Dynamics around the binary system (65803) Didymos

R. Machado Oliveira[1], O. C. Winter[1], R. Sfair[1], G. Valvano[1], T. S. Moura[1] and G. Borderes-Motta[2]

[1]Grupo de Dinâmica Oribtal e Planetologia, São Paulo State University, UNESP, Guaratinguetá, CEP 12516-410, São Paulo, Brazil

[2]Bioengineering and Aerospace Engineering Department, Universidad Carlos III de Madrid, Leganés, 28911, Madrid, Spain

Abstract. Didymos and Dimorphos are primary and secondary, respectively, asteroids who compose a binary system that make up the set of Near Earth Asteroids (NEAs). They are targets of the Double Asteroid Redirection Test (DART), the first test mission dedicated to study of planetary defense, for which the main goal is to measure the changes caused after the secondary body is hit by a kinect impactor. The present work intends to conduct a study, through numerical integrations, on the dynamics of massless particles distributed in the vicinity of the two bodies. An approximate shape for the primary body was considered as a model of mass concentrations (mascons) and the secondary was considered as a massive point. Our results show the location and size of stable regions, and also their lifetime.

Keywords. Asteroids; Binary system; Computational simulations; Mascons.

1. Introduction

The sub-kilometer asteroid Didymos and its moon Dimorphos form a binary system classified as a Near-Earth Asteroid and member of both the Apollo and Amor group†. The system was chosen as the target for the Double Asteroid Redirection Test (DART) mission, the first one dedicated to study of planetary defense (Cheng et al. 2018). The main DART objective is to test the asteroid deflection technique by intentionally impacting Dimorphos and measuring the changes in its orbit. Ground-based observatories will also monitor these changes, and more precise information about the orbital evolution of Dimorphos after the impact will be assessed by the Hera mission‡.

Here we investigate the dynamics around the binary system, taking into account the irregular shape of the primary and also the gravitational disturbance of Dimorphos. Our goal is to analyze the orbital evolution of test particles in the vicinity of the system, and verify the existence of stable regions where particles can remain for an extended period and eventually pose a threat to the mission.

Damme et al. (2017) made a similar study, but considering spacecraft (CubeSats) instead of natural particles. They adopted a gravitational model of Didymos, including spherical harmonics up to order and degree two, and integrating the system for short timescales (a few months). Here we consider a more complex gravitational model based on a polyhedron shape model and look for orbital stability on much longer timescales (several years).

† https://ssd.jpl.nasa.gov/sbdb.cgi?sstr=2065803
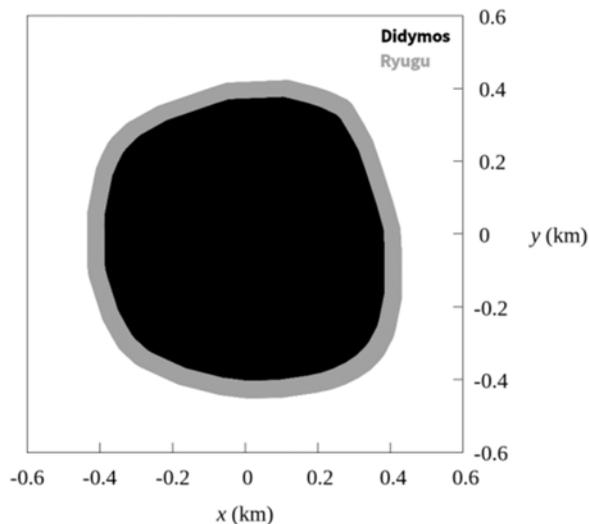‡ https://www.esa.int/Safety_Security/Hera/Hera

Figure 1. Comparative size between Didymos and Ryugu model.

This paper is organized as follows: in Section 2 we present the shape model adopted for Didymos, while the numerical setup and the main results are described in Section 3. The last section presents our final remarks.

2. Shape model

Given the irregular shape of Didymos, particles at the vicinity of the body are subject to a gravitational potential that cannot be reasonably modeled as originated from a point of mass or even an ellipsoid. However, the proper shape model for Didymos is not publicly available, and given that the object resembles the asteroid Ryugu, we assumed the shape as a scaled version of the latter.

From ground-based radar observations, Scheirich and Pravec (2009) determined an equivalent diameter of 780 m and Naidu et al. (2020) reported a bulk density as 2.17 gcm^{-3} for the primary. Starting from a polyhedra representation of Ryugu composed of 574 vertices and 1144 triangular faces (Müller et al. 2011), we determined the scaling factor that must be applied to Ryugu's shape to match the expected mass and volume for Didymos. A comparison between the two models is shown in Fig. 1.

