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Asteroid Impact and Deflection Assessment (AIDA) mission: science investigation of a binary system and mitigation test

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Abstract

The Asteroid Impact & Deflection Assessment (AIDA) mission will be the first space experiment to investigate a binary near-Earth asteroid (NEA) and to demonstrate asteroid impact hazard mitigation by using a kinetic impactor. AIDA is a joint ESA-NASA cooperative project, which includes the ESA Asteroid Impact Mission (AIM) rendezvous spacecraft and the NASA Double Asteroid Redirection Test (DART) mission. The primary goals of AIDA are (i) to investigate the binary NEA (65803) Didymos, (ii) to test our ability to impact its moon by an hypervelocity projectile in 2022 and (iii) to measure and characterize the impact deflection both from space with AIM and from ground based observatories.

1. Introduction

AIDA is a joint ESA-NASA cooperative project, which includes the ESA Asteroid Impact Mission (AIM) rendezvous spacecraft and the NASA Double Asteroid Redirection Test (DART) mission. The AIM study entered Phase A/B1 at ESA in early 2015 and will proceed through summer 2016. The DART study entered NASA Phase A in late spring 2015 and will also proceed through summer 2016. The critical decisions on AIM and DART to proceed to the next phases at ESA and NASA will be made at roughly the same time (second half 2016).

The target of AIDA is the binary NEA (65803) Didymos, with the deflection experiment to occur in October, 2022. The DART impact on the secondary member of the binary at ~6 km/s will alter the binary orbit period, which can be measured by Earth-based observatories. The AIM spacecraft will be launched in 2020 and arrive at Didymos in spring 2022. AIM will characterize the Didymos binary system by means of remote sensing and in-situ instruments and monitor results of the DART impact.

AIDA addresses issues that interest a large variety of communities, such as communities of researchers and engineers working on impact physics, planetary defense, seismology, geophysics (surface and internal properties), dynamics, mineralogy and resources, spectral and physical properties of small bodies, low-gravity environments and human exploration.

2. AIM: science return

AIM [1] is a rendezvous mission that focuses on the monitoring aspects i.e., the capability to determine in-situ the key properties of Didymos' satellite used as the target of the deflection test. AIM will also give access to the detailed conditions of the DART impact and its outcome, allowing for the first time to get a complete picture of such an event, a better interpretation of the deflection measurement and a possibility to compare with numerical modeling predictions. Baseline payloads for AIM include the following remote sensing and in-situ instruments: a Visual Imaging System, a lander (based on DLR MASCOT heritage), a thermal infrared imager, a high frequency (decimeter-wave) radar, and a low frequency (60 MHz) radar, to measure Didymos surface and sub-surface physical properties and to study internal structures. AIM also includes an optical communication demonstration that can be used as a laser altimeter and CubeSat payloads.

AIM has several objectives. First, AIM will characterize for the first time the secondary of a binary asteroid, allowing us to better understand the formation and properties of these systems that represent 15% of the NEA population. Second, AIM will demonstrate the technologies required by a simple monitoring spacecraft as well as establishing the suitability of binary asteroids as candidates for future explorations and asteroid deflection tests. Finally AIM will demonstrate, on the minimum expression of a deep-space mission, technologies related to autonomous navigation, optical communication, on-board resources management and close proximity operations.

AIM is not meant to be a purely scientific mission but rather a technology demonstration. However, AIM will improve drastically our scientific knowledge on small asteroids, in very relevant areas of Solar System science, such as asteroid geophysics, granular mechanics, impact processes, and thermal effects/properties.

The characterization of Didymos' satellite by AIM will provide precious knowledge on the physical/compositional properties of at least a component of a near-Earth-Asteroid (NEA). Physical and compositional properties of small bodies provide crucial information on the dynamical and collisional history of our Solar System. In addition, the formation mechanism of small binaries is still a matter of debate, although several scenarios have been proposed to explain their existence. In particular, rotational disruption of an NEA, assumed to be an aggregate, as a result of spin-up above the fission threshold due to the YORP effect (a thermal effect which can slowly increase or decrease the rotation rate of irregular objects) has been shown to be a mechanism that can produce binary asteroids with properties that are consistent with those observed. These properties include the oblate spheroidal shape of the primary, the size ratio of the primary to the secondary and the circular equatorial secondary orbit [2]. Other fission scenarios have been proposed which imply different physical properties of the binary and its progenitor [3]. Binary formation scenarios therefore place constraints on, and implications for the internal structure of these objects.

