Modeling and Simulation of Impact Outcomes: Ejecta Properties and Evolution

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The Asteroid Impact and Deflection Assessment Mission

The Asteroid Impact Deflection and Assessment (AIDA) mission is the first actual deflection test currently under study by two main space agencies [1]. This mission, which is under Phase-A/B1 study at ESA and Phase-A study at NASA until summer 2016, plans to characterize the secondary of the near-Earth binary asteroid 65803 Didymos and to perform a deflection test using a kinetic impactor in 2022 (Fig. 1). ESA is tasked with the design of an orbiting spacecraft, Asteroid Impact Mission (AIM) [2], and NASA is tasked with the design of a kinetic impactor, Double Asteroid Redirect Test (DART) [3]. The AIDA target is the near-Earth binary asteroid 65803 Didymos, which will make an unusually close approach to Earth in October, 2022. The ~300-kg DART spacecraft is designed to impact the Didymos secondary at 7 km/s and demonstrate the ability to modify its trajectory through momentum transfer.

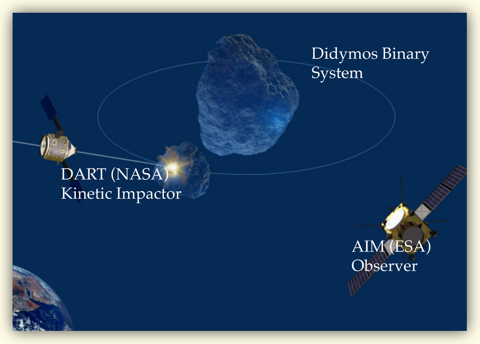

Figure 1: The AIDA mission concept—an effort to perform and observe a planetary-scale impact on a well-characterized body. DART + AIM = AIDA.

Why Conduct a Study on the DART Impact Ejecta?

- It contributes to the understanding of the spacecraft's working environment and is crucial to risk management.
- It provides important information for the ground-based observation of the impact outcome, which is planned for AIDA.
- Ejecta contribute to the overall momentum that is transferred to the impacted body.
- Knowledge about the evolution of the ejecta contributes to the theoretical understanding of formation mechanisms of small binaries.
- Just a few studies to date have been devoted to assessing the ejecta that result from a kinetic impactor deflection attempt, e.g., [4–6].

Ejecta Velocities

Within the parameters defined by observational and experimental data, different assumptions about the physical properties of the Didymos secondary will lead to different ejection properties of the generated debris. Useful bounds on ejection velocities can be made by conducting impact experiments in the lab using a variety of target materials.

Porosity

The porosity of the target is known to have a strong effect on ejection velocities. Figure 2 shows the ejecta velocity distribution in nondimensional form [7] for materials with porosity ranging from 0% (water) up to 85% (granular pumice). Other materials, with intermediate porosities, are shown as well. The y-axis is the ejection speed divided by the impact speed. These experimental results clearly show that, for a given launch position, the ejection speed steadily decreases with increasing target porosity. Although comprehensive experiments are typically confined to Earth-gravity conditions, this general trend should hold in different gravitational regimes. In support of these two conclusions, and exploring ejecta properties based on additional target parameters (different forms of friction, cohesion), we have used distinct types of numerical tools, e.g., the shock physics code iSALE [8], smoothed particle hydrodynamics codes, e.g., [9], and the granular code PKDGRAV [10–13]. The iSALE models show that under 1-g conditions, the ejection angle tends to be steeper for the early ejecta, although certain SPH/PKDGRAV simulations suggest that this latter result may not hold in microgravity [14].

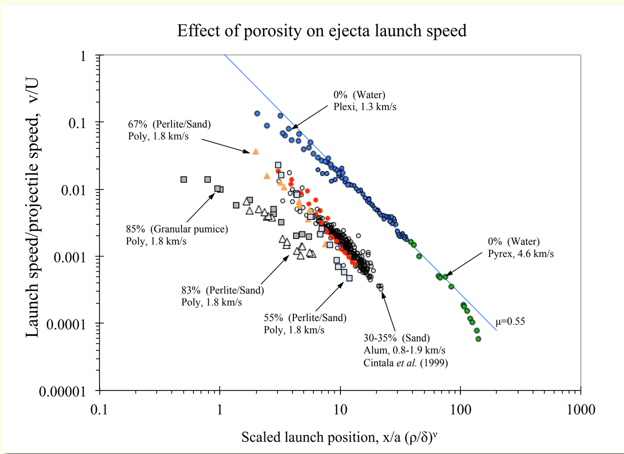

Figure 2: Measurements of the crater ejecta velocity distribution from lab experiments. Each data set is labeled by the target porosity, material type, impactor material, and impact speed. Data are from experiments conducted by K.R. Housen in the Boeing Shock Physics Lab, save for the dataset for sand [15].

v: launch speed; **U**: impactor speed;
x: launch distance from impact point;
a: impactor radius; **ρ**: target density;
v: point-source scaling exponent = 0.4;
δ: impactor density.

