

## ABSTRACT

Operating spacecraft in a perturbed environment of a binary asteroid system is a challenging task. In light of the near-future exploration of the 65803 Didymos system by the Hera probe and the lack of study of orbital evolution of naturally-levitated regolith particles in this system, a method is here proposed to identify regions of high risk of collision with the levitated regolith grains. Regions of regolith levitation are identified, periodic orbits and regions of stable motion are computed through a grid search method, and the distance between trajectories leading from the off-surface levitation of the grains from the primary body and the trajectories of bounded motion is then assessed to determine the occurrence of temporary capture. A qualitative evaluation of the expected patterns of motion of regolith particles is presented together with a discussion of the key conclusions in the context of *in situ* operations planning for the Hera probe.

## INTRODUCTION

Limited information available on the Didymos binary system introduces large uncertainties in the anticipated state of the system upon the arrival of the Hera spacecraft. One of the potential hazards to the probe may be posed by regolith grains floating in the binary system. To comprehend this hazard, the following phenomena must be considered: (1) trajectories of potential mass transfer between the bodies and (2) temporary capture of levitated regolith grains in periodic orbits or other types of bounded stable motion. This work thus focuses on determining the conditions leading to temporary capture of naturally-levitated regolith particles within the system using a high-fidelity model, the augmented bicircular problem. It is an augmentation of the circular-restricted three-body problem [1] with the ellipsoidal shapes (and mass distributions) of the asteroids, the Sun's third-body and solar-radiation pressure perturbations. The dynamical model is used to determine regions of levitation of 5-centimeter-diameter particles from the surface of Didymos and to study their fates. Periodic orbits and regions of bounded motion are identified using the grid search method. This work is concluded by performing an intersection of the results of two previous investigation parts, i.e., the set of initial conditions on the surface leading to levitation and the set of initial conditions leading to the temporary capture in bounded trajectories.

## DYNAMICAL MODEL

The Didymos system is composed of Didymos and Dimorphos. The former is of approximately 780 m and the latter of about 160 m in diameter. The bodies are assumed to be tri-axial ellipsoids of equal density. The system is semi-asynchronous, i.e., the period of Didymos' rotation is equal to 2.26 h, whereas the period of Dimorphos' and the binary system's rotation is equal to 11.92 h [2]. The binary orbit has an approximately null eccentricity.

The dynamical model used to study the motion of particles in the binary system is the augmented bicircular problem (ABP). It is an augmentation of the circular-restricted three-body problem [1]. The Sun's third-body and solar-radiation pressure (SRP) perturbations are also taken into account, where the Sun's motion is modeled as uniform, circular motion around the barycenter-located origin of the synodic reference frame (see fig. 1). The asteroids are modeled as tri-axial ellipsoids using the spherical-harmonics gravity model. The spherical-harmonic models of the asteroids use  $C_{2,0}$  and  $C_{2,2}$  Stokes coefficients computed by Damme et al. [3] from the radar-derived shape model of Didymos and assuming it to be a tri-axial ellipsoid of constant density. The use of the ABP is limited to the inside of the Hill sphere of the Didymos system and the outsides of the Brillouin spheres of the primaries.

