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Abstract

The European component of the joint ESA-NASA Asteroid Impact & Deflection Assessment (AIDA) mission has been redesigned from the original version called Asteroid Impact Mission (AIM), and is now called Hera. The main objectives of AIDA are twofold: (1) to perform an asteroid deflection test by means of a kinetic impactor under detailed study at NASA (called DART, for Double Asteroid Redirection Test); and (2) to investigate with Hera the changes in geophysical and dynamical properties of the target binary asteroid after the DART impact. This joint mission will allow extrapolating the results of the kinetic impact to other asteroids and therefore fully

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validate such asteroid deflection techniques. Hera leverages technology and payload pre-developments of the previous AIM, and focuses on key measurements to validate impact models such as the detailed characterisation of the impact crater. As such, AIDA will be the first documented deflection experiment and binary asteroid investigation. In particular, it will be the first mission to investigate a binary asteroid, and return new scientific knowledge with important implications for our understanding of asteroid formation and solar system history. Hera will investigate the smallest asteroid visited so far therefore providing a unique opportunity to shed light on the role cohesion and Van der Waals forces may play in the formation and resulting internal structure of such small bodies.

Keywords: Near-Earth asteroids; Binary asteroid; Planetary defense; Asteroid impact hazards; Kinetic impactor; Asteroid resources utilization

1. Introduction

The European component of the AIDA mission has been redesigned and is called Hera hereafter. Hera is a small mission of opportunity built on the previous Asteroid Impact Mission (AIM) concept, whose objectives are to investigate a binary asteroid, to observe the outcome of a kinetic impactor test, and thus to provide extremely valuable information for asteroid impact threat mitigation, mining, and science purposes (Michel et al., 2016). It is part of the Asteroid Impact & Deflection Assessment (AIDA) mission, in which the second component is NASA's Double Asteroid Redirection Test (DART) mission. DART's primary objective is to impact the small moon of a binary asteroid system, thus performing the first asteroid deflection test, and to observe the outcome from ground-based observatories (Cheng et al., 2016). The target is the binary near-Earth asteroid (NEA) (65803) Didymos (1996 GT). Within the NEA population, Didymos provides currently the best astrodynamics properties to conduct an efficient deflection mission. In particular, its secondary component, called hereafter Didymoon, is the target of the DART mission. With its 163 ± 18 m diameter (in the following we indicate 163 m for its diameter although there is no significance in the last digit), it allows for the first time to gather detailed data not only from a binary asteroid but also from the smallest asteroid ever visited. Such a size is considered to be the most relevant for mitigation, mining, and science purposes, as explained below.

The original AIM design and objectives, as studied by ESA up to phase B1 until December 2016, were presented in Michel et al. (2016), while the DART mission is detailed in Cheng et al. (2016). In this paper we discuss an optimised version of AIM called Hera. This version keeps the main objectives and is capable of providing crucial data for the interpretation of the DART impact. However, this modified mission concept provides the opportunity to further reduce risk and cost in particular by simplifying the spacecraft design and by relaxing the very close asteroid-proximity operational constraints. In its current formulation, Hera will be the first mission to carry, deploy, and communicate with an interplanetary 6U CubeSat in the vicinity of a small body, which will perform complementary *in-situ* spectral observations. The satellite and its CubeSat will also observe for the first time the outcome of a kinetic impact deflection test and drastically improve our understanding of the impact process at asteroid scale, which will serve for the extrapolation to other scenarios, with many important implications for solar system science. Section 2 presents the main objectives of Hera, including the payloads and associated requirements. Section 3 presents the relevance of this mission for mitigation purposes. The relevance for mining purposes is given in Section 4, while the science return is briefly described in Section 5. Section 6 gives the conclusions.

2. Main objectives

In order to further optimize the original AIM mission design, a baseline payload package was defined that addresses directly all primary objectives of the mission (full characterization of an asteroid deflection, close-proximity operations, and interplanetary CubeSat operations), and indirectly all secondary objectives (e.g., internal structure through a bulk density estimate, and dynamics of the system). The spacecraft design allows for 40 kg of additional payload mass. Consequently, a number of valuable payload opportunities are being considered and are discussed below. The current cost estimate of Hera is 215 million Euros, including operations and launch but excluding the payload set and its operations.

DART is planned to launch in 2021 and impact Didymoon in 2022 (Cheng et al., 2016). The development of Hera (if approved) foresees instead a launch in October 2023, therefore arriving at the asteroid a few years after DART. There are then two cases considered, called hereafter Case I and Case II: (I) DART's launch is postponed in order to perform the impact while Hera is already at the binary asteroid; (II) Hera arrives a few years after the DART impact. In the latter case, all original objectives can still be met, except for the direct observation of the impact and the ejecta evolution. We note that the outcome of the impact, except for the ejecta dynamics, can still be measured a few years after the impact itself, as no change in the outcome is expected to happen on this short timescale, as demonstrated by NASA's Stardust-NEXT mission that returned in 2011 images of the crater on Comet Tempel 1 resulting from the 2005 NASA Deep Impact mission. The baseline payload (see Table 1) includes the Asteroid Framing Camera, a miniaturized LIght Detection And

Table 1
Hera payloads (optional are indicated as such). Payloads from the original AIM that are not considered in the current version of Hera are indicated in italics.

Payload	Acronym
Asteroid Framing Camera	AFC
Laser Altimeter	LIDAR
Asteroid SPECTral Imaging CubeSat	ASPECT
Monostatic High-Frequency Radar	HFR (optional)
Small Carry-on Impactor (JAXA)	SCI (optional)
Bistatic low-frequency radar	*LFR*
Micro lander	*MASCOT-2*
Thermal infrared imager	*TIRI*
Optical terminal	*OPTEL*

Ranging (LIDAR) instrument and a 6U CubeSat carrying two additional instruments (a hyperspectral imager called ASPECT for Asteroid SPECTral Imaging and a second instrument addressing one among the following: radio science, seismology, gravimetry, or volatile detection). As mentioned above, the current Hera design allows for additional payload opportunities. Current options under investigation include the Small Carry-on Impactor proposed by JAXA (a replica of the one on-board the Hayabusa-2 sample-return mission) and a high-frequency radar for the measurement of subsurface properties. Other options, such as a small lander, are not completely ruled out but are not described here as they are not yet under investigation. A Radio Science Experiment (RSE) will also be performed, which does not involve any additional on-board hardware but only complex on-ground data processing.