Small asteroids undergo substantial physical evolutions, and yet the geophysics and mechanics of these processes are still a mystery. AIM will allow us to address fundamental questions, such as: what are the subsurface and internal structures of asteroid's satellites and how does an asteroid's surface relate to its subsurface? What are the geophysical processes that drive binary asteroid formation? What are the strength and thermal properties of a small asteroid's surface? What is the cohesion within an aggregate in micro-gravity? What are the physical properties of the regolith covering asteroid surfaces and how does it react dynamically to external processes, such as the landing of a surface package and/or an impact?

3. DART: science return

The primary goals of DART [4] are (i) to demonstrate a hypervelocity spacecraft impact on a small near-Earth asteroid (NEA) and (ii) to measure and understand the deflection caused by the impact. The DART mission includes ground-based optical and radar-observing campaigns of Didymos both before and after the kinetic impact experiment, as well as modeling and simulation programs. DART has the further objective to learn how to mitigate an asteroid threat by kinetic impact and to develop and validate models for momentum transfer in asteroid impacts. AIM will further make detailed measurements of the DART impact and its outcome.

6. Summary and Conclusions

The DART and AIM missions, comprising AIDA, will return fundamental new information on a binary system, on its mechanical response, on the impact cratering process, and consequently on the collisional evolution of asteroids with implications for planetary defense, human spaceflight, and Solar System science. AIDA mission studies involve various scientific activities regarding binary dynamics and impact modeling, asteroid geophysics, observations. AIDA will be the first fully documented impact experiment at real asteroid scale, allowing numerical codes to be tested and used for similar and other scientific applications at those scales.

Acknowledgements

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Internal structure of small asteroids by N-body numerical simulations of non-spherical fragment shapes

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Abstract

The internal structure of asteroids and comets is fundamentally unknown due to difficulties in sounding their interiors. The measurements carried on by space probes and the observations of binary asteroids (optical and radar) have allowed acceptable estimates of the masses of only a few asteroids. From their sizes and shape models estimates of their bulk densities are derived. Such bulk densities are usually smaller than the values corresponding to typical densities of meteorites with compositions matching spectroscopical observations of the surfaces of those asteroids, rising doubts about the actual composition and structure of their interiors [1]. Similar arguments –but with much larger uncertainties- hold for comets.

The interpretation of such low bulk densities is that part of the volume inside some of those objects is occupied by voids in between the coherent components forming their global structures, qualifying them as gravitational aggregates (also, “rubble-piles”). The origin of such bodies is clearly related to former catastrophic or gradual [2] disruptions. Moreover, numerical simulations of the collisional evolution of the asteroid belt predict that most of the bodies between some hundreds of meters and about 100 km should be gravitational aggregates [3]. The situation is a little fuzzier in the case of comets.

1. Methodology.

In this work we go one step beyond the standard spherical approximation for the shapes of single components of gravitational aggregates. Firstly we try to reproduce the internal structure of some of the asteroids with best known physical characteristics (mass, size, shape, spin rate). Secondly, we investigate the dynamics of the components of gravitational aggregates under different initial conditions corresponding to the event forming the final object and to the circumstances of shattering of the parent body. We perform that by means of numerical simulations that produce irregularly shaped asteroid components. Simulations are performed by the soft-sphere discrete element model PKDGRAV code that manages the N-body gravitational problem and accounts for collisions and friction between components. In order to create non-spherical shapes for the fragments constituting our synthetic asteroids, groups of spherical particles –the basic elements of the PKDGRAV code- are clumped together and forced to keep their mutual distance constant so they can be handled and behave like rigid bodies. We draw at random mass and shape distributions for the components of each synthetic aggregate from the corresponding distributions found in a set of laboratory shattering experiments performed at NASA-Ames facilities (S. José, CA, U.S.A.) in July 2013 [4].

Considering an arbitrary number of such irregular components and different mass spectra, we allow for self collapse by mutual gravitational interactions, starting from disperse initial space configurations and angular momenta. By varying the density of components we try to get gravitational aggregates with observable physical characteristics.

2. Results.

In this way we obtain families of qualitatively similar shapes and we are able to reproduce the best density estimates available for the two parts of asteroid Itokawa [5]. According to our simulations, the formation of small body structures so-called “contact binaries” (Itokawa, Toutatis, Castalia, Comet Borrelly, …) would be a natural outcome of gravitational reaccumulation rather than the collapse of binary systems. As a consequence of our simulation results, we also point out the possibility that current bulk densities for asteroids with poorly determined shapes may be overestimated.

