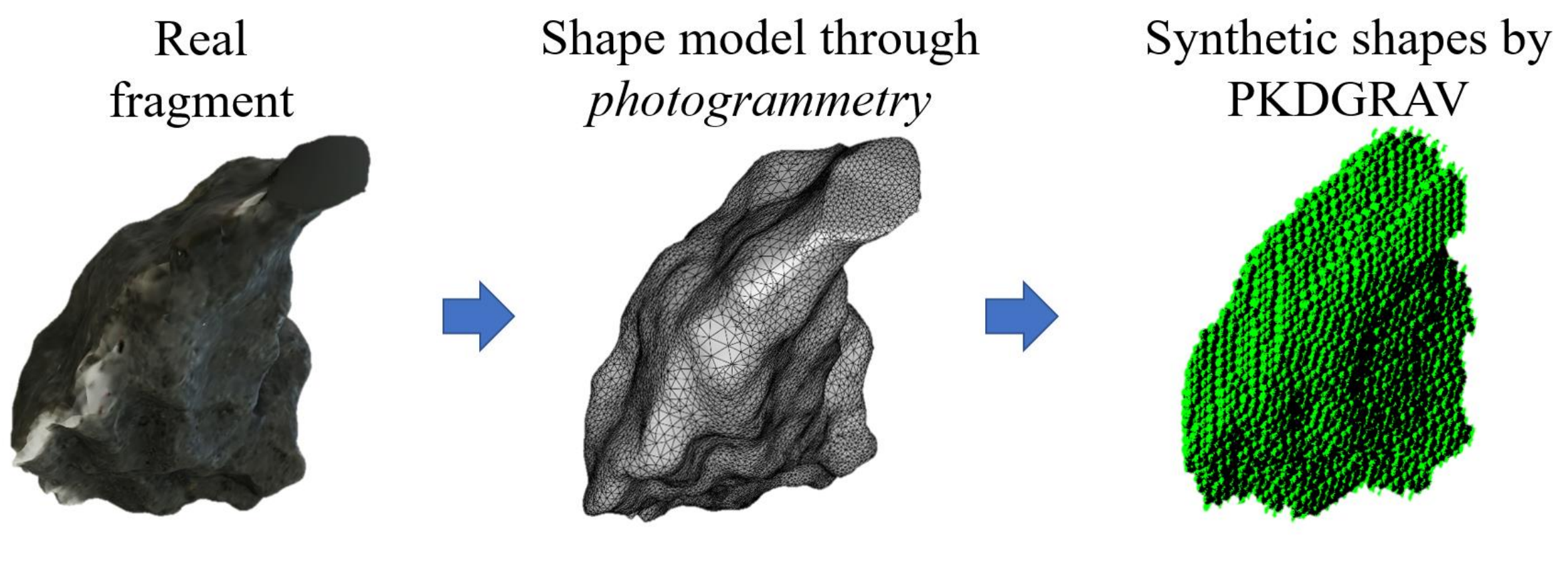

Fig. 2. Process of generating synthetic irregular shape components from real fragments produced in shot experiments.

Except for the internal structure, the rest of our parameters of our simulations are the very similar to the nominal simulations of DE19 for the convenience of comparison. The exact orientation of Apophis at the time of the CE is poorly determined so far, and it is therefore treated as a free parameter in the literatures. DE19 showed that both changes in Apophis's principal axes and spin period depend on the exact orientation during the CE. In our current work, we use the orientation solution provided in Brozović et al. (2018) [9] as a preliminary approximation. More different cases of orientations will be simulated in our future work.

