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Dynamics of ejecta from a binary asteroid impact in the framework of the AIDA mission: a NEOShield-2 contribution

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Abstract

The dynamics of the ejecta cloud that results from a binary asteroid impact is one of the tasks of the NEOShield-2 project, funded by the European Commission in its program Horizon 2020. Results from such an investigation will have great relevance to the Phase-A study of the AIDA space mission, a collaborative effort between ESA and NASA, which aims to perform a kinetic impactor demonstration. Our study presents a multi-scale dynamical model of the ejecta cloud produced by a hypervelocity impact, which enables us to check the behaviors of the ejecta at different spatial and time scales. This model is applied to the impact into the small moon of the binary Near-Earth asteroid (65803) Didymos on October 2022 as considered by the AIDA mission. We attempt to model the process by including as much practical information as possible, e.g., the gravitational environment influenced by the non-spherical shapes of the bodies (based on observed shape of the primary), the solar tides, and the solar radiation pressure. Our simulations show the general patterns of motion of the ejecta cloud, which we use to assess the potential hazard to an observing spacecraft. We also look into the grain-scale dynamics of the ejecta during this process, which has influence on the re-accumulation of particles orbiting in the vicinity.

1. Introduction

The study of the fate of ejecta from a hypervelocity impact is part of the NEOShield-2 project funded by the European Commission in its program Horizon 2020. It is applied to the case of the AIDA mission, which aims at deflecting the small moon of the binary NEA (65803) Didymos using a kinetic impactor at its close approach to the Earth in October 2022.

The evolution and fate of the ejecta from an impact performed by a hypervelocity projectile in the context of a space mission is still poorly understood, and only a few studies were devoted to it [e.g., 1–3]. The importance of the study of ejecta dynamics is apparent: (i) it contributes to the understanding of the spacecraft's working environment for better risk management; (ii) it provides crucial information for the ground-based observation of the impact outcome, which is planed for AIDA; (iii) it contributes to the theoretical understanding of small binary formation mechanisms with a wealth of empirical data.

In this study, we apply different methodologies in modeling the behaviors of the ejecta cloud at different time and size scales. The initial conditions of the ejecta are defined from the results of the excavation stage [4]. A series of simulations are run forward to assess the fate of ejected grain fragments based on the considered impact conditions at Didymos in 2022. As results, we show the basic patterns of motion of the ejecta cloud as well as the grain-scale dynamics of the ejecta during this process.

2. Multi-scale modeling of the ejecta cloud

The ejecta cloud produced by a hypervelocity impact is a complex dynamical problem, because it involves large- and small-scale behaviors, i.e., the orbital motion at the astronomical scale is as important as the interactions are between the ejecta materials at the granular scale. In this section, we develop multi-scale models to describe the evolution of the ejecta cloud, informed by physics at all relevant size scales, while maintaining a balance between accuracy and efficiency.

2.1 Analytical model based on CRTBP

The circular restricted three-body problem (CRTBP) is applied as an analytical model for the orbital evolution of the ejecta cloud. It provides fundamental information on the trajectory morphology, accessible region and stability (see Figure 1), serving as a rough guide for detailed simulations.

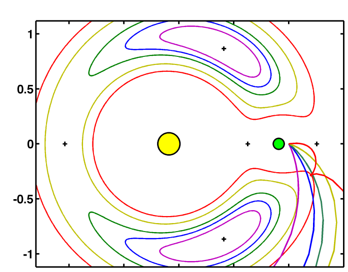

Figure 1: Sample ejecta trajectories based on CRTBP model with corresponding zero-velocity curves, marked with the same color. The solid circles indicate the

primary (yellow) and secondary (green), and the plus signs indicate the Lagrange points.

2.2 Modeling of the near-field motion

A precise near-field model is under construction, in order to replicate the ejecta cloud moving and fluctuating near the binary asteroid. The latest shape model of the primary of Didymos is applied (Figure 2), and for the secondary we use a sphere with its current estimated diameter of 170 m.

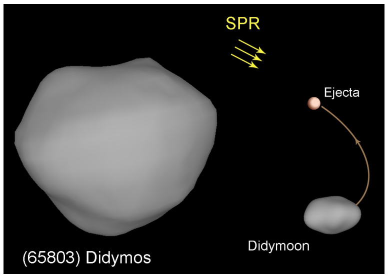

Figure 2: Diagram of the near-field model

A full two-body model is developed to assess the coupling motion of binary system. The potential of the primary is derived using the polyhedral method. The ejecta are modeled explicitly as small spheres whose exact sizes follow a power-law distribution (the effects of gravity from the ejecta on the binary system are neglected). The solar radiation pressure (SPR) and solar tide are also taken into account. A shadow algorithm based on ray-tracing is applied for resolving the occultation problem as the ejecta moving in the vicinity of the binary system. And for the asteroid surface collisional routine, we apply an algorithm based on quartic Bézier patches.

2.3 Modeling the interactions among the ejecta

We use pkdgrav for granular modeling, which implements a soft-sphere collisional routine in a parallel gravitational *N*-body tree code [5]. It is adapted to model a great number of particles with mutual gravity and contact forces (see Figure 3).

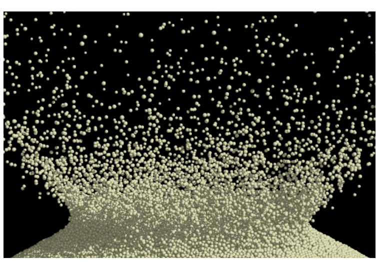

Figure 3: Ejecta grains after a simulated hypervelocity impact on a sandpile, running in space with intermittent collisions between.

3. Fates of the ejecta

With a combination of three models in different scales, we show the ejecta behavior both for the orbital evolution and the granular behaviors. This enables us to predict the fates of the ejecta, with special attention given to the potential hazards of large debris and the re-accumulation of the ejecta. Three aspects will be discussed further: (i) the characterization of ejecta cloud motion, composed of a great number of particles, each of which may experience complicated behavior in transient orbit or on the surfaces of the asteroids; (ii) the accessible regions of the ejecta, and the probability distributions of the ejecta mass and kinetic energy; (iii) the re-accumulation of the ejecta, including the material that re-impact the surface (greatly influenced by the shapes of the two asteroids) and the orbiting components (possible clues to satellite formation).

4. Summary and discussion

In the framework of the NEOShield-2 project and applied to the AIDA mission, this study looks at the dynamics of the ejecta cloud around the binary NEA Didymos. Different modeling methods are employed due to the various behaviors of the ejecta at different spatial and time scales. Numerical simulations are performed to explore the general pattern of the ejecta cloud motion and the fates of ejected grain fragments based on the considered impact mission with Didymos in October 2022. Owing to the mission requirement, the potential hazard from the ejecta is the focus of the predictive analysis. The accessible regions and the spatial distribution of the ejecta are analyzed; we also pay attention to the parameter dependence, e.g., the selection of impact points on Didymos' secondary.

Acknowledgements

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