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Catastrophic collisions: structure of the ejecta velocity field and reaccumulation

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1. Introduction

According to hydrodynamic simulations, the outcomes of catastrophic collisions involving asteroids are usually small fragments (below the observability threshold), which are later re-accumulated into larger bodies, leading to the formation of observable dynamical families. The re-accumulation into a large number of bodies is not a trivial outcome of any possible ejecta velocity field. If the field has a regular structure, such as those envisaged by the so-called Semi Empirical Models (SEM) a couple of decades ago [1], the re-accumulation usually involves a few bodies [2].

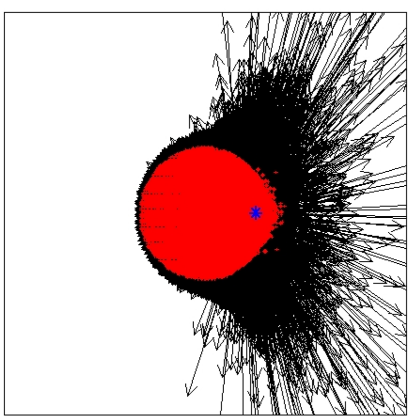

Figure 1: An example of ejection velocity field produced by hydrodynamic simulations. Red dot represents the initial positions of the particles, while black arrows their velocities. The blue star is the irradiation point.

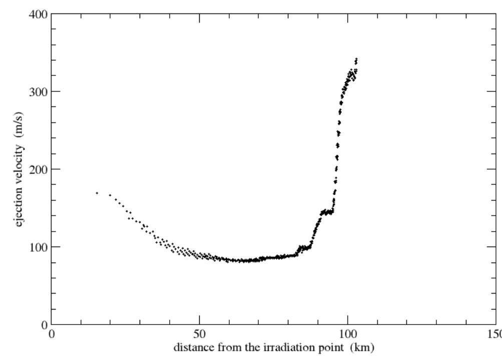

Figure 2: Module of the ejection velocity versus distance from the irradiation point for some particles of a hydrodynamic simulation. The particles are selected such that their initial positions were along a common line passing by the irradiation point.

2. Reconstruction of ejecta velocity fields

In a previous paper [3] we have analyzed the outcomes of a couple of hydrodynamic simulations to infer the kinematical properties of the ejecta velocity field. Like in SEM, hydrodynamic produce ejection velocity fields characterized by the presence of an irradiation point, that is a point (different from the center of the body) from which the trajectories of the fragments seem to emanate (Fig. 1). On the other hand, we have found that the field presents two main "irregularities":

1. a wave in the intensity of the field or, in other terms, bodies ejected along a line have a velocity which is not regularly increasing or decreasing with the distance from the irradiation point (Fig. 2);

2. a systematic misalignment of the velocities, that is the ejection velocities of fragments are not perfectly radial.

The main consequence of this structure is the possibility of early collisions between fragments, involving a significant fraction of them. As opposite, in the typical ejection velocity field modeled by the SEM, the collisions can occur only at a later stage, due to mutual gravity.

3. Preliminary computations

As a natural continuation of the analysis we have created a few new synthetic fields, in such a way to mimic the overall properties of those obtained from the hydrocodes, and we have simulated the evolution of the fragments using the software `pkdgrav` [4], to verify the later reaccumulation properties and to obtain a final mass function, to be compared to those obtained from hydrocodes and to real asteroid families. Preliminary results will be presented.

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Simulations of vibration-driven regolith segregation in the low-gravity asteroid environment