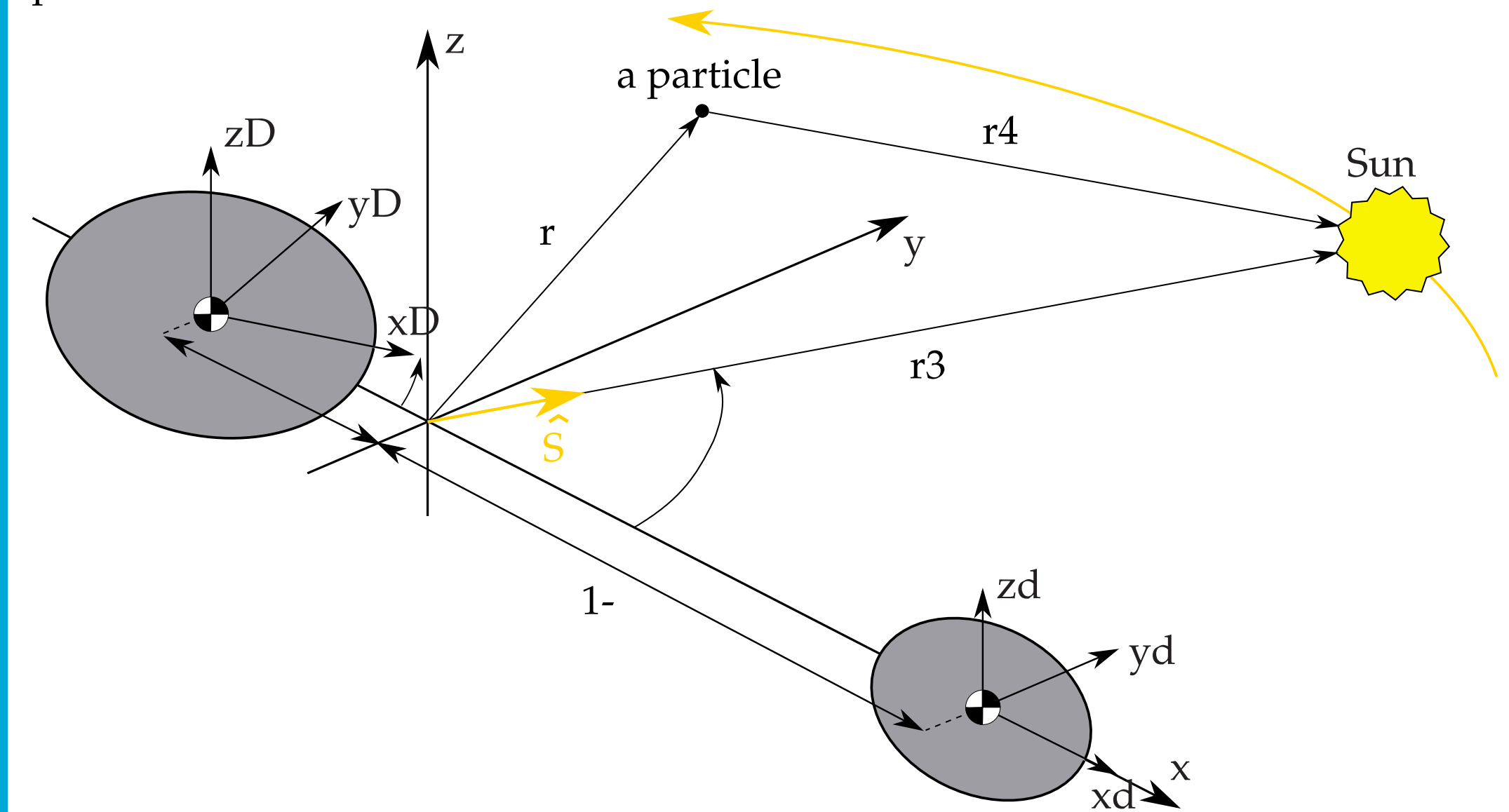


Figure 1 - Augmented bicircular problem

## DYNAMICAL MODEL (CONT.)

Since, contrary to the CR3BP, the primaries in the ABP are not point masses, a cylindrical eclipse model is introduced; therefore, the particles experience umbra, full-phase, or transition lighting (and, therefore, SRP) conditions.

The regolith particles are assumed to be perfectly round, uniformly reflective particles of three degrees of freedom and 5 cm of diameter. The density of the particles is assumed to be uniform and equal to the density of the asteroids.

Since the use of the ABP is limited to the outside of the Brillouin sphere, the proximity dynamical model (PDM) is introduced to allow for motion simulation between the surface of Didymos and its Brillouin sphere. The PDM is a modification of the ABP, where the spherical harmonics gravity field model of Didymos is substituted with a mass-concentration gravity field model [4]. The region of validity of this dynamical model is bounded by the surface of the Didymos, the Brillouin sphere of Dimorphos, and the Hill sphere of the Didymos system.

