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The Hera space mission in the context of small
near-Earth asteroid missions in the past, present
and future

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Abstract

The Hera mission of the European Space Agency was launched successfully on October 7, 2024 and will perform the first rendezvous with a binary asteroid in fall 2026. It will measure in great detail the characteristics of the binary asteroid (65803) Didymos. This will include for the first time the interior of an asteroid, as well as the outcome of the impact of the NASA DART mission on the small moon, called Dimorphos; of the binary system. The first asteroid deflection test will thus be fully validated, enabling impact model extrapolations to other cases. Hera uses a unique architecture that includes for the first time a main spacecraft and two cubesats for deep space asteroid exploration. It takes place in the context of the golden age of asteroid exploration, with no less than 8 missions in development or already flying to asteroids and great successes of past missions, in particular the two recent asteroid sample return missions OSIRIS-REx by NASA and Hayabusa2 by JAXA. Up to now, all new asteroids visited by a spacecraft have generated great surprises, especially regarding their often counter-intuitive response to external actions, showing that we are still far from fully understanding the properties of these bodies in their low-gravity environment. By investigating and interacting with small asteroids, we should eventually be able to better understand and predict their properties as a function of common characteristics identified by ground-based observations. We are not there yet. In this paper, we present how Hera will contribute to this endeavor.

Keywords: asteroids, binary asteroids, planetary defense, space mission

1 Introduction

The Hera mission, which belongs to the Space Safety Program of the European Space Agency (ESA), is the European contribution to the planetary defense Asteroid Impact & Deflection Assessment (AIDA) international cooperation (Michel et al., 2022). AIDA supports the development, operations and data interpretation of Hera as well as the

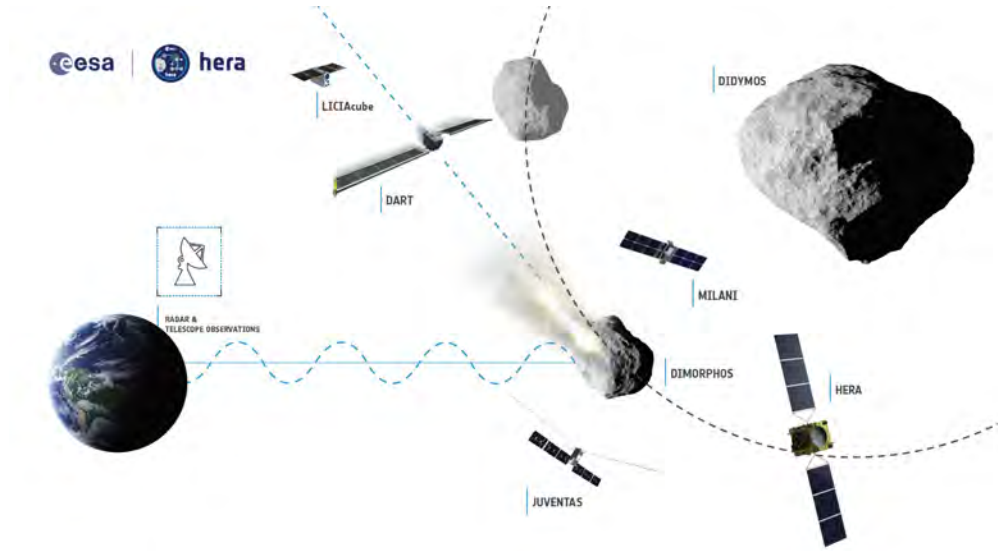


Fig. 1 Illustration of the NASA DART and ESA Hera missions targeting Dimorphos in the framework of the AIDA international cooperation. DART first performs the impact on the small moon, called Dimorphos, of the binary asteroid Didymos, and the Italian LiciaCube collects images within a few minutes after the impact. Hera, which includes a main spacecraft and two CubeSats, Milani and Juventas, reaches the asteroid a few years later to investigate in detail the characteristics of the two binary components and the DART impact outcome. The diameter of Didymos is 730 m, and its rotation period is 2.26 h, while the diameter of Dimorphos is 151 m and it is assumed that it was spin-locked before impact. Credit: ESA Science Office.