Instead of computing the gravitational potential directly from the polyhedron (Werner 1994), our simulations were carried out with the more efficient, and yet precise, approach of mass concentrations – mascons (Geissler et al. 1996), implemented in the N-BOM package (Winter et al. 2020). From a regularly spaced tridimensional grid that encompasses the object, the mascons are those grid points that lie within the shape model. Assuming that Didymos is homogeneous, the total mass of the asteroid is evenly distributed among the 26070 mascons.

In our model, Didymos rotates with a period of 2.26 hours (Pravec et al. 2006). Dimorphos is represented as a point of mass with 3.45x10^9 kg orbiting the primary with a semimajor axis of 1178 m, and the eccentricity of 0.05 (Scheirich and Pravec 2009).

3. Stable regions

In order to explore the stability in the neighbourhood of the two bodies, we randomly distributed 20 thousand massless particles in a radial range between 0.45 and 1.45 km.
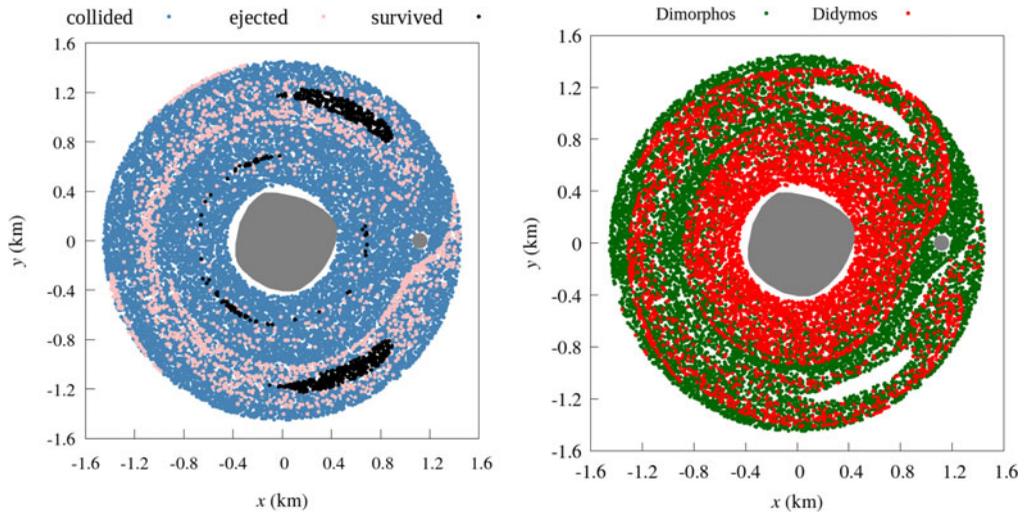
Figure 2. Fate of the particle after 5 years of simulation. The particles are shown at their initial positions. Left: The blue dots represent the particles that collided with one of the bodies, the pink dots indicate the ejected particles and the black dots the survived particles. Right: This plot shows only the collisions. The red dots represent the particles that collided with Didymos, while the green dots indicate the particles that collided with Dimorphos.

The initial conditions of the particles were determined by keplerian orbits with eccentricity and inclination equal to zero. The system was integrated for five years, which is the approximated interval between the DART† and HERA‡ missions. The criterion for the remotion from the system was a collision or an ejection. For the collision we took into account the approximated dimension of the primary's mascons model and the estimated mean radius of the secondary given by Scheirich and Pravec (2009). In the case of ejection, it was adopted 6 km as the maximum radial distance from the primary, the same as considered in Damme et al. (2017). This distance is about five times the value of the semi-major axis of Dimorphos.

The results are summarized in Fig. 2. It shows the particles at their initial positions and the colors indicate the fate of the particles at the end of the simulations. After five years of simulations, 8.74% were ejected, 30.3% collided with Didymos, 56.94% collided with Dimorphos and just 4.02% survived. From the features of this plot can be made some considerations. The particles that collided are initially spread over several regions (left plot). However, there is a pattern separating the the two groups of collision. As can be seen in the right plot, the particles that collided with Dimorphos are mainly located in two spiral arms that depart from the satellite. In the case of particles that collided with Didymos, they can be separated into two groups: one in a disk inside the orbit of Dimorphos and other involving the stable regions around the triangular lagrangian points. On the other hand, the particles that were ejected and those that survived are found initially in specific regions. The ejected particles were preferentially in places close to the orbit of Dimorphos. Their fate was determined by close encounters with the secondary.