## PERIODIC ORBITS

The ABP describes a non-autonomous system due to the time-dependency of the primary's gravity field, the SRP acceleration and the third-body effect. Therefore, orbital motion in the system under analysis can only be periodic when it is aligned with the synodic periods of the motion of the Sun and the rotation of Didymos. The smallest common multiple of the two synodic periods  $T$  is found to be equal to 5 days 11 h (47 synodic periods of Didymos' rotation and 11 synodic periods of the binary orbit).

A classical grid search technique is used to identify initial conditions that lead to quasi-periodic solutions. The search is divided into two stages: coarse and refined. The coarse search studies the entirety of the discretized search domain via propagating the initial conditions over a time span  $T$  in the ABP model. Around the nodes in the grid search where the error (Euclidean norm of the difference of the initial and final state vectors) is below a defined threshold, a refined grid search is performed. By lowering the required Euclidean norm of the distance between the initial and final conditions in the refined search, only two sets of initial conditions for quasi-satellite orbits (QSO) and two for distant retrograde orbits (DRO) trajectories were found to satisfy the condition (see tab. 1 and fig. 2). The presented refinement of the domain resulted in an improvement of the solutions by a factor of 2 and 5, respectively to the DO and QSO, and may be performed iteratively to further improve the precision of the solutions. The search is performed for only one set of the initial position of the Sun and orientation of Didymos).

Table 1 - Overview of the coarse and refined grid search results

Stage	No. of nodes	Threshold value of $\ \mathbf{x}(t=0) - \mathbf{x}(t=T)\ $	No. of solutions	Smallest value of $\ \mathbf{x}(t=0) - \mathbf{x}(t=T)\ $
<b>DO</b>				
Coarse	16335	0.1	15	0.0145
Fine	17760	0.01	2	0.0073
<b>QSO</b>				
Coarse	20700	0.1	23	0.0271
Fine	54450	0.01	2	0.0054