The porosity of the Didymos secondary is difficult to determine with good precision, although estimates can be made. Other material properties remain highly unknown. Nevertheless, based on a range of assumptions of their values, we can use these results to help form some basis for numerical simulations of the fate of the material ejected during the DART impact.

Low-speed Ejecta

Material at speeds safely above the escape speed of the system are cleared from the vicinity relatively quickly. It is the low-speed material that lingers that can cause problems to the AIM spacecraft days or weeks after the event. Escape speeds from all points on the surface of the Didymos secondary are expected to be below 10 cm/s. If we assume Fig. 1 holds for gravity regimes at 4 or more orders of magnitudes below Earth's gravity and extrapolate **v**/**U** to values sufficiently below 10^{-6}, we can arrive at some rough estimates for the amounts of ejecta that leave the impact crater at speeds below escape speeds, and for their ejection angles. However, in regimes of weak gravity, the effects from non-gravitational forces, such as intermolecular forces and those due to grain-charging, are enhanced. This significantly adds to the uncertainty in predicting the ejecta behavior at the ejecta speeds that we are most interested in. Therefore, a necessary task of our working group is to explore a wide range of material properties and ejecta behaviors in order to try to account for the the type of environment that AIM may encounter.

Lofting of Loose Surface Regolith

In addition to low-speed material ejected from the impact crater, impacts on asteroids can have effects far beyond the final crater radius, resulting from re-impacting ejecta, and also from seismic energy propagation. The seismic efficiency and quality factor as a function of porosity is being investigated by applying numerical models to impact experiments equipped with seismic sensors and pressure gauges [16]. Seismic effects in microgravity can be expressed as the low-speed lofting of material not initially lying within the nominal crater radius, as well as structural changes (fissures, slumps) occurring regionally or globally, as well as crater erasure [17–20]. One science objective of AIDA is to compare detailed before-and-after asteroid geomorphology, down to the precise (~10 cm) locations and orientations of major boulders and the precise (~1 m) global shape. These displacements can be translated into models for ground motion and cohesion. Such models will complement the in-situ seismology of the AIM lander, providing global- and regional-scale context, and will compensate for the likelihood that the seismic array itself will be displaced by DART.

Working Group Members

The study of the properties and evolution of ejecta resulting from the Double Asteroid Redirection Test (DART) is the task of the Modeling and Simulation of Impact Outcomes Working Group, in support of the Asteroid Impact and Deflection Assessment (AIDA).

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DART-induced Dust Tail

Several asteroid disruptions have been observed recently (P/2010 A2 [21–22] and 596 Scheila [23]). In these cases dust clouds similar to a comet tail were created and remained visible from ground based observatories for weeks to months afterward. Numerical simulations of these tails can be used to date the event, but also to study the complex dynamics of the ejecta, including post-impact fragmentation of large chunks of ejected material [21].

We are now performing such simulations to predict the size, shape, and magnitude of the tail to be generated by DART. We are particularly interested in looking for signatures of the binary system in the tail morphology. For instance tidal forces may periodically accelerate the dust, leading to overdense regions in the tail.

Full-scale Modeling of the Ejecta Fate

Multiple efforts to model the evolution of the cloud after the DART impact are currently underway by participants in our working group. These efforts are being undertaken with different approaches, employing different numerical modeling, largely independently of each other. This allows individual studies to develop their own best strategies of addressing the problem, which can be of benefit to an investigation such as this, especially at early stages, as it promotes creative approaches and may avoid the propagation of certain biases.

Gravitational and Radiative Perturbations

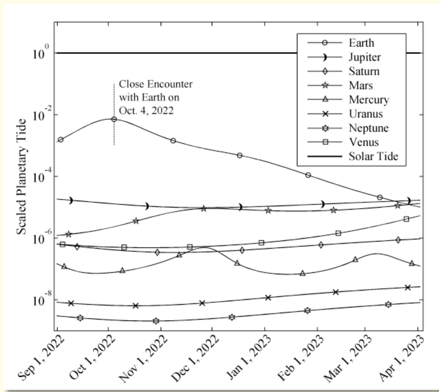

Figure 3: Planetary tides on Didymos from Sep. 1, 2022 to Apr. 1, 2023, normalized to the solar tide. The dashed line marks the encounter date.

Figure 3 shows the relative strength of the planetary tides compared with the solar tide. As illustrated, in this timeframe, the tidal perturbations caused by the planets are considerably smaller than those caused by the Sun by at least 2 orders of magnitude. The main planetary contribution comes from the Earth, which peaks on Oct. 4, 2022 when Didymos has its close-approach, and decreases monotonically afterwards. This indicates that planetary tides can be neglected in the vicinity of Didymos, and that the solar tide is the major gravitational perturbation to the ejecta from the DART impact. This conclusion does not exclude the possibility that some of the ejecta may enter the vicinity of or collide with a planet at later times. We also estimate that solar wind and Poynting-Robertson drag forces are about 4 orders of magnitude less than solar radiation pressure and thus can be neglected [24].

