Icarus 242 (2014) 82–96

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Numerical predictions of surface effects during the 2029 close approach of Asteroid 99942 Apophis

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ARTICLE INFO

Article history:
Received 5 December 2013
Revised 24 June 2014
Accepted 24 July 2014
Available online 7 August 2014

Keywords:
Asteroids, dynamics
Asteroids, surfaces
Near-Earth objects
Regoliths
Tides, solid body

ABSTRACT

Asteroid (99942) Apophis' close approach in 2029 will be one of the most significant small-body encounter events in the near future and offers a good opportunity for *in situ* exploration to determine the asteroid's surface properties and measure any tidal effects that might alter its regolith configuration. Resurfacing mechanics has become a new focus for asteroid researchers due to its important implications for interpreting surface observations, including space weathering effects. This paper provides a prediction for the tidal effects during the 2029 encounter, with an emphasis on whether surface refreshing due to regolith movement will occur. The potential shape modification of the object due to the tidal encounter is first confirmed to be negligibly small with systematic simulations, thus only the external perturbations are taken into account for this work (despite this, seismic shaking induced by shifting blocks might still play a weak role and we will look into this mechanism in future work). A two-stage approach is developed to model the responses of asteroid surface particles (the regolith) based on the soft-sphere implementation of the parallel *N*-body gravity tree code `pkdgrav`. A full-body model of Apophis is sent past the Earth on the predicted trajectory to generate the data of all forces acting at a target point on the surface. A sandpile constructed in the local frame is then used to approximate the regolith materials; all the forces the sandpile feels during the encounter are imposed as external perturbations to mimic the regolith's behavior in the full scenario. The local mechanical environment on the asteroid surface is represented in detail, leading to an estimation of the change in global surface environment due to the encounter. Typical patterns of perturbation are presented that depend on the asteroid orientation and sense of rotation at perigee. We find that catastrophic avalanches of regolith materials may not occur during the 2029 encounter due to the small level of tidal perturbation, although slight landslides might still be triggered in positions where a sandpile's structure is weak. Simulations are performed at different locations on Apophis' surface and with different body- and spin-axis orientations; the results show that the small-scale avalanches are widely distributed and manifest independently of the asteroid orientation and the sandpile location. We also include simulation results of much closer encounters of the Apophis with Earth than what is predicted to occur in 2029, showing that much more drastic resurfacing takes place in these cases.

1. Introduction

In this paper, we investigate numerically the behavior of granular material at the surface of an asteroid during close approach to the Earth. We focus on the specific case of Asteroid (99942) Apophis, which will come as close as 5.6 Earth radii on April 13th, 2029. We provide predictions about possible reshaping and spin-alteration of—and surface effects on—Apophis during this passage, as a function of plausible properties of the constituent granular material. Studies of possible future space missions to Apophis are underway, including one by the French space agency CNES calling for international partners (e.g., Michel et al., 2012), with the aim of observing this asteroid during the 2029 close encounter and characterizing whether reshaping, spin-alteration, and/or surface motion occur. The numerical investigations presented here allow for estimation of the surface properties that could lead to any observed motion (or absence of motion) during the actual encounter.

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http://dx.doi.org/10.1016/j.icarus.2014.07.027
0019-1035/

Apophis made a passage to the Earth at ~2300 Earth radii in early 2013. At that time, the Herschel space telescope was used to refine the determination of the asteroid's albedo and size (Müller et al., 2014). According to these observations, the albedo is estimated to be about 0.23 and the longest dimension about 325 ± 15 m, which is somewhat larger than previous estimates (270 ± 60 m, according to Delbo' et al., 2007). Concurrent radar observations improved the astrometry of the asteroid, ruling out the possibility of a collision with the Earth in 2036 to better than 1 part in 10^6. However, Wlodarczyk (2013) presented a possible path of risk for 2068. This finding has put off any crisis by ~32 years and makes exploring Apophis in 2029 to be more for scientific interest. To date, nothing is known about the asteroid's surface mechanical properties, and this is why its close passage in 2029 offers a great opportunity to visit it with a spacecraft, determine its surface properties, and, for the first time, observe potential modifications of the surface due to tidal effects. And as Apophis approaches, it is likely that international interest in a possible mission will increase, since such close approaches of a large object are relatively rare.

The case for tidally induced resurfacing was made by Binzel et al. (2010; also see DeMeo et al., 2013) and discussed by Nesvorný et al. (2010) to explain the spectral properties of near-Earth asteroids (NEAs) belonging to the Q taxonomic type, which appear to have fresh (unweathered) surface colors. Dynamical studies of these objects found that those bodies had a greater tendency to come close to the Earth, within the Earth–Moon distance, than bodies of other classes in the past 500 kyr. The authors speculated that tidal effects during these passages could be at the origin of surface material disturbance leading to the renewed exposure of unweathered material. We leave a more general and detailed investigation of this issue for future work, but if this result is true for those asteroids, it may also be true for Apophis, which will approach Earth on Friday, April 13, 2029 no closer than about 29,500 km from the surface (i.e., 4.6 Earth radii, or 5.6 Earth radii from the center of the planet; Giorgini et al. (2008)). It is predicted to go over the mid-Atlantic, appearing to the naked eye as a moderately bright point of light moving rapidly across the sky. Our aim is to determine whether, depending on assumed mechanical properties, it could experience surface particulate motions, reshaping, or spin-state alteration due to tidal forces caused by Earth's gravity field. The classical Roche limit for a cohesionless fluid body of bulk density 2.4 g/cm^3 to not be disrupted by tidal forces is ~3.22 Earth radii, so we do not expect any violent events to occur during the rocky asteroid's 2029 encounter at 5.6 Earth radii.