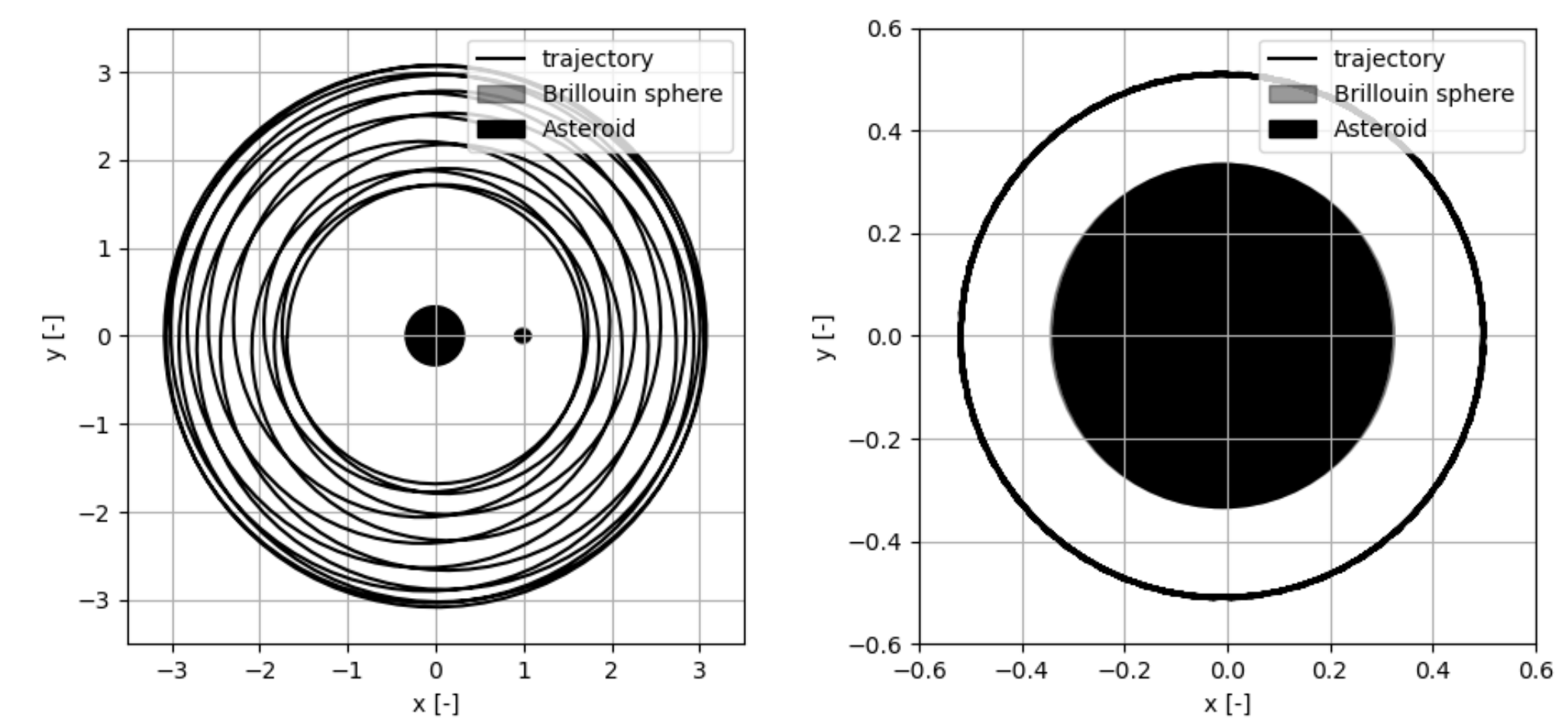


Figure 2 - Examples of the identified distant (left) and quasi-satellite (right) orbits

## LEVITATION ANALYSIS

Regions of levitation are determined by discretizing the ellipsoidal surface and projecting the acceleration vector experienced by a particle on the unit vector normal (outward) to the asteroid's surface. This enables us to determine levitation, which occurs if the dot-product of the two vectors is positive. Then, motion of the

## LEVITATION ANALYSIS (CONT.)

levitated particles is propagated until the Brillouin sphere or until redeposition on the surface of Didymos. Computation of acceleration vectors used to determine the levitation conditions and to conduct numerical propagation of the equations of motion was done using the PDM.

The analysis was conducted for 16 sets of initial conditions of the binary system: for initial orientations of the primary body  $\{0, \pi/2, \pi, 3\pi/2\}$  and initial positions of the Sun  $\{0, \pi/2, \pi, 3\pi/2\}$ . It is found that the regions of levitation and the statistics of fates of the particles do not change significantly between the sets of initial conditions;  $29\% \pm 2.5\%$  of the levitated particles survive in orbit for a period of time of approximately 15 days,  $62.15\% \pm 2.5\%$  redeposit on Didymos,  $7.35\% \pm 0.35\%$  collide with Dimorphos (half of which, in total  $3.75\% \pm 0.5\%$  rests on the non-Didymos facing hemisphere of the tidally-locked moonlet), and  $1.04\% \pm 0.55\%$  escape from the system. Examples of trajectories found after levitation are given in fig. 3.