Table 1 presents the payloads included in Hera, with mention of those proposed in the original AIM for comparison.

Hera will demonstrate European capabilities to:

- determine the momentum transfer by the hyper-velocity impact of DART and the resulting effects on Didymoon's surface;
- carry, deploy and operate a CubeSat in interplanetary space, dedicated for the first time to the spectral characterization of a small body, with a second scientific investigation among radio science, seismology, gravimetry, and volatile detection;
- perform close-proximity operations in the environment of a binary system and the smallest asteroid ever visited.

The knowledge of Didymoon's surface/internal properties and the observation of the DART impact outcome are of high value to address fundamental scientific questions and to support the planning of potential surface activities related to mitigation, resources utilization, or sampling.

Table 2 presents the main measured properties with the associated measurement accuracy and the corresponding payloads (except the optional ones) of Hera (see Section 2.1 for a full list and details).

Table 3 summarizes the main objectives related to asteroid threat mitigation, while Table 4 summarizes the main objectives relevant to asteroid resources utilization.

2.1. Payloads

In the following, the requirements are indicated for each of the considered payloads. Note, when the terms *before the impact* are used, they apply to Case I.

2.1.1. AFC

The Asteroid Framing Camera (AFC) is a flight spare of the NASA DAWN mission camera. It is described in detail by Sierks et al. (2011). Here, we just reproduce its main specifications (Table 5).

The AFC will be used both for Guidance, Navigation & Control (GNC) and for scientific measurements. In its scientific role it will be imaging the target asteroid system from multiple positions, viewing angles and various distances during the course of the Hera asteroid observation phases. The purpose of the measurements is to provide information on the binary asteroid dynamics and physical characteristics (focusing in particular on DART's target) including Didymoon's mass, which is required to measure the actual transfer of momentum of the DART impact. This will be obtained indirectly by measuring the reflex motion of the Didymos primary as it is orbited by the secondary (called hereafter the wobble). The mass of the primary is about 100 times the mass of the secondary, thus the expected "wobble" radius is about one percent of the distance of 1180 m between the two, or about 10 m, and can be measured as described in Grieger et al. and Küppers (2016). Spectral information is gained using multiple filters.

Most operations will be done at 10 km from Didymoon's surface but occasionally much closer approaches are foreseen. For instance, 2–3 flybys may be performed to obtain a nearly complete map of the object at higher resolution. This is considered in some of the objectives described below.

The requirements of the AFC are:

- The resolution of the images shall be such that the mass of Didymoon can be determined with an accuracy of at least 10% (goal 1%). This can be done by measuring the wobble with an accuracy equal to or less than 1 m. The accuracy needed is derived for the case where Didymoon has its nominal density of 2.1 g/cm^3, orbiting about Didymos with its density of 2.1 g/cm^3. For a density of 1 g/cm^3, the accuracy should be equal to or better than 50 cm.
- The resolution of the images shall be such that surface landmarks can be identified in order to determine the mass of Didymoon with the expected accuracy. The required values will depend on the mass determination

Table 2
Main measured properties, associated accuracy, and baseline payloads of Hera. Objectives related to Case I (Hera in time to observe the impact) are indicated in italics and all other measurements will be performed before and after the impact.

Parameter	Required accuracy	Associated payload
Size, mass, shape, density	• Mass: 10% • Density: 20%	AFC, RSE, ASPECT
	Global shape: better than 5 m lateral resolution and 2 m height resolution	AFC, LIDAR
Dynamical state (period, orbital pole, spin rate, spin axis)	• Period already known to better than 0.1% • Orbital pole: 5° • Spin rate: 1% • Spin axis: 1°	AFC
Geophysical surface properties, topology, DART crater's properties	• Global surface resolution: 1 m • Local surface resolution (10% of the surface): 10 cm	AFC
Chemical and mineral composition of Didymoon and Didymos	Spectral resolution: 40 nm for all colour filters except near-IR (980 nm) that has 80 nm band width (AFC)	AFC, ASPECT
Impact ejecta	*Due to the large uncertainties in the properties of the dust cloud, not a driver in requirements on the payload. Therefore, no accuracy requirements provided*	*AFC, ASPECT*

Table 3
Threat Mitigation Demonstration. Estimates (in italics) mean information that can be indirectly determined from other measurements.

Goals	Measurements/*Estimates*
Assess momentum transfer efficiency of the hypervelocity asteroid impact	Mass of Didymoon. Didymos orbital and rotational states.
Determine global asteroid parameters that drive the momentum transfer efficiency (to allow scaling to other bodies)	Mass and volume of Didymoon to measure density and porosity. Crater size/morphology. Ejecta size and velocity distributions (Case I). Surface disturbances and displacements induced by impact. *Tensile strength.*
Determine local variation of parameters that drive the momentum transfer efficiency	*Tensile strength variation.* Surface and subsurface morphology (from crater interior, grooves, etc.).
Demonstrate close proximity operations around a 163 m-diameter asteroid	

approach but will be of about 1 m in height with respect to the center of mass for a given landmark. Simulations confirm that with a camera resolution of 0.005 deg/pixel the mass of the secondary can be measured from 10 km distance with an accuracy of a few percent (Grieger et al. and Küppers, 2016).

- For the purpose of volume estimation, a closed shape model shall be obtained with an accuracy of 2 m in height and less than 5 m in spatial resolution with respect to the center of mass.
- The binary system orbital period, the spin parameters, and semimajor axis of Didymoon shall be determined with an accuracy of 1% before and after DART impact. The system shall be monitored over several orbits to investigate irregular rotation.
- The surface of Didymoon shall be characterized at a resolution of 50 cm/pixel before and after DART impact.

Table 4
Asteroid Resources Utilization Demonstration. Estimates mean information that can be indirectly determined from other measurements.