DART mission by NASA (Fig. 1) that performed successfully the first asteroid deflection test using the kinetic impactor technique (Daly et al., 2023; Cheng et al., 2023). The target of this first test is Dimorphos, the small moon of the binary asteroid (65803) Didymos. On September 26, 2022, the 580 kg DART spacecraft impacted the 151 m-diameter Dimorphos at 6.1 km/s, which resulted in the reduction of the original 11h 55m orbital period of Dimorphos around Didymos (Pravec et al., 2022) by 33 minutes (Thomas et al., 2023). Images of the asteroid and its ejecta were taken a few minutes after impact by the ASI CubeSat, LICIACube (Dotto et al., 2024), released from DART 15 days before impact, while ground-based observations were used to measure the orbital change. Images from HST were obtained up to a few weeks after impact (Li et al., 2023), showing a long tail of ejecta and that some boulders were still present, escaping slowly from the system a few months after impact (Jewitt et al., 2023).

On October 7, 2024, Hera was launched successfully from Cape Canaveral on a SpaceX Falcon 9 rocket. The science objectives, mission design, instruments, and team structure can be found in [Michel et al. \(2022\)](#). A few days after launch, the Asteroid Framing Cameras (AFC), the Hyperspectral Imager (HyperScout-H), and the Thermal Infrared Imager (TIRI) were activated and took pictures of the Earth-Moon system (Fig. 2), confirming their performance in the space environment. A functional checkout of the two CubeSats, Milani and Juventas, together with their payloads, was also performed successfully. On October 23rd, Hera fired its three orbital control thrusters for ≈ 100 minutes, kicking off its first deep-space manoeuvre and changing its velocity by approximately 146 m/s. A second burn on 6 November lasted 13 minutes with the aim of providing an additional boost of around 20 m/s. A much smaller correction manoeuvre of a few tens of cm/s was executed on 21 November to fine-tune the trajectory and line it up for the gravity assist at Mars in March 2025. After a fly-by of Mars and Deimos on March 12, 2025 and further deep space maneuvers, Hera will reach the Didymos system in October 2026, with close proximity operations starting in December 2026 for at least 6 months, offering the first deep space asteroid investigation involving a mother spacecraft and two CubeSats (Fig. 3) for close proximity operations and landing.

In this paper, we present Hera in the context of other missions to asteroids, focusing on those devoted to small near-Earth asteroids or asteroids of similar sizes to Didymos and Dimorphos. In Sec. 2, we present the lessons learned from JAXA Hayabusa and Hayabusa2. Sec. 3 is devoted to the lessons learned from NASA OSIRIS-REx. Data obtained about Didymos and Dimorphos, as well as the DART impact, from DART and LICIACube data are briefly reviewed in Sec. 4. Sec. 5 summarises the planned measurements to be obtained by Hera, while the context of future missions is described in Sec. 6. Discussion and conclusions are then provided in Sec. 7.