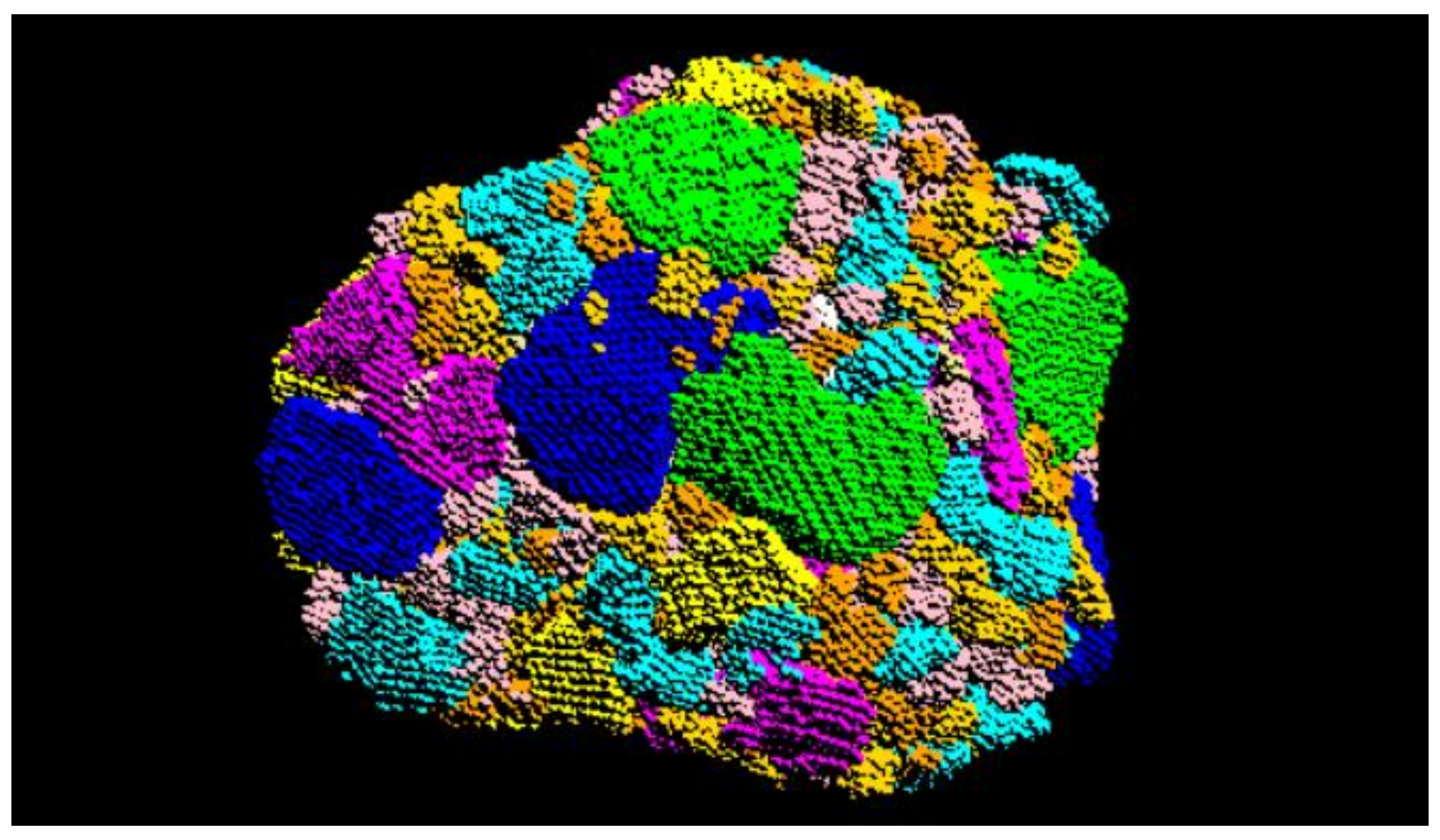

Fig. 3. Resulting Apophis model from *SHEXSSPY* method.

3. Results

For the changes in the angular momentum and spin frequency (**Fig. 5**), the result from our model is consistent with some of the cases presented in DE19 with decreases in spin period and an abrupt change during around ±1 h relative to the time of close encounter (T_{CE}). We find a spin period change of -10.3 h (initial spin period = 30.62 h) after the CE.