Goals	Measurements/*Estimates*
Determine physical properties of the surface and subsurface that are crucial for the choice of mining technique	*Tensile and compressive strength.* Crater size/morphology. Surface morphology. Surface particle size distribution. Ejecta properties (Case I).
Determine composition to evaluate the presence of materials relevant for mining	Composition from spectral mapping.
Demonstrate close proximity operations around a 163 m-size asteroid	
Deploy and communicate with an interplanetary CubeSat	

Table 5
Main specifications of the Asteroid Framing Camera (from Sierks et al., 2011)

Item	Specification
Focal length	150 mm
F-number	7.5
Back Focal Length	42.1 mm
Field Of View (FOV)	5.5° × 5.5°
Instantaneous FOV	93.7 μrad
Field of Curvature	<10 μm
Distortion	<0.1%

- The surface of Didymoon shall be characterized at a vertical and horizontal precision of 10 cm locally on ~10% of the surface before and after DART impact. With a camera resolution of 0.005 deg/pixel this corresponds to a distance requirement of 500 m from the surface.
- The crater density and geomorphology to ≈5 pixels in diameter equivalent to a size resolution of 5 m from 10 km distance will be determined and compared for both Didymos and Didymoon, noting that Didymos is 5 times larger than Didymoon. Therefore the requirements for Didymoon hold for Didymos.
- The impact ejecta will be observed (Case I) at high cadence, stored locally onboard the spacecraft with up to 20 images per minute covering a period of ≈50 min, or for a longer time period at lower cadence. The local AFC image store can host up to 1000 images.
- The possible presence of dust in the surroundings of Didymoon will be searched by long-exposure measurements that can last minutes to hours (operational maximum of 3.5 h).
- The study of chemical and mineralogical properties of the surface materia will be supported using multiple filters and co-registered colour-ratio techniques by the 7 filters spanning the wavelength range from 410 to 1020 nm.

Table 6
ASPECT technical objectives

Objective 1	Demonstration of CubeSat autonomous operations in deep-space environment
Objective 2	Navigation in the vicinity of a binary asteroid
Objective 3	Demonstration of satellite survival during the DART impact (Case I)
Objective 4	Demonstration of joint spacecraft-CubeSat operations
Objective 5	Demonstration of spectral imaging of asteroid materials

A full coverage of Didymos should be achieved in the course of the Hera asteroid observation phases. As required for navigation and by the standard collision avoidance algorithms, the AFC shall keep Didymos and Didymoon within its Field Of View (FOV) during the global observation phases. A novel Fault Detection Identification and Recovery (FDIR) system based on multiple sensor data-fusion will also be tested as part of Hera technology demonstration, allowing for this constraint to be relaxed and in order to perform very close-proximity flybys. Finally, the AFC limiting magnitude allows detection of the Didymos system early enough to be compatible with the expected heliocentric orbit uncertainty (due to both ground navigation and Didymos position uncertainties). The spacecraft might need to provide a range of solar phase angles for phase function analysis.

2.1.2. LIDAR

The objectives of the LIDAR are to measure the shape of both objects in the Didymos system. It will also provide measurements for constraining the mass of Didymoon.

The requirements of the LIDAR are:

- To provide the accurate three-dimensional shape of Didymoon before and after the DART impact. The volume is needed (together with the mass) to get the density. Note that for a density accuracy of 20% (enough to discriminate between interior models) and a mass accuracy of 10%, the accuracy on the volume must be at least 17%. The measured accuracy shall be equal to or better than 50 cm, with a precision better than or equal to 20 cm. The sampling of the surface between footprints shall be 1 m or less by a footprint no bigger than 1 m in diameter, assuming pointing knowledge of 0.5 mrad (1-sigma) or better and a distance from the spacecraft to the surface of 10 km, a spacecraft orbit knowledge to better than 1.8 m, and an assumed surface roughness similar to that of asteroid Itokawa.
- To determine the mass by measuring the amplitude of the wobble of Didymos with an accuracy equal to or better than 1 m before and after the DART impact.

The measurement may be performed for the mass determination with the spacecraft at 10 km from Didymoon, but the actual distance still requires verification. The accuracy needed is derived for the case where Didymoon has its nominal density of 2.1 g/cm^3, orbiting about Didymos with its density of 2.1 g/cm^3. For a density of Didymoon of 1 g/cm^3, the accuracy should be equal to or better than 50 cm.

- To determine Didymoon surface topography, i.e., highlands, lowlands, ponds, and measure fine-scale features (regolith, bedrock, boulders) before and after the DART impact with a precision of 20 cm and a sampling of the surface between footprints of 30 cm by a footprint no bigger than 30 cm in diameter.
- To support the study of surface chemical and mineralogical properties, through measurements of intensity or albedo returned.

2.1.3. *CubeSat ASPECT*

Once in the asteroid vicinity, the Hera spacecraft will deploy a 6U CubeSat including the ASPECT payload and another instrument among a few options that will be further analyzed in the course of the phase B1 studies starting in the first semester of 2018. This section focuses on the requirements for ASPECT.

ASPECT is a visible and near-infrared instrument. It is a spectral imager from 0.5 μm to 1.6 μm and a spectrometer from 1.6 μm to 2.5 μm. ASPECT will orbit Didymos at a distance of about 4 km and observe both binary components. Details on ASPECT are given in Kohout et al. (2018).

The ASPECT requirements within the Hera mission are:

- ASPECT will contribute to the measurement of the mass of Didymoon by measuring the amplitude of the wobble and to the creation of a shape model. The resolution of ASPECT will be comparable to or slightly better than that of AFC (depending on final orbit selection), while the orbit reconstruction may be less accurate.
- The surface of Didymoon shall be characterized at a spatial resolution better than 2 m before and after DART impact.
- To provide ground truth for Earth-based observations of other asteroids by measuring the effects of space weathering.
- To measure possible changes in the shape of Didymoon after the DART impact with an accuracy of about 10 m.
- To measure the local effect of the impact shock in the crater created by the DART impact.
- To determine and compare the crater density and geomorphology of both Didymos and Didymoon with an accuracy of at least 10 m. This includes investigation of the changes due to fall-back ejecta.
- To perform impact ejecta observations with 2 m per pixel resolution.

Table 7
ASPECT scientific objectives and **values**

Objective 1	Map the surface composition of the Didymos system
Value	Changes in the composition and homogeneity of the asteroid as a result of the DART impact (Case I). Information on the origin and evolution of the binary system.
Objective 2	Photometric observations and modeling of the Didymos system under varying phase angle and distance
Value	Surface particle size distribution and composition for Didymoon and Didymos (simultaneous modeling of photometry and spectroscopy)
Objective 3	Evaluate space weathering effects on Didymoon by comparing mature and freshly exposed material
Value	Information on the surface processes on airless bodies due to their exposure to the interplanetary environment
Objective 4	Identify local shock effects on Didymoon based on spectral properties of crater interior
Value	Information on the processes related to impacts on small solar system bodies
Objective 5	Observations of the ejecta plume produced by the DART impact (Case I)
Value	Evolution and composition of the DART impact plume
Objective 6	Map global fallback ejecta on Didymoon and Didymos
Value	Detailed global mapping of fallback ejecta on both Didymos and Didymoon

- To determine the chemical and mineralogical surface composition of Didymos and Didymoon with a spectral resolution of 45 nm or better.