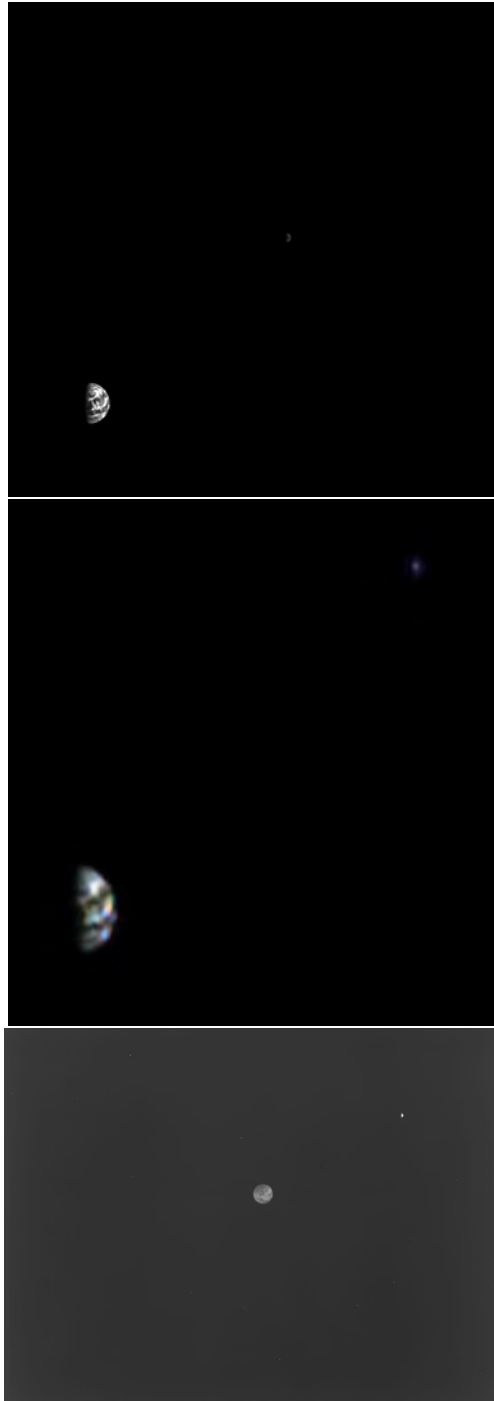


Fig. 2 Images of Earth and Moon taken by one the two Asteroid Framing Cameras (top), the HyperScout-H Spectral Imager (centre), and the Thermal Infrared Imager (bottom). The distance of Hera from Earth was 1.4 million km for the image in the thermal infrared and about 1.6 million km for the other two images.



Fig. 3 Illustration of the Hera spacecraft and its two CubeSats, Milani and Juventas, deployed in proximity of Dimorphos (left) and Didymos (right). Note that neither the shape nor the crater on Dimorphos are expected to represent what Hera will discover, which is still unknown, when arriving at the binary asteroid. Credit: ESA.

2 Lessons learned from JAXA Hayabusa and Hayabusa2

The JAXA Hayabusa mission was launched on May 9, 2003, with an M-V rocket to reach the near-Earth asteroid (25143) Itokawa in 2005 ([Kawaguchi et al., 2008](#)). For this first asteroid sample return mission, the main goal was to demonstrate several technologies to prepare another science-oriented mission. However, and despite several difficulties, Hayabusa allowed a new step in our understanding of small bodies. Indeed, it was the first time that a space mission had visited an asteroid as small as a few hundred meters in diameter. Images of Itokawa, which belongs to the S taxonomic class ([Binzel et al., 2001](#)), has the appearance of a small rubble pile asteroid ([Fujiwara et al., 2006](#)). It has an elongated shape consisting of two lobes, referred to as the head and a body, separated by a neck, with dimensions of 535 m 294 m 209 m (mean diameter of 320 m), and its surface is covered with boulders and pebbles as well as

a few large smooth areas (See Fig. 4). Through mass and volume measurements, the density could be obtained, which is about 1.9 g/cm^3 (Abe et al., 2006). Comparison with the density of meteorite analogues, ordinary chondrites, indicates that Itokawa contains about 40% of internal porosity, which is consistent with a rubble pile structure (Britt et al., 2002; Scheeres et al., 2015). In fact, collisional evolution models indicate that asteroids of the size of Itokawa in the main belt have a lifetime that is shorter than the age of the Solar system (Bottke et al., 2005). Itokawa originates from the main belt (Michel and Yoshikawa, 2006) and therefore must have been born from the disruption of a larger parent body. Numerical simulations of such disruptions show that asteroids of a size above 100-200 meters are the outcome of gravitational reaccumulation of small fragments produced by the disruption, leading to a rubble pile structure (Michel et al., 2001). Furthermore, the reaccumulation process can lead to a wide variety of shapes, which explains the observed diversity. A direct application to Itokawa and its shape was performed by Michel and Richardson (2013) who then showed that when the head and the body come together through the reaccumulation process, this is followed by smaller boulders coming back on the surface of the bigger components at low speed, explaining the high boulder abundance on Itokawa. An offset of the centre of mass of Itokawa has been identified by independent approaches. It is required to reconcile YORP model predictions with the observed spin rate increase. It has also been found by modeling the gravity field and fitting the smooth terrains on Itokawa to equi-potential surfaces. Both approaches lead to significantly different densities for the two lobes of Itokawa with the head having a higher density than the body. The first approach estimates a density for the head of 2.85 g/cm^3 and for the body of 1.75 g/cm^3 , while the second approach leads to a density for the head of 2.45 g/cm^3 and for the body of 1.93 g/cm^3 (Lowry et al., 2014; Kanamaru et al., 2019). This difference in density for the two main components of Itokawa may be explained by the different relative sizes of the largest impact fragments within the