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Abstract

Since the release of the first *in situ* images of asteroid surfaces by various space missions, several studies have attempted to understand the origin of visible evidence of possible regolith motion, accumulation, and segregation on asteroid surfaces (for example, boulders on the surface of asteroid Itokawa [1]). A plausible explanation for these phenomena that has recently been explored is that motion is caused by seismic waves, engendered by numerous micro-meteoroid impacts that asteroids undergo in their lifetime. In fact, vibrations induced by small impacts have already been considered in the study of regolith segregation, and more specifically in the case of the so-called Brazil nut effect (BNE) on asteroids [2, 3]. To further investigate this, we perform numerical simulations with an extension of the *N*-body code PKDGRAV [4] used by Matsumura et al. [2]. Our interest is in going beyond the classic BNE scheme (a single intruder of bigger size in a granular bed) and in looking into potential size and/or density segregation of regolith materials, and the dependency of the outcomes on material parameters. In order for our simulations to better represent actual asteroid surface conditions, we have introduced periodic boundary conditions, i.e., we have removed the simulated container of the granular bed, and at the same time, any artifacts that may arise by its presence. Preliminary results of our simulations will be presented. Going forward, we aim to establish scaling laws for regolith segregation in micro-gravity environments, which take into account material properties. To better apply our results in an asteroid-related context, we plan additionally to use realistic impact-generated seismic profiles (e.g., [5]) instead of the continuous sinusoidal shaking implemented until now.

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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.

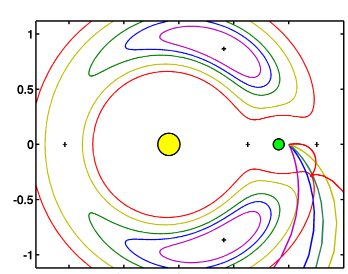

Figure 1: Sample ejecta trajectories based on CRTBP model with corresponding zero-velocity curves, marked with the same color. The solid circles indicate the

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.

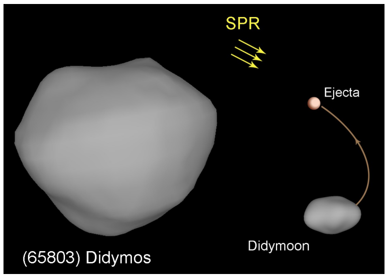

Figure 2: Diagram of the near-field model

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).

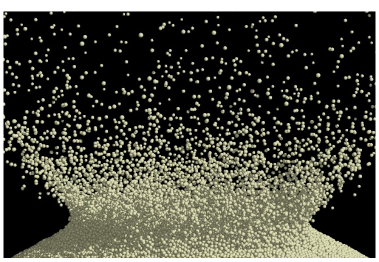

Figure 3: Ejecta grains after a simulated hypervelocity impact on a sandpile, running in space with intermittent collisions between.

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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A Survey for Extreme Shape Hilda Asteroids

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Abstract

We will present results of a survey of Hilda asteroids to look for extreme shape objects. We used WISE [1, 2] sparse IR photometry to identify objects with high photometric variability in different bands. Highly variable candidates were targeted by densely sampled, follow-up ground-based photometry.

Similar strategies were successfully used to identify extreme shape objects among Jovian Trojans [3] (see Fig. 1) and Kuiper belt objects [4]. These surveys found high intrinsic abundances of highly variable objects in both population and led to the discovery of contact binaries.

Contact binaries and extreme shape objects are useful as they permit useful bulk density estimates [5, 6] which in the long run can be used to, e.g., trace differences in the bulk composition of different populations. Repeated variability observations of candidate contact binaries among Hilda asteroids will be used to measure their obliquity, which may shed light on how these objects formed [7].

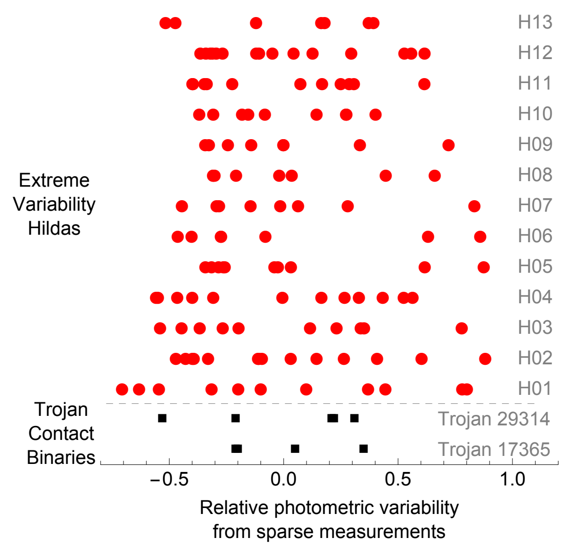

Figure 1: WISE sparse photometry of highly variable Hilda asteroids (red circles; each row represents a Hilda asteroid, labeled H01-H13, and show relative photometry along the x-axis). Also shown is similar sparse photometry from [3] (black squares) that led to the discovery of Trojan contact binaries 29314 and 17365.

Acknowledgements

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