Table 6 summarizes the technological objectives of ASPECT, while Table 7 gives the scientific objectives and values.

2.2. *Radio Science Experiment (RSE)*

Radio science will be performed requiring precise orbit determination of the spacecraft within the Didymos system. By using radiometric and optical measurements, it is possible to estimate a number of dynamical parameters of scientific interest, including the masses and the extended gravity fields of Didymos and Didymoon, their relative orbit, and their rotational states. Improving the Didymoon orbit will contribute to our understanding of the dissipation and tidal evolution of the asteroid binary system, as well as the coupling between orbital and rotational dynamics. Gravity field estimation, combined with the shape derived from the camera, will then contribute to indirect information on the internal structure through the determination of the bulk density, moment of inertia, gravity anomalies, and density distribution. At 10 km from Didymoon, after 8 flybys dedicated to gravity science, the masses of the primary and secondary can be estimated to about 0.2% and 1.6%, respectively; the orbit of the secondary around the primary can be estimated to about 1 m; and the pole orientation of the primary and the secondary can be estimated to about 0.1 deg and 0.4 deg, respectively (Zannoni et al., 2018). Moreover, range tracking will allow the heliocentric orbit determination of Didymos to be improved.

When a part of the signal is scattered by asteroid regolith, bistatic radar acquisition is a way to characterize the surface (Simpson, 2007; Virkki and Muinonen, 2016). The received signal power, its Doppler and its polarization state (Same Circular polarization to Opposite Circular polarization power ratio) give the bistatic scattering coefficient, which is related to the dielectric properties and the degree of disorder at the wavelength scale. This allows accessing information on the surface roughness and texture of the first decimeters of the regolith (as done for Vesta by the Dawn mission; Palmer et al., in press).

2.3. Optional payloads

As mentioned above, the current spacecraft design allows for up to 40 kg of additional payload mass. Optional Hera payloads under study include a High-Frequency Radar (HFR) and the Small Carry-on Impactor (SCI) proposed by JAXA. The latter is described in Saiki et al. (2017). Here, we indicate the requirements for the HFR.

The Hera Monostatic HFR main objective is to obtain information on the structure of the asteroid's outermost surface and sub-surface layers, up to a depth of 10 to 20 m.

The primary requirements are:

- To determine the structure and layering of Didymoon's shallow sub-surface down to a few metres with a vertical resolution of approximately 1 m (goal 0.20 m) and equally 1 m (goal 0.20 m) in horizontal position before and after DART impact.
- To map, with the same resolution, the spatial variation of the regolith texture, which is related to the size and mineralogy of the grains and macro-porosity.
- To study the 2-D distribution of geomorphological elements (rocks, boulders, etc.) that are embedded in the subsurface with the same resolution.
- To derive an estimate of dielectric permittivity of the surface material with a horizontal resolution of a few meters by analyzing the surface echo amplitude and an estimate of the average permittivity of the sub-surface material in some specific places by analyzing the spatial signature from individual reflectors.

This can be achieved with a frequency range of 300–800 MHz.

The secondary requirements are:

- To support asteroid mass determination, shape modeling, and orbit characterization with range measurements (resolution = 10 cm or better) before and after DART impact.
- To support ground-based bistatic radar measurements with a high-frequency channel compliant with Arecibo and Goldstone and offering better resolution and sensitivity (2.5–3 GHz).
- To determine the structure and layering, as well as the mapping of the regolith texture and the 2D distribution of geomorphological elements with a resolution down to a few meters. Lower resolution or sensitivity could be envisaged to allow complete coverage within the mission resources envelope.
- To derive the dielectric permittivity of Didymos with a resolution down to a few meters.

A priori, the HFR operation preparation requires an orbitography model. The accuracy should be 100 m for the orbit of Didymoon.

The HFR performance increases with closer proximity to the object, therefore more accurate results can be expected when dedicating a few close-proximity flybys to radar measurements. In addition, the higher the angular aperture the better. This may require operating within a short range of the asteroid surface, which could be on the order of 10 km, although further analysis is needed to define the best compromise in terms of distance. The instrument could be used for navigation (i.e., ranging/altimetry mode and ejecta detection) in addition to performing scientific measurements.

3. Hera relevance to mitigation

Although the probability of an asteroid impact on Earth during the coming years is low, the potential consequences to our society could be very severe. Small bodies are continuously colliding with Earth, however, the vast majority of these objects are very small (below 10 m in size) and pose no threat to human activity. Larger impacts (1 km or more) occur far less often but, when they do occur, they can lead to a major natural catastrophe. Fortunately more than 90% of the asteroid population with diameter of 1 km or larger is known and poses no risk. On the intermediate size (100–500 m range), damage can still be of regional scale (a country or a continent) and impact location is the most significant driver of casualties for impacts in this size range (Mathias et al., 2017). Thus, the specific impact location shift due to mitigation attempts by a kinetic impactor is very sensitive to the impact physics, and dominates the casualty expectation. Only a small fraction of objects are known in this size range while their impact frequency becomes high enough (centuries to millennia, i.e., within the duration of a civilization) to draw the attention of space agencies to put in place realistic and proven means to protect our society from the threat they pose. Indeed, the impact of an asteroid is the only natural disaster that can be accurately predicted and also prevented. For this to happen it is necessary to (1) improve the knowledge of the geophysical properties of bodies in this size range, (2) test our ability to deflect such a small asteroid, and (3) complete the inventory of this population.