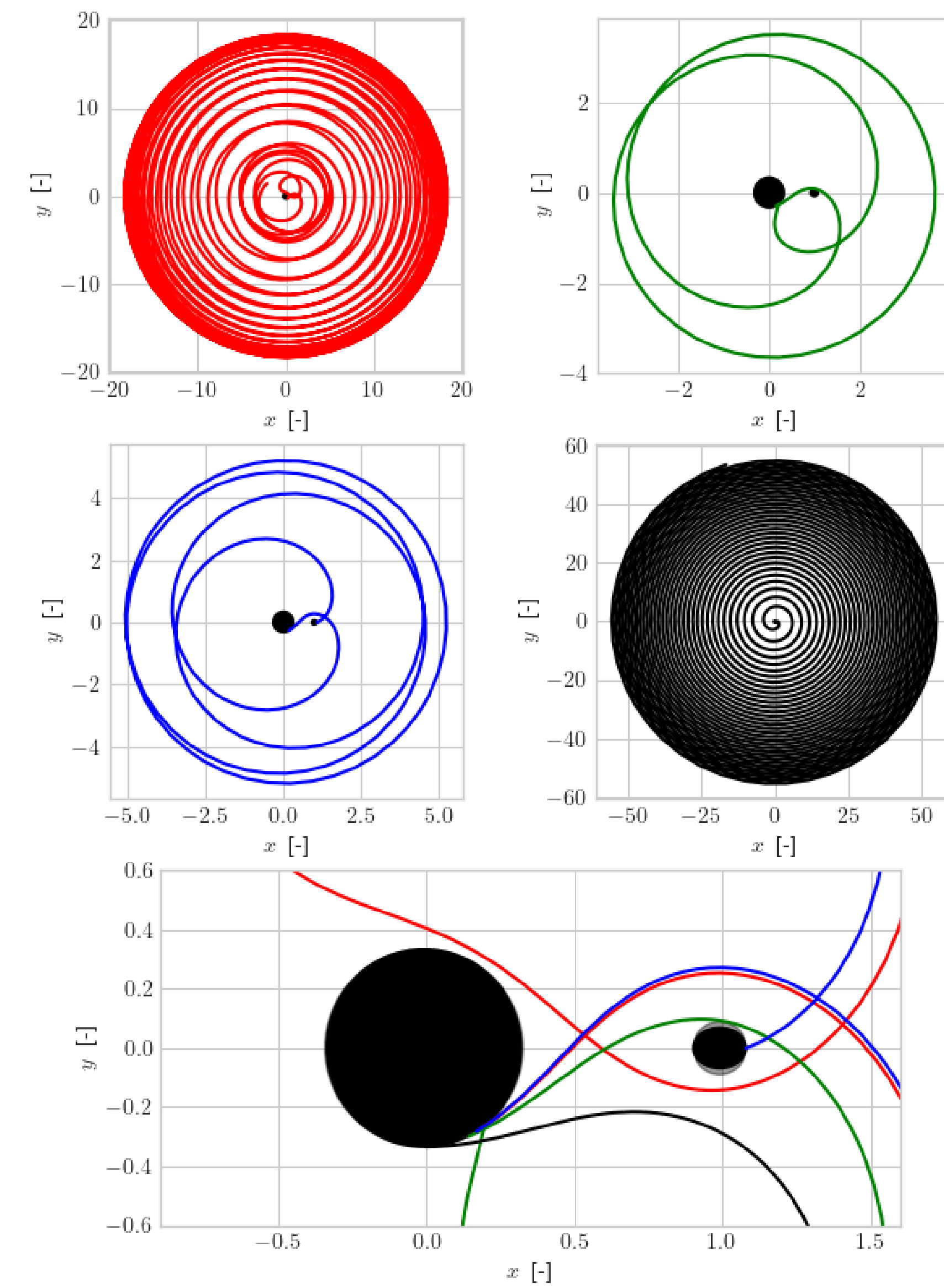


Figure 3 - Examples of topology of trajectories for each of the four fates of the levitated particles (red - survival, green - collision with Didymos, blue - collision with Dimorphos, black - escape)

## TEMPORARY CAPTURE

Temporary capture of levitated particles may occur if the escape trajectory (in the state space sense) passes close to a trajectory identified as a periodic orbit. The flow of the state space is not stationary due to the non-autonomous character of the problem; hence, the conventional 6-element state space does not represent all degrees of freedom of the problem. The state space is expanded by two additional dimensions: the orientation of the primary and the angular position of the third body in the bicircular problem. The occurrence of temporary capture is determined by finding the capture error, i.e., the minimum distance between the levitation and orbital trajectories at any point in the augmented state space.