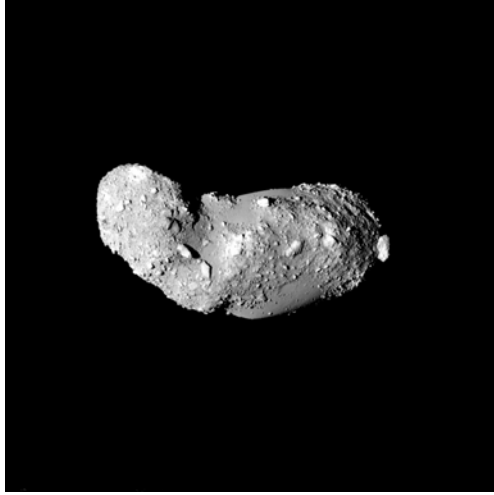


Fig. 4 The asteroid Itokawa as seen by Hayabusa facing its longest dimension of 535 meters. Credit: JAXA.

lobes ([Campo Bagatin et al., 2020](#)). Such model-dependent results highlight the need for direct measurements of the surface and subsurface properties to constrain them. The analysis of samples returned in 2010 confirmed the link between asteroids of the S taxonomic class, to which Didymos and Dimorphos also belong, and the LL chondrite meteorite class ([Nakamura et al., 2011](#)).

Despite this high knowledge return, Hayabusa was confronted by many issues during its journey (see, e.g., [Yoshikawa et al., 2015](#)), showing that operations in close proximity to low-gravity bodies are complex. This complexity is enhanced by the fact that until we reach an asteroid, most of the knowledge needed to design the operations relies on assumptions. Indeed, it is limited to ground-based observation data, which cannot provide the detailed characteristics of the surface as well as the asteroid environment (presence of moons that are smaller than detection capabilities from Earth), which are essential to design the adapted navigation strategy. Therefore the operations plan must be established with great flexibility to be able to cope with surprises once at the asteroid. One interesting experience, which was not planned, is that the spacecraft bounced a few times on the surface at the first touch-down operation and then

settled down near the polar region for almost 30 minutes. The analysis of the bouncing properties, which may contain big errors, seems to indicate that the surface was not extremely soft but had some strength, with a restitution coefficient of 0.84 (Yano et al., 2006), which is equivalent to that of a rubber on concrete. This is at odds with further experiences of surface interactions (see the following cases of Hayabusa2 and OSIRIS-REx). In the Hera mission, for the first time, a CubeSat is planned to land on a body as small as Dimorphos. The Juventas Cubesat effectively needs to land so that its gravimeter can perform the measurements of the asteroid’s gravity field. Being equipped with accelerometers, it will then be possible to analyse the bouncing behavior of Juventas on such a small asteroid. It will then be interesting to compare it with that of Hayabusa on a body of the same spectral type but slightly higher gravity. The Cubesat Milani is also planned to attempt a landing. Unlike Juventas, Milani is not required to land to achieve its scientific goals, and a landing on Didymos is also considered as end-of-life strategy. In addition, like Juventas, Milani is also equipped with Inertial Measurement Units (IMUs) and, therefore, can provide similar information on the CubeSat’s bouncing behaviour and surface interaction after touchdown.

The second Japanese mission to an asteroid, Hayabusa2, was launched on December 3, 2014, with an H-2A rocket (Tsuda et al., 2013). It included a series of complex and diverse operations at the target asteroid (162173) Ryugu, a C-type object (Binzel et al., 2001), all of which were successful (Tsuda et al., 2022). With a diameter of 900 meters (Fig. 5), about 3 times the mean diameter of Itokawa, and based on the Hayabusa experience, some smooth areas with a width of at least 50 meters were expected to be present on the surface of Ryugu. On the contrary, the first images obtained in June 2018 of the asteroid’s surface showed a very dark object with a spinning top shape, whose surface was entirely covered with large boulders with no wide smooth areas (Watanabe et al., 2019). This was in contrast to the original assumptions and, therefore, the operation team had to revise entirely the landing strategy.

The original 50 meter-accuracy had to be improved to a 10 meter-accuracy, as no area wider than about 10 meters existed on Ryugu ensuring a safe landing. Details can be found in [Kikuchi et al. \(2