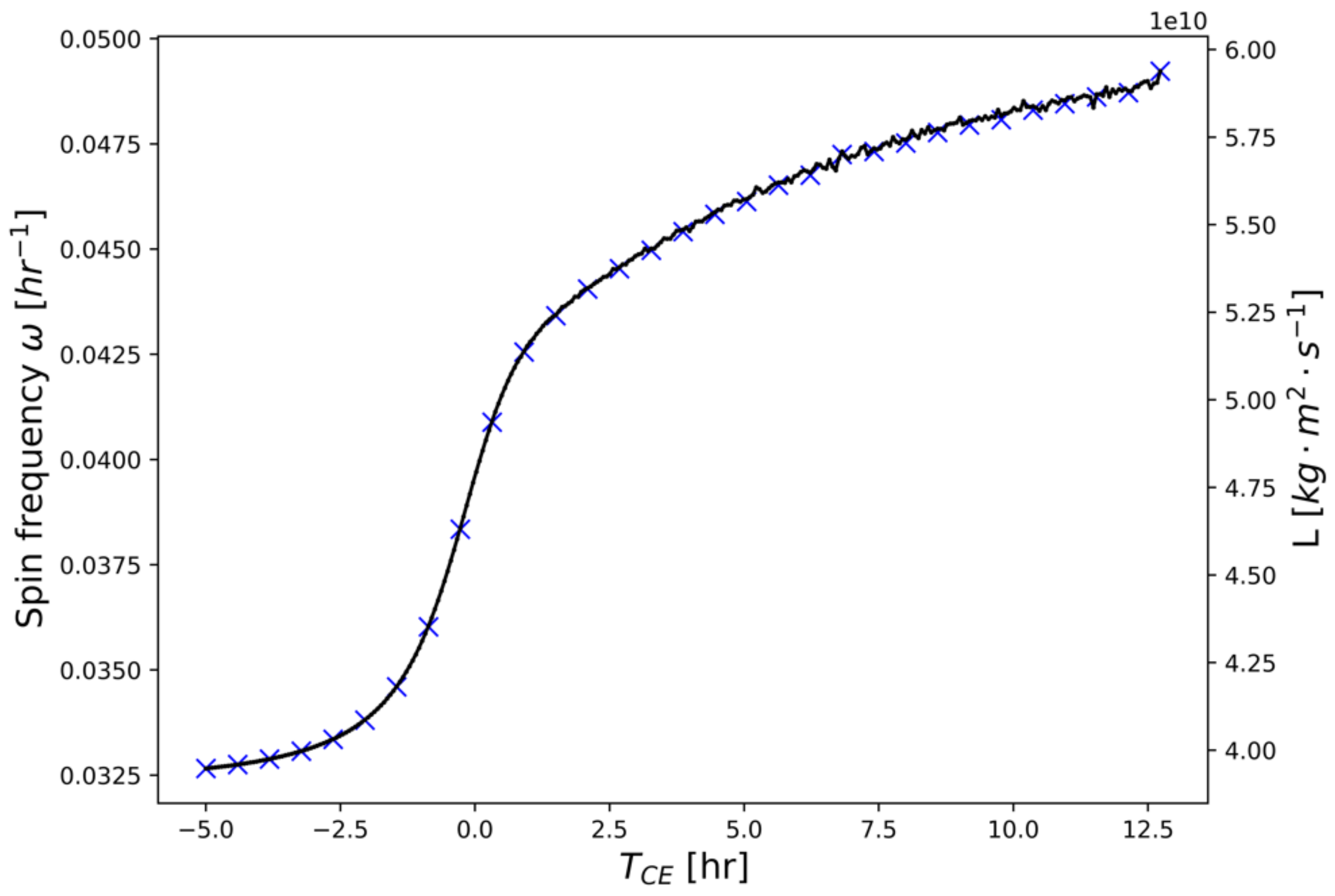

Fig. 5. Evolution of spin frequency and magnitude of the angular momentum of Apophis during the CE. The blue cross and black line represent the magnitudes of angular momentum and spin frequency, respectively.

We measure the changes in the lengths of 3 principal axes using the concept of "Equivalent Ellipsoid" [10], which computes an equivalent triaxial ellipsoid from the principal moments of Apophis' diagonal inertia tensor. The resulting equivalent ellipsoid at each time step has principal semiaxes a_t, b_t, and c_t ($a_t > b_t > c_t$), which can be compared with the values at t=0 according to the following equations:

$$\frac{a_t}{a_0} = \sqrt{\frac{(I_{yy} + I_{zz} - I_{xx})}{(I_{yy,0} + I_{zz,0} - I_{xx,0})}} \quad \frac{b_t}{b_0} = \sqrt{\frac{(I_{xx} + I_{zz} - I_{yy})}{(I_{xx,0} + I_{zz,0} - I_{yy,0})}} \quad \frac{c_t}{c_0} = \sqrt{\frac{(I_{xx} + I_{yy} - I_{zz})}{(I_{xx,0} + I_{yy,0} - I_{zz,0})}}$$

We find that the changes in the principal axes are on the order of a few hundred microns, which is at the same magnitude as DE19. Therefore, we conclude that changing the internal structure model does not significantly alter the results presented in DE19. The 2029 flyby event substantially change the spin period of Apophis instead of its shape.

Acknowledgement

P.-Y. Liu, A. Campo Bagatin and P. G. Benavidez acknowledge the NEO-MAPP project (H2020-SPACE- 2019).

References

[1] DeMartini, J. V. et al. (2019) *Icarus*, *328*, 93-103.
[2] Benson, C. J. et al. (2023) *Icarus*, *390*, 115324.
[3] Richardson, D. C. et al. (2000) Icarus 143, 45–59.
[4] Stadel, J. G. (2001) Ph.D. Thesis, 3657.
[5] Schwartz, S. R. et al. (2012) Granular Matter 14, 363–380.
[6] Campo Bagatin, A. et al. (2001) Icarus, 149, 198-209.
[7] Richardson, D. C. et al. (2002) Asteroids III. University of Arizona Press, Tucson.
[8] Durda, D. D. et al. (2015) Planetary and Space Science, 107, 77-83.
[9] Brozović, M., et al. (2018) Icarus 300, 115–128.
[10] Dobrovolskis A. R., 1996, Icar, 124, 698.