The presence of granular material (or regolith) and boulders at the surface of small bodies has been demonstrated by space missions that visited or flew by asteroids in the last few decades (e.g., Veverka, 2000; Fujiwara et al., 2006). It appears that all encountered asteroids to date, from the largest one, the main belt Asteroid (4) Vesta by the Dawn mission, to the smallest one, the NEA (25143) Itokawa, sampled by the Hayabusa mission, are covered with some sort of regolith. In fact, thermal infrared observations support the idea that most asteroids are covered with regolith, given their preferentially low thermal inertia (Delbo' et al., 2007). There even seems to be a trend as a function of the asteroid's size based on thermal inertia measurements: larger objects are expected to have a surface covered by a layer of fine regolith, while smaller ones are expected to have a surface covered by a layer of coarse regolith (Clark et al., 2002). This trend is consistent with observations by the NEAR-Shoemaker spacecraft of the larger (~17 km mean diameter) Eros, whose surface is covered by a deep layer of very fine grains, and by the Hayabusa spacecraft of the much smaller (320 m mean diameter) Itokawa, whose surface is covered by a thin layer of coarse grains. However, interpretation of thermal inertia measurements must be made with caution, as we do not yet have enough comparisons with actual asteroid surfaces to verify that the suggested trend is systematically correct.

Thus, we are left with a large parameter space to investigate possible surface motion during an Earth close approach of an asteroid with unknown surface mechanical properties. Our approach is to consider a range of simple and well-controlled cases that certainly do not cover all possibilities regarding Apophis' surface mechanical properties, but rather aim at demonstrating whether, even in a simple and possibly favorable case for surface motion, some resurfacing event can be expected to occur during the passage. For instance, instead of considering a flat granular surface, we consider a sandpile consisting of a size distribution of spherical grains (Section 2.1) and vary the grain properties in order to include more or less favorable cases for motion (from a fluid-like case to a case involving rough particles). Slight disturbances may manifest as very-small-scale avalanches in which grain connections readjust slightly, for example. The forces acting on the sandpile are obtained by measuring all "external" perturbations during the encounter, including body spin magnitude and orientation changes, for cases in which the global shape remains nearly fixed, and again assuming simple and favorable configurations of the asteroid. Indirectly, the encounter may also lead to internal reconfigurations of the asteroid, which in turn produce seismic vibrations that could propagate to the surface and affect the regolith material. These secondary modifications are not modeled here, although it may be possible in future work to account for this by shaking the surface in a prescribed manner. In any case, for this particular encounter, we demonstrate (Section 3.1) that any global reconfiguration will likely be small to negligible in magnitude.

In the following, we first present, in Section 2, the numerical method used to perform our investigation, including the initial conditions of the sandpile adopted to investigate surface motion, the representation of the encounter, and the mechanical environment. Results are described in Section 3, including potential reshaping of the asteroid, tidal disturbances for Apophis' encounter in 2029, which is a function of the sandpile properties, spin orientation changes, and the dependency of the location of the sandpile on the asteroid to the outcome of the encounter. We also show the responses of the sandpiles for artificially close approaches (4.0 and 2.0 Earth radii) to demonstrate that our method does predict significant alteration of the sandpiles when this is certainly expected to happen. The investigation is discussed in Section 4 and conclusions are presented in Section 5.

2. Numerical method

We use pkdgrav, a parallel *N*-body gravity tree code (Stadel, 2001) adapted for particle collisions (Richardson et al., 2000; Richardson et al., 2009; Richardson et al., 2011). Originally collisions in pkdgrav were treated as idealized single-point-of-contact impacts between rigid spheres. A soft-sphere option was added recently (Schwartz et al., 2012); with this new functionality, particle contacts last many timesteps, with reaction forces dependent on the degree of overlap (a proxy for surface deformation) and contact history—this is appropriate for dense and/or near-static granular systems with multiple persistent contacts per particle. The code uses a 2nd-order leapfrog integrator, with accelerations due to gravity and contact forces recomputed each step. Various types of user-definable confining walls are available that can be combined to provide complex boundary conditions for the simulations. The code also includes an optional variable gravity field based on a user-specified set of rules.

The spring/dash-pot model used in pkdgrav's soft-sphere implementation is described fully in Schwartz et al. (2012). Briefly, a (spherical) particle overlapping with a neighbor or confining wall