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On the dynamics of asteroid deflection using boulders

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Abstract

Every year NEA surveys discover hundreds of new asteroids. To date, more than 20,000 near-Earth asteroids (NEAs) are known, including potentially hazardous asteroids (PHAs), which are objects larger than 140 meters and that can get closer than 0.05 AU, or ~20 lunar distances (LD). Besides discovering and tracking NEAs, another important step to support planetary defense is characterization. Ground based telescope observations enable to obtain the shape, rotation period, surface properties and to discover multiple asteroid systems [1]. Finally, planetary defense also involves the need to study asteroid mitigation strategies, in the event it is ever required.

This work presents a tether assisted asteroid deflection method using boulders on the surface of the PHA in order to change its center of mass, consequently altering its orbit.

1. Introduction

While asteroid impact could have irreversible consequences, it is the only natural disaster that could be avoided. Knowing the characteristics of asteroids enables to plan ahead a proper mitigation strategy.

Among NEAs there are innumerous bodies considered rubble piles. These agglomerates of rocks bounded by self-gravity have significant bulk porosity, and are usually between hundreds of meters to few kilometers long. With the increase of small bodies missions visited by a spacecraft, more asteroids are confirmed to be rubble piles having the surface filled with regolith and boulders. Examples are asteroids Itokawa and Ruygu, visited by JAXA's Hayabusa and Hayabusa 2 missions, respectively. More recently, the ongoing NASA's Osiris-Rex sample return mission to Bennu revealed a surface covered with boulders of various sizes, the largest ones up to ~90 meters in diameter. For targets not yet visited by a spacecraft, ground radar measurements can also give clues about the surface properties, like surface roughness and composition.

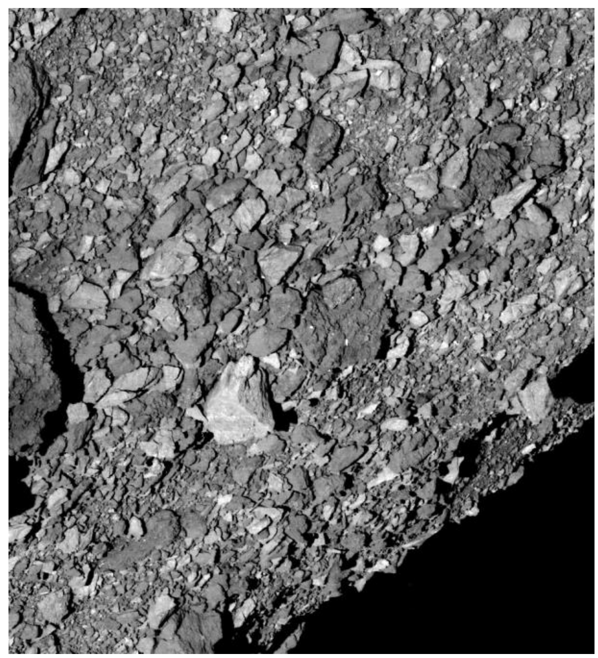

Figure 1: Surface of Bennu from Osiris-Rex. Credit: NASA/Goddard/University of Arizona.

In this work a methodology using the boulders on the surface of the asteroid to change its trajectory is proposed. The concept is similar to a sample return mission, but the boulder collected would stay connected to the asteroid forming a bounded system, consequently changing its initial orbit by displacing its center of mass. Previously it was studied the possibility of deflecting a PHA by bringing a ballast mass from the Earth [2], or capturing a smaller asteroid and connecting it with a space tether [3, 4]. However, the methodology proposed here would be an alternative to avoid the costs of bringing a heavy mass from the Earth, or the logistics of needing to select and capture a smaller asteroid before reaching the PHA.

2. Methodology

In the dynamics model adopted, four degrees of freedom are considered: R (distance between the Sun and the PHA), ν (true anomaly of the PHA), θ (rotation angle of the PHA) and α (angle between boulder-tether and the PHA). The system can be seen in Figure 2, where m_A is the mass of the PHA, and m_B the mass of the boulder. The tether is considered to be rigid and massless.