In the case of the survivors, Fig. 2 (left plot) shows that they are initially located in the coorbital region, around the lagrangian points L_4 and L_5, and also in arcs of a ring formed between the two bodies. The particles around one of the two triangular lagrangian points present behaviours expected in binary systems. Since these are stable equilibrium

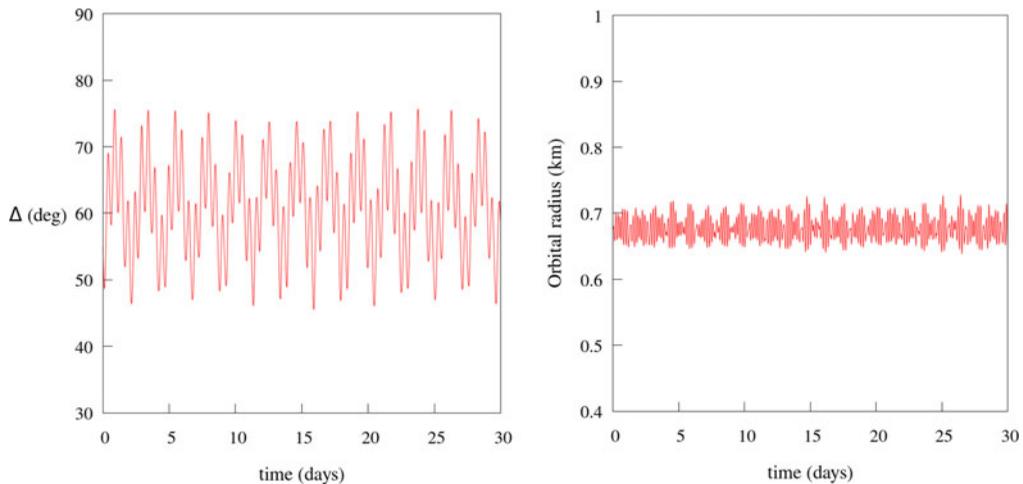**Figure 3.** Left: Example of the evolution of the angle between Dimorphos and a particle located around L_4 lagrangian point. Right: Example of the radial evolution of the trajectory of a particle located in one of the stable arcs close to Didymos.

points for the given mass ratio of the binary, it is coherent to have survivors around them. These particles show a tadpole like trajectory, as in the example given in Fig. 3 (left plot). The trajectories of the particles in the stable regions close to Didymos show a very narrow amplitude of radial variation. An example is given in Fig. 3 (right plot).

An idea of the time evolution of the system as a whole can be seen in Fig. 4. This plot shows the lifetime of the particles according to their initial location. The survivors are indicated in green. The system as seen in Fig. 2 is quickly defined, since 79% of the particles are removed within 10 days. Those that were removed in just a few hours are the ones that were close to the surface of Didymos and those that were in spiral arms associated to Dimorphos. The satellite is the responsible for the large majority of this fast removal in the first orbital periods of the particles, by collision with Dimorphos or ejection of the region.

Note in the Fig. 4 that the particles which live longer (very dark color) are in the neighbourhood of the survivors (in green). Some of these particles can stay alive for even more than one year of integration. The orbital period of the particles in the dark ring shown in Fig. 4 is a value in the range between five and six hours.

A comparison of these results with those of Damme et al. (2017) shows that the general structure is similar. However, in their work was found a large stable ring of initial conditions close to Didymos which is not the case in our results. That is certainly due to the large difference in timescales considered (a few months for them, while some years in ours), but the effects due to different gravitational potential models also contributed in the evolution of the trajectories with initial conditions closer to Didymos.

4. Final comments

In this work we explored the long term stability of massless particles in the Didymos-Dimorphos system. In order to take into account the gravitational contribution of Didymos, we developed an approximated shape model in terms of a polyhedron composed of triangular faces and then, transformed it in a model of Mascons.