First Results

Figures 4 & 5 show results from the ejecta model of [24], which considers ejecta particles ranging in size from 0.1 mm to 1 m with initial ejection speeds assigned according to the scaling laws of Housen & Holsapple with parameters for weakly cemented basalt [7]. Solar tides and solar radiation pressure are included along with the gravitational effects of the two bodies of the Didymos system. The positions of the bodies are computed in advance, and thus the ejecta does not influence their trajectories in this model. Ejecta do not interact with each other gravitationally or collisionally, and they stick upon contact with either of the two bodies.

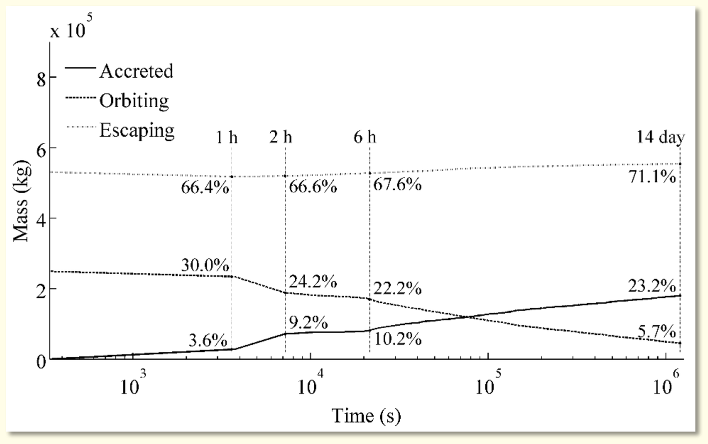

Figure 4: Proportions (mass) of ejecta in different states vs. Time. Each particle initially liberated by the DART impact is categorized into one of three states: *accreted*, *orbiting*, and *escaping*, indicated by solid, dashed, and dotted lines, respectively. Timespan considered is 14 days.

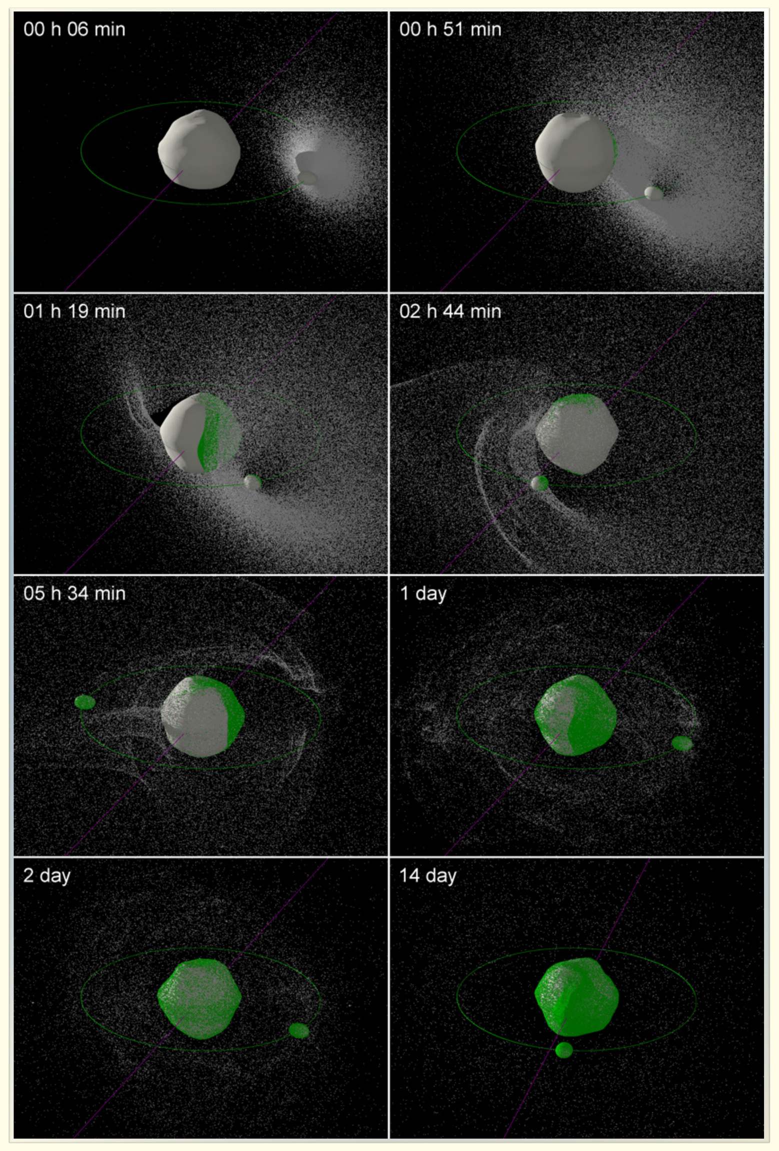

Figure 5: Snapshots of the time evolution of ejecta cloud near Didymos (view size ~ 4.6 km). The binary and heliocentric orbits are marked with solid lines of color green and purple, respectively. Fictitious large particle size is adopted for visual enhancement, and the accreted particles are colored in green.

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