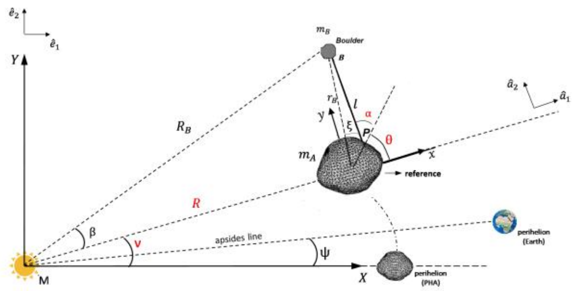

Figure 2: Configuration of a boulder connected to a PHA by a tether.

Equation 1 shows the Lagragian of the system. The four equations of motion for the PHA-tether-boulder system are obtained deriving equation 1 in relation to R, ν, θ and α, as represented in equation 2.

$$\begin{aligned} L = {} & \frac{I_A}{2}(\dot{\theta}+\dot{\nu})^2 + \frac{m_A}{2}(\dot{R}^2 + R^2\dot{\nu}^2) + \frac{m_B}{2}[(\dot{R}^2 + R^2\dot{\nu}^2) \\ & + 2l(\dot{\theta}+\dot{\alpha}+\dot{\nu})(-\dot{R}\sin(\theta+\alpha) + R\dot{\nu}\cos(\theta+\alpha)) \\ & + 2r_{P/A}(\dot{\theta}+\dot{\nu})(-\dot{R}\sin\theta + R\dot{\nu}\cos\theta + l^2(\dot{\theta}+\dot{\alpha}+\dot{\nu})^2 \\ & + 2lr_{P/A}(\dot{\theta}+\dot{\alpha}+\dot{\nu})(\dot{\theta}+\dot{\nu})\cos\alpha + r_{P/A}{}^2(\dot{\theta}+\dot{\nu})^2] \\ & + \frac{GMm_B}{R_B} + m_B V_{AST} + \frac{GMm_A}{R} \end{aligned} \quad (1)$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} \equiv 0, q_i = R, \nu, \theta, \alpha \quad (2)$$

The potential of the PHA is obtained through equation 3, taking into account the shape of the PHA.

$$V_{AST}(r_B, \varphi, \lambda) = \frac{Gm_A}{l}\left\{1 - \frac{C_{20}}{2}\left(\frac{r_o}{l}\right)^2 + 3C_{22}\cos(2\theta_0 + 2\alpha)\left(\frac{r_o}{l}\right)^2\right\} \quad (3)$$

3. Simulations

Asteroid Bennu (1999RQ36) is used for the simulations. Bennu is a B-type asteroid, about 492 meters in diameter, and spinning every 4.3 hours. It passes close to Earth about every 6 years, and the next close approach within 2 LD (~0.005 AU), will happen in 2060. For the simulations, we consider boulders ranging from 10 to 100 meters in size [5]. Table 1 shows the mass ratios considered.

Table 1: Boulder size and mass ratio for Bennu

Boulder (m)	M_B (kg)	M_B/M_A
10	$6.2x10^5$	$8x10^{-6}$
20	$5x10^6$	$6.4x10^{-5}$
30	$1.7x10^7$	$2.2x10^{-4}$
40	$4x10^7$	$1.9x10^3$
50	$7.8x10^7$	$1x10^{-3}$
60	$1.4x10^8$	$1.7x10^{-3}$
70	$2.1x10^8$	$2.7x10^{-3}$
80	$3.2x10^8$	$4.1x10^{-3}$
90	$4.6x10^8$	$5.8x10^{-3}$
100	$6.2x10^8$	$8x10^{-3}$

Results for several configurations will be presented, including different boulder sizes, tether lengths and points of attachment for the tether. The deflection is measured by analyzing the difference between the initial unperturbed orbit, before displacing the boulder from the surface of the asteroid, and the perturbed orbit, after connecting the boulder with the tether and releasing it around the asteroid.
This methodology offers the flexibility to adjust the amount of deflection with different configurations, considering the warning time available. In addition, this method doesn't result in fragmentation, which could be a potential risk.

Acknowledgements

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