AIDA will allow addressing (1) and (2) for the first time. In terms of deflection techniques, we will never know whether a deflection technology is ready if no test is performed beforehand. Hera images will thus provide the first details of two asteroids in such a medium-size class (163 m- and 780 m-diameter) which today draws the attention of the planetary defense scientific community, with important information regarding the geophysical and surface properties of both bodies. Moreover DART will hit the smallest component, whose size is the most relevant one for mitigation purposes, as explained above (the typical impact energy of an asteroid of this size is of the order of 10,000 Hiroshima bombs). With its geophysical characterization by Hera, AIDA will provide the first documented asteroid deflection experiment. Such an experiment at actual asteroid scale is the only direct way to check our ability to use the kinetic impact deflection techniques, to validate/refine our numerical impact models and, most importantly, to extrapolate the results of this particular experiment to other asteroids with higher confidence at such scales.

4. Hera relevance to asteroid resource utilization

Asteroid resources utilization, which needs appropriate tools for material extraction, relies currently on our poor knowledge of asteroid properties, in particular the mechanical properties at the surface and sub-surface, including regolith/dust properties. Moreover, a better understanding of the response of asteroid material to an external action in the appropriate low-gravity environment is strongly needed. Finally, a better knowledge of the composition of asteroids is needed, as it is not yet clear whether meteorite material is representative of material in space, and spectral observations from the ground only provide disk-integrated information on the first microns of an asteroid surface. This prevents determining the potential compositional heterogeneities within an asteroid. The validity of the extrapolation of the abundance of rare materials in meteorites to an entire asteroid remains unproven.

Hera is a crucial step in this ambitious adventure that could eventually lead to successful asteroid mining. The high-resolution images of Didymos' surface returned by Hera will shed light on whether it is made of bare rock or granular material (including depth and grain size distribution down to the camera resolution limit), and measure its global physical properties (including the subsurface ones if the optional high-frequency radar is on-board). All space missions that will obtain images and consequently access the detailed physical properties of an asteroid are valuable in order to cope with these bodies efficiently. Two sample-return missions underway, Hayabusa-2 (JAXA) (Watanabe et al., 2017) and OSIRIS-REx (NASA) (Lauretta et al., 2015), will greatly improve our understanding of primitive asteroids in the diameter range of 0.5–1 km in the coming years, and their preparation has generated a great deal of technical expertise towards the design of proper sampling tools and the optimal sampling strategies considering the poor knowledge of the respective asteroid targets. The earlier space mission Hayabusa (JAXA) (Fujiwara et al., 2006) increased the technical know-how necessary to return samples back to Earth even under extreme operational constraints and failures. Finally, the Rosetta space mission to a comet (Taylor et al., 2017) has built a unique knowledge base on small-body close-proximity operations under the extreme environment of small gravity combined with outgassing and solar radiation pressure. These unique experiences are important building blocks to increase robustness of future missions to small bodies. Hera will enable yet another step forward by performing measurements of the geophysical properties of an object smaller in size than previous targets. Equipped with filters on the camera and on the CubeSat, Hera will be able to contribute to the so-called ground truth by comparing the compositional heterogeneity of the surface with Earth-based observations, improving the interpretation of future ground-based observations.

Another important aspect of Hera is the size of Didymoon, which is very relevant for asteroid resources utilization. Asteroid mining relies on the abundance of targets to exploit. Large (km-size and larger in diameter) objects are rare, in particular if we account for their accessibility from Earth. Conversely, very small objects (below 100 m diameter) are very numerous, however they cause technical difficulties because of their extremely low gravity and their tendency to have a high spin rate, making it technically challenging to interact with them. Bodies of a few hundred meters' diameter are thus extremely interesting as they remain small enough to be numerous (some 10,000 are estimated to exist in the near-Earth space according to, e.g., Granvik et al. (2016)) but large enough to decrease the mentioned difficulties. Therefore, any data on bodies of this size, like Hera will obtain, is of high value for asteroid mining. Moreover, as the target of Hera is a binary asteroid, the mission will provide the opportunity to study two asteroids at the same time. Although the investigations of the primary asteroid are not expected to be as detailed as for the secondary, Hera will study the binary dynamical environment and will be able to provide information about the morphology and surface properties of the primary. Given that almost one sixth of asteroids larger than 200 m are expected to be binary (Walsh and Jacobson, 2015) this information is very important for future asteroid exploration and resource utilization.

Thus, all this information and the experience gained by Hera on close-proximity operations are precisely what is needed to make a big step towards actual asteroid mining.

5. Science return

The science case of the original AIM mission is described in Michel et al. (2016). The science return of Hera is similar except for the direct measurement of the internal structure as such measurement depends on a low-frequency radar instrument placed on the surface of the asteroid (Herique et al., 2018).

The science return from Hera includes:

- First detailed images of a binary asteroid in orbit, offering informed constraints to models describing binary formation and dynamics, and verifying/constraining predictions arising from the radar shape model.
- First images and *in-situ* compositional analyses of the smallest asteroid ever visited, enabling the determination of the geophysical and compositional properties of such a small body compared to larger ones.
- Understanding of physical/compositional properties and geophysical processes in low gravity, with implications for our understanding of small-body surface properties and their evolution.
- First documentation of an asteroid-scale impact outcome (from DART and optionally the SCI), orders of magnitude beyond the scale accessible in the laboratory.

The last item will provide crucial data to validate numerical simulations of hyper-velocity impacts that are used in planetary science (planet and satellite formation, impact cratering and surface ages, asteroid belt evolution). It will offer new constraints for collisional evolution models of small-body populations and planetary formation.

It is important to emphasize that about 15% of NEAs larger than 200 m in diameter are binaries, and many of these may be similar to Didymos (see, e.g., Benner and Busch, 2015; Margot et al., 2015). Therefore, it is expected that some systematic process is at the origin of the creation of such systems. According to current knowledge, the YORP spin-up of a rubble pile is the most likely process (see, e.g., Walsh and Jacobson, 2015). The characterization of Didymos by Hera will provide information not only about an individual asteroid but also about a sizable fraction of near-Earth and potentially hazardous asteroids.

Hera will perform the geophysical characterization of the target mostly based on images (and Doppler tracking for mass characterization). This will allow us to achieve a big step in our knowledge in such a low-gravity environment, in terms of shape, mass (and density), surface features, presence and kind of surface regolith (dust versus gravel), crater abundance and size distribution, boulder size distribution down to the resolution limit of the camera, as well as local slopes. Color filters will provide clues about possible compositional heterogeneity.