The capture errors found in the analysis are large; the smallest capture error was found for the DO1 orbit, which amounts for 389.84 m error in position and

## TEMPORARY CAPTURE (CONT.)

1.056 cm/s in velocity. The smallest capture error for the QSOs is significantly larger than those for the DO case and corresponds to the instant of levitation of the particles. Therefore, the results are not sufficient to formulate conclusions with regards to the feasibility or infeasibility of temporary capture of off-Didymos-levitated regolith particles into periodic orbits in the binary system. In light of the large capture errors, for further research it is recommended to restrict the set of orbits considered for possible temporary capture by studying only orbits of similar orbital energy amplitudes as the levitated particles.

The primary region of hazard to the spacecraft would be the vicinity of the invariable plane of the system due to the small latitudes of levitated conditions and given the symmetry in the  $z$ -axis of the ABP and PDM. The levitation analysis showed that the survival rate after a time  $3T$  of the levitated particles is 16-68 times larger than the escape rate. Accounting for the regions of motion of the two types of fates of the levitated particles, existence of two dust disks is anticipated around the binary system: (1) the outer disk is composed of regolith particles that follow escaping trajectories; the dust grains can be found as far as the Hill Sphere, their motion is highly ordered, and an approximately uniform density in the disk is expected, whereas (2) the inner disk spans as far as 20 km from the barycenter of the binary, motion of particles is chaotic, which suggests an existence of both time- and spatial fluctuations of the disk density. The ultimate fate of the inner-disk trajectories is likely a collision with one of the asteroids; however given the small escape rates of the dust from the system after levitation and the long orbital lifetimes of the inner-disk trajectories, the inner disk is anticipated to be an ever-changing, dynamic, and self-exciting dust cloud spanning 20 km from the barycenter of the system in the invariable plane and up to 80 m in the normal-to-invariable-plane direction. Nevertheless, due to the uncertainties related to the properties of the asteroids of the Didymos binary, it is impossible to assess the densities of the two dust disks without the *in situ*-collected information about the levitation mass flow off Didymos, which the DART-accompanying probes might soon deliver [2].

## CONCLUSIONS

Analysis of the orbital evolution of trajectories originating upon levitation from the primary body, Didymos, resulted in a comprehensive overview of the behavior of the loose regolith from the equatorial regions of Didymos: about 60% of the levitated particles were found to redeposit on Didymos within 15 days of levitation, whereas 7% of the levitated particles collide with the secondary body, Dimorphos. The rate of collision with Dimorphos is approximately equal between the Didymos- and outer space-facing hemispheres of the tidally-locked moonlet. One of the most important takeaways of the study is the discovery of escape of a relatively large portion of the levitated particles (about 1%). Almost 30% of the levitated trajectories remain in the binary system (do not escape and do not deposit on any of the asteroids) after the propagation period slightly exceeding 15 days; prominent existence of dust ejecta clouds in the Didymos system months after the DART spacecraft's impact indicate that the survival periods might be much longer than the 15 days which constituted the propagation limit in the study. The phenomena of extended survival in the binary system and slow, spiraling escape from the system suggest existence of a very polluted (in the sense of the regolith) regions throughout the binary system, in the vicinity of its invariable plane. Existence of two dust disks is suggested as potential region of elevated hazard for the visiting spacecraft. Temporary capture of particles in periodic orbits in the binary system has not been demonstrated due to large capture errors. The findings are anticipated to render important contributions to planning of the Hera spacecraft's operations in the Didymos system and to provide a valuable starting point for further investigation of the dust dynamics in said system. The recent arrival of the DART probe to the binary is expected to deliver much more detailed data on the binary and remove numerous uncertainties pointed out in this work.

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