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Detecting Internal Shifts Within Apophis Across its Earth Flyby

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Extended Abstract—
On April 13, 2029 the asteroid (99942) Apophis will have a close approach to Earth and be observed with optical telescopes and the DSN's Goldstone planetary radar in the weeks before and after closest approach [1]. This paper will describe how these observations can be leveraged to provide information on Apophis' interior and to detect shifts within its mass distribution due to tidal effects around closest approach.

A driving scientific question related to the Apophis flyby is whether its close Earth passage will induce any global or localized mass redistributions due to tidal forces. It is well understood that the close approach will radically change the tumbling asteroid's spin state and orbit [2] (see Fig. 1), but it is much more controversial whether the flyby will induce any mass redistribution. This question has been studied by numerous researchers (see the summary in [2]) with the conclusion that changes in the surface distribution of material are likely minimal, if they occur at all (see Fig. 2), but that shifts in the Apophis mass distribution could occur if the asteroid is a multi-component, contact binary asteroid. The current Apophis shape and spin state are consistent with such a morphology [3] (see Fig. 1). A strong analogy can be made with the investigation into the crack that was seen between the head and body of comet 67P [5]. Such a localized region between two components will be naturally weaker and susceptible to relative motion.

Such shifts within Apophis can be constrained or detected by a combination of radar and optical observations and precise modeling. The Apophis observations will enable the asteroid spin state and moments of inertia to be estimated before and after closest approach, enabling a direct detection of significant shifts within the body, as well as identifying the peak stresses experienced by the asteroid. A previous study and analysis of the asteroid (4179) Toutatis demonstrated this approach using similar radar and optical observations, however the level of precision for Apophis will be improved significantly over those demonstrated in [4] due to the much closer Earth passage and the large number of dedicated observations.

The moment of inertia ratios of the asteroid Toutatis were determined to an accuracy of around 1% 1-sigma [4]. Thus we expect to reach at least this level of accuracy for the incoming and outgoing observation legs of the Apophis Earth flyby. In fact we expect significant improvements over these levels of accuracy due to several considerations.

1. The observations will be at SNR much greater than the bulk of the Toutatis observations used in [4].
2. The resolved imaging observations should cover over 10 complete rotations of the asteroid, assuming a 30 hour effective rotation period. The Toutatis observations in general covered less than a full rotation period of that body at each observation epoch (about 7 days).
3. The number of observations will be significantly greater than those accumulated for Toutatis, which consisted of only several poses at each apparition, compared with near constant observations across the resolved imaging period of 2 weeks.
4. The mass parameters through which the Earth torques act on the asteroid through closest approach are directly related to those estimated from the complex spin state, and thus the accuracy of these parameters should be greatly increased.

Based on simulations reported in [2] we were able to estimate the sensitivity of the Apophis flyby rotation state to small changes in the moments of inertia. We determined the deviation in the spin state over a time period of 1.6 hours (which encapsulates the significant changes to the spin state, see Fig. 3). For a 1% change in the moment of inertia value, we found that the angular velocity deviated by about 4% from nominal and the total attitude orientation deviated by 2.5°, and in the following period its angular deviation would increase by about 5° per day. Thus, these direct interactions with the Earth's gravity gradient torques on the body should further improve the estimates if a fit can be made through the closest approach.

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A more exciting scenario occurs if the body suffers some sort of reconfiguration during the Earth passage. In that case we would expect an abrupt change in the body's moments of inertia. This would prevent a single solution with fixed moments of inertias to be estimated. However, if attitude orientations of the asteroid are available through the close approach (perhaps from visible imaging in addition to radar imaging), it becomes possible to identify the epoch at which the change becomes effective. This, when combined with the precise orientation knowledge, the estimated moments of inertia, and the pathway up to this moment will provide precise information on the internal stresses when the failure occurred. This in turn will provide a unique measurement of the asteroid's internal strength. If such a reconfiguration is detected, then it will be of paramount importance to re-estimate the asteroid's moments of inertia and spin state during its outbound departure from Earth. A later visiting spacecraft, such as OSIRIS-APEX, could also perform this post-flyby determination.

References

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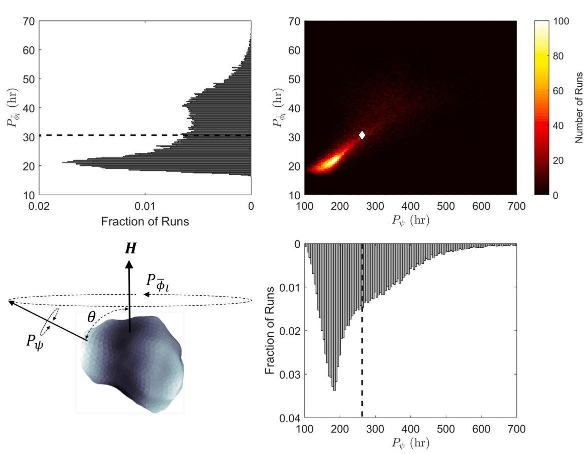

Figure 1: Possible changes in Apophis complex spin periods as a function of attitude at closest approach.

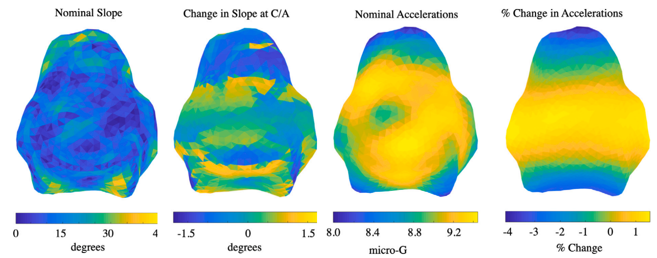

Figure 2: Nominal slope and acceleration of Apophis and computed changes in these quantities at closest approach (for a given attitude).

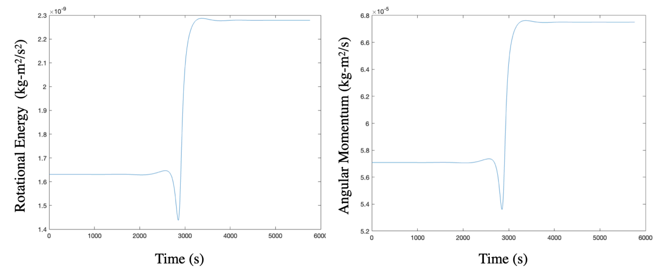

Figure 3: Change in rotational energy and angular momentum through closest approach. The time span covers 1.67 hours. It is clear that significant change in energy and angular momentum due to the Earth's interaction only occurs within a period of 2000 seconds (a bit over one 1/2 hour).