In addition to surface properties, indirect information on the internal structure will be obtained. In fact, surface images allow for the evaluation of surface structures, such as lineaments, crater shapes, crater ejecta, boulder existence/distribution, and mass wasting features. From these features, one can also derive information on material strength, cohesion, porosity, etc., both for the asteroid regolith and interior. For instance, if the largest boulders found at the surface are comparable in size to the asteroid itself, this can indicate that they were produced during a catastrophic disruption or reaccumulation event (like in some binary formation scenarios), and the asteroid is more likely to have a rubble-pile structure (Michel and Richardson, 2013). The Radio Science Experiment will also contribute to internal structure estimates.

Finally, in Case I, by comparing the surface images taken before and after DART impact, it may also be possible to perform some science of seismic transmission/attenuation by monitoring landscape changes, analogous to how Thomas and Robinson (2005) correlated the last, large impact on asteroid Eros (Shoemaker Regio) to the regional degradation of $\sim$100 m craters. Hera can be used to conduct investigations at finer scales, using a known source crater, and benefiting from pre-impact knowledge, to constrain the decay of seismic energy with distance from the impact point, by measuring:

- the displacement of large boulders;
- the triggering of mass movements;
- the degradation of pre-existing landforms.

The sizes of displaced boulders, the amplitude of their movement, and the spatial scale of features that are erased may all serve as a proxy for seismometers on the surface, albeit at much lower resolution. Furthermore, the presence or absence of antipodal focusing (increased feature degradation at the antipode) can provide constraints on global internal structure.

6. The DART component of AIDA

The Double Asteroid Redirection Test (DART) is the NASA element of the AIDA mission (Cheng et al., 2016). The primary goals of DART are to demonstrate the ability to perform a high-speed spacecraft impact on a potentially hazardous NEA, and to measure and characterize the deflection caused by the impact so as to validate and improve models of kinetic impactor performance.

The DART impact will alter the binary orbital period. It is expected to change the orbital speed of Didymoon by at least $\sim$0.6 mm/s, which causes an orbital period change of $\sim$7 min, which is $\sim$1% of the orbital period (Cheng et al., 2017).

The DART kinetic impactor baseline mission design has changed from that described in Cheng et al. (2016). DART will now launch as a secondary payload to geosynchronous orbit and use the NASA Evolutionary Xenon Thruster (NEXT) ion propulsion system to spiral out from Earth orbit and transfer to Didymos. DART will be the first mission to demonstrate the NEXT ion propulsion (Cheng et al., 2017). The DART spacecraft mass with NEXT is

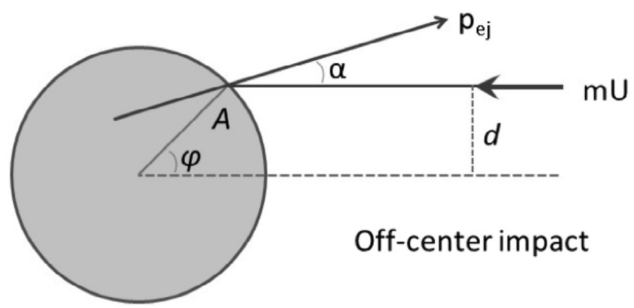

Fig. 1. Angular momentum transfer to target from off-center impact.

increased by about 65% from that of the previous chemical baseline design, and the impact speed at Didymos is decreased by about 15%, such that the incident momentum with the DART impact is increased by about 40%.

A primary AIDA objective is to determine the amount of momentum transferred to the target by the kinetic impact, as quantified by the β parameter, which is the ratio of momentum transferred to the target body over the incident momentum. The value of β is important because it determines how large a kinetic impactor, or how many kinetic impactors, would be needed to achieve a given deflection (velocity change) of a target body. It is expected that $\beta > 1$ because of the momentum returned from the incident direction by impact ejecta. However, β predictions for kinetic impacts on asteroids cover a wide range of values from near unity to well above three (e.g., Walker and Chocron, 2011; Holsapple and Housen, 2012; Jutzi and Michel, 2014; Stickle et al., 2015; Cheng et al., 2016; Bruck Syal et al., 2016). Results of laboratory impact experiments can be scaled up (though the scaling is very uncertain) to predict asteroid deflection by kinetic impacts, using numerical simulations and analytical scaling models (Housen and Holsapple, 2011; Walker et al., 2013; Flynn et al., 2015). Laboratory measurements of β found, for a porous 297 g pumice target impacted at 3.92 km/s, $\beta = 2.3$ (Flynn et al., 2015), and for much larger 1 m-diameter nonporous granite targets (two impact experiments at 2 km/s, Walker et al., 2013), $\beta = 2.1$ and 2.2.

DART is expected to be able to measure with ground-based observations the change in the orbital period of the