The results clearly show the location and size of the stable regions. An analysis of the lifetime of the particles indicated that the huge majority of the particles with unstable
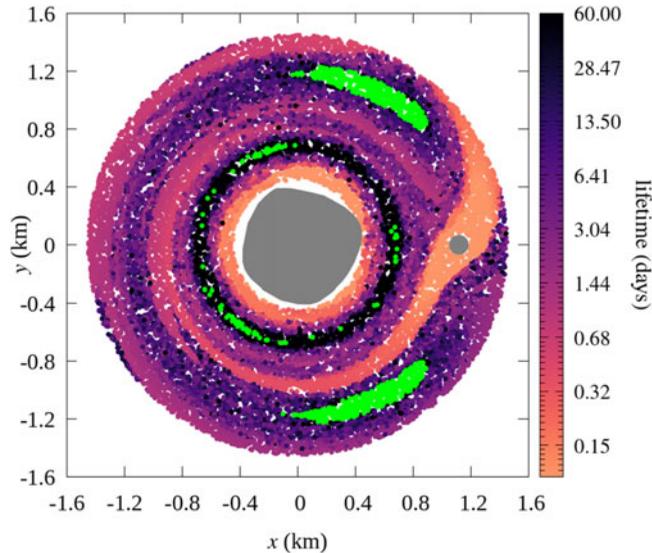
Figure 4. Lifetime of the particles according to their initial location. The particles that survived the whole integration time (5 years) are indicated in green.

trajectories are removed in just ten days. The largest amount of particles in the stable regions have tadpole like trajectories around the triangular lagrangian equilibrium points.

5. Acknowledgements

References

Cheng, A. F., Rivkin, A. S., Michel, P., Atchison, J., Barnouin, O., Benner, L., Chabot, N. L., Ernst, C., Fahnestock, E. G., Kueppers, M., Pravec, P., Rainey, E., Richardson, D. C., Stickle, A. M., & Thomas, C. 2018, Aida dart asteroid deflection test: Planetary defense and science objectives. *Planetary and Space Science*, 157, 104–115.

Damme, F., Hussmann, H., & Oberst, J. 2017, Spacecraft orbit lifetime within two binary near-earth asteroid systems. *Planetary and Space Science*, 146, 1–9.

Geissler, P., Petit, J. M., Durda, D. D., Greenberg, R., Bottke, W., Nolan, M., & Moore, J. 1996, Erosion and Ejecta Reaccretion on 243 Ida and Its Moon. *Icarus*, 120, 140–157.

Müller, T. G., Ďurech, J., Hasegawa, S., Abe, M., Kawakami, K., Kasuga, T., Kinoshita, D., Kuroda, D., Urakawa, S., Okumura, S., Sarugaku, Y., Miyasaka, S., Takagi, Y., Weissman, P. R., Choi, Y. J., Larson, S., Yanagisawa, K., & Nagayama, S. 2011, Thermo-physical properties of 162173 (1999 JU3), a potential flyby and rendezvous target for interplanetary missions. *Astronomy & Astrophysics*, 525, A145.

Naidu, S., Benner, L., Brozovic, M., Nolan, M., Ostro, S., Margot, J., Giorgini, J., Hirabayashi, T., Scheeres, D., Pravec, P., Scheirich, P., Magri, C., & Jao, J. 2020, Radar observations and a physical model of binary near-earth asteroid 65803 didymos, target of the dart mission. *Icarus*, 348, 113777.

Pravec, P., Scheirich, P., Kušnirák, P., Šarounová, L., Mottola, S., Hahn, G., Brown, P., Esquerdo, G., Kaiser, N., Krzeminski, Z., Pray, D., Warner, B., Harris, A., Nolan, M., Howell, E., Benner, L., Margot, J.-L., Galád, A., Holliday, W., Hicks, M., Krugly, Y.,

Tholen, D., Whiteley, R., Marchis, F., DeGraff, D., Grauer, A., Larson, S., Velichko, F., Cooney, W., Stephens, R., Zhu, J., Kirsch, K., Dyvig, R., Snyder, L., Reddy, V., Moore, S., Gajdoš, Világi, J., Masi, G., Higgins, D., Funkhouser, G., Knight, B., Slivan, S., Behrend, R., Grenon, M., Burki, G., Roy, R., Demeautis, C., Matter, D., Waelchli, N., Revaz, Y., Klotz, A., Rieugné, M., Thierry, P., Cotrez, V., Brunetto, L., & Kober, G. 2006, Photometric survey of binary near-earth asteroids. *Icarus*, 181(1), 63–93.

Scheirich, P. & Pravec, P. 2009, Modeling of lightcurves of binary asteroids. *Icarus*, 200(2), 531–547.

Werner, R. A. 1994, The Gravitational Potential of a Homogeneous Polyhedron or Don't Cut Corners. *Celestial Mechanics and Dynamical Astronomy*, 59(3), 253–278.

Winter, O. C., Valvano, G., Moura, T. S., Borderes-Motta, G., Amarante, A., & Sfair, R. 2020, Asteroid triple system 2001 SN$_{263}$: surfaces characteristics and dynamical environment. *Monthly Notices of the Royal Astronomical Society*, 492, 4437–4455.