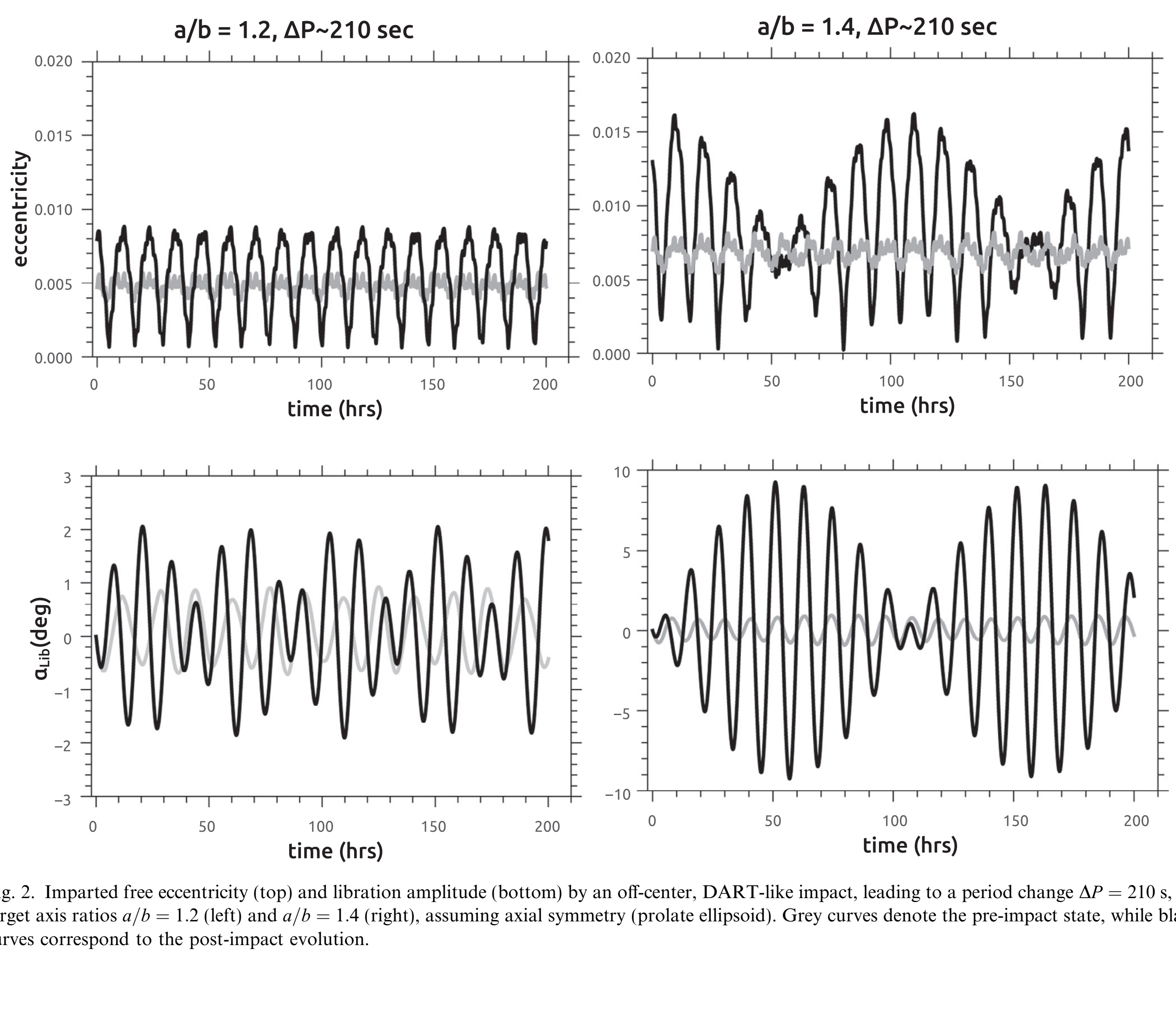

Fig. 2. Imparted free eccentricity (top) and libration amplitude (bottom) by an off-center, DART-like impact, leading to a period change $\Delta P = 210$ s, for target axis ratios $a/b = 1.2$ (left) and $a/b = 1.4$ (right), assuming axial symmetry (prolate ellipsoid). Grey curves denote the pre-impact state, while black curves correspond to the post-impact evolution.

target asteroid to within a precision of ±7.3 s, amounting to a measurement precision of ≈1% for a predicted period change of 7 min assuming $\beta = 1$. As the orbit is approximately circular, the corresponding measurement precision in the circular velocity change (or deflection) becomes 3%. However, in order to find the momentum transfer to the target body, the target mass is needed. Hera will measure this mass so as to determine β for the DART impact.

Furthermore, Hera imaging will measure dynamical changes in the rotation state of the secondary. These will comprise both a forced libration stemming from the changed orbital period and eccentricity of Didymoon as well as a free libration if as expected the DART impact is not directed exactly through the target body center of mass. The initial rate of spin associated with the free libration induced by the DART impact is simply estimated by considering Fig. 1 for an off-center impact on a spherical body of radius A and mass M, where an impactor with momentum mU misses the center by a distance d.

We write $\beta mU = p_{ej} \cos \alpha + mU$, where p_{ej} is the ejecta momentum and α is the angle between p_{ej} and the projectile momentum (see Fig. 1), and then consider the angular momentum transferred to the target, which has moment of inertia I:

$$I\Delta\Omega = p_{ej} A \sin(\varphi - \alpha) + mUd = \beta_L mUd, \quad (1)$$

where $\Delta\Omega$ is the change in the angular speed induced by the projectile impact. The quantity β_L is defined as the amplification factor for angular momentum transfer, analogous to β for linear momentum transfer:

$$\beta_L = 1 + (\beta - 1)\frac{A \sin(\varphi - \alpha)}{d \cos \alpha}. \quad (2)$$

With the estimate for the DART impact that $\frac{mU}{M} = 0.6$ mm/s, and with $\alpha = \varphi$ for simplicity (in which case $\beta_L = 1$, independent of β),

$$\Delta\Omega \cong \frac{0.6\ \text{mm/s}}{A} \beta_L \left(\frac{d}{A}\right)\left(\frac{MA^2}{I}\right) \sim 2 \times 10^{-6}\ \text{rad/s} \quad (3)$$

For a miss distance $d = 10$ m, this rotation is readily measurable by Hera imaging. This measurement may determine I to obtain an important constraint on internal structure.

Assuming the binary is in orbital equilibrium, its eccentricity has to be different from zero, primarily due to the non-zero effective second degree zonal harmonic, J_2, of the primary's gravity model, which accounts for its oblateness. The equilibrium forced eccentricity also depends on the axis ratio a/b of Didymoon and is of order 0.005–0.0075, for $1.2 \leqslant a/b \leqslant 1.4$, as verified by orbital computations (see Cheng et al., 2017). A DART-like impact that changes the orbital period by ~200 s will necessarily impart a free eccentricity of order $\delta e/e \sim 0.010$–0.015. This eccentricity change instantaneously displaces the synchronous spin-orbit equilibrium in phase space, thus exciting a free libration on the moon. For an off-center impact, even if $\Delta\Omega$ is very small, the amplitude of libration, α_{Lib}, can be several degrees (see Fig. 2), easily measured by Hera imaging.

7. Conclusions

The Hera mission provides a robust and cost-effective means to perform a planetary defense validation test with a solid balance between risk and innovation. In the frame of the AIDA collaboration, Hera concretely contributes to a truly international planetary defense initiative. It will bring completely new knowledge and insights on asteroid science that will be of great benefit not only to the planetary defense community as a whole but also to those seeking a deeper understanding of the processes underlying solar system formation as well as to future asteroid resources utilization. Hera builds upon a unique knowledge base gained in Europe with the Rosetta mission on close-proximity operations and offers a great opportunity to develop them further by increasing on-board autonomy and testing new technologies developed for future in-orbit servicing missions. It will bring European industry one step forward in CubeSat relayed operations, enabling future mission architectures such as swarms and deep-space exploration. In addition, such distributed systems will enable future close-proximity inspections for deep-space habitats. Finally, a mission like Hera will certainly fire the imagination of young people and adults, as the science is accessible and understandable to those audiences and is associated with fascinating challenges and goals of planetary defense.

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References

Benner, L.A.M., Busch, M.W., Giorgini, J.D., et al., 2015. Radar observations of near-Earth and main-belt asteroids. In: Michel, P. et al. (Eds.), Asteroids IV. Univ. of Arizona Press, Tucson, pp. 165–182.

Bruck Syal, M., Owen, J.M., Miller, P.L., 2016. Deflection by kinetic impact: sensitivity to asteroid properties. Icarus 269, 50–61.

Cheng, A.F., Michel, P., Jutzi, M., et al., 2016. Asteroid impact and deflection assessment mission: kinetic impactor. Planet. Space Sci. 121, 27–35.

Cheng, A.F., Michel, P., Barnouin, O., et al., 2017. The Double Asteroid Redirection Test (DART): element of the Asteroid Impact and Deflection Assessment (AIDA) mission. Lunar Planet. Sci. XLVIII, 1510.

Flynn, G.J., Durda, D.D., Patmore, E.B., et al., 2015. Hypervelocity cratering and disruption of porous pumice targets: implication for crater production, catastrophic disruption, and momentum transfer on porous asteroids. Planet. Space Sci. 107, 64–76.

Fujiwara, A., Kawaguchi, J., Yeomans, D.K., et al., 2006. The rubble-pile asteroid Itokawa as observed by Hayabusa. Science 312, 1330–1334.

Granvik, M., Morbidelli, A., Jedicke, R., et al., 2016. Super-catastrophic disruption of asteroids at small perihelion distances. Nature 530, 303–306.

Grieger, B., Küppers, M. 2016. Determining the mass of Didymos' secondary by visual imaging. In: EGU General Assembly Conference Abstracts, vol. 18, EPSC2016-12296.

Herique, A., Agnus, B., Asphaug, E., et al., 2018. Direct observations of asteroid interior and regolith structure: science measurement requirements. Adv. Space Res. 62, 2141–2162. https://doi.org/10.1016/j.asr.2017.10.020.

Holsapple, K.A., Housen, K.R., 2012. Momentum transfer in asteroid impacts. I. Theory and scaling. Icarus 221, 875–887.

Housen, K.R., Holsapple, K.A., 2011. Ejecta from impact craters. Icarus 211, 856–875.

Jutzi, M., Michel, P., 2014. Hypervelocity impacts on asteroids and momentum transfer I. Numerical simulations using porous targets. Icarus 229, 247–253.

Kohout, T., Näsilä, A., Tikka, T., et al., 2018. Feasibility of asteroid exploration using CubeSats ASPECT case study. Adv. Space Res. 62, 2239–2244. https://doi.org/10.1016/j.asr.2017.07.036.

Lauretta, D., Bartels, A.E., Barucci, M.A., et al., 2015. The OSIRIS-REx target asteroid (101955) Bennu: constraints on its physical, geological, and dynamical nature from astronomical observations. Meteorit. Planet. Sci. 50, 834–849.

Margot, J.-L., Pravec, P., Taylor, P., et al., 2015. Asteroid systems: binaries, triples, and pairs. In: Michel, P. et al. (Eds.), Asteroids IV. Univ. of Arizona Press, Tucson, pp. 355–374.

Mathias, D.L., Wheeler, L., Dotson, J.L., 2017. A probabilistic asteroid impact risk model: assessment of sub-300 m impacts. Icarus 289, 106–119.

Michel, P., Richardson, D.C., 2013. Collision and gravitational reaccumulation: possible formation mechanism of the asteroid Itokawa. Astron. Astrophys. 554, L1–L4.

Michel, P., Cheng, A.F., Kueppers, M., et al., 2016. Science case for the Asteroid Impact Mission (AIM): a component of the Asteroid Impact and Deflection Assessment (AIDA) mission. Adv. Space Sci. 57, 2529–2547.

Palmer, E., Heggy, E., Kofman, W., 2017. The first orbital Bistatic radar observations of an asteroid: an opportunistic experiment by the dawn mission. Nat. Commun. (in press).

Saiki, T., Imamura, H., Arakawa, M., et al., 2017. The Small Carry-on Impactor (SCI) and the Hayabusa2 impact experiment. Space Sci. Rev. 208, 165–186.

Sierks, H., Keller, H.U., Jaumann, R., et al., 2011. The dawn framing camera. Space Sci. Rev. 163, 263–327.

Simpson, R., 2007. Planetary exploration. In: Willis, N.J., Griffiths, H.D. (Eds.), Advances in Bistatic Radar. SciTech Publishing, Raleigh, pp. 56–77.

Stickle, A.M., Atchison, J.A., Barnouin, O.S., et al., 2015. Modeling momentum transfer from kinetic impacts: implications for redirecting asteroids. Procedia Eng. 103, 577–584.

Taylor, G.G.T., Altobelli, N., Buratti, B.J., et al., 2017. The Rosetta mission orbiter science overview: the comet phase. Philos. Trans. Roy. Soc. A 375 (2097) 20160262.

Thomas, P.C., Robinson, M.S., 2005. Seismic resurfacing by a single impact on the asteroid 433 Eros. Nature 436, 366–369.

Virkki, A., Muinonen, K., 2016. Radar scattering by planetary surfaces modeled with laboratory-characterized particles. Icarus 269, 38–49.

Walker, J.D., Chocron, S., 2011. Momentum enhancement in hypervelocity impact. Int. J. Impact Eng. 38, A1–A7.

Walker, J.D., Chocron, S., Durda, D.D., et al., 2013. Momentum enhancement from aluminum striking granite and the scale size effect. Int. J. Impact Eng. 56, 12–18.

Watanabe, S., Tsuda, Y., Yoshikawa, M., et al., 2017. Hayabusa2 mission overview. Space Sci. Rev. 208, 3–16.

Walsh, K.J., Jacobson, S.A., 2015. Formation and evolution of binary asteroids. In: Michel, P. et al. (Eds.), Asteroids IV. Univ. of Arizona, Tucson, pp. 375–393.

Zannoni, M., Tommei, G., Tortora, P., et al., 2018. Radio science investigations with the asteroid impact mission. Adv. Space Res. 62, 2273–2289. https://doi.org/10.1016/j.asr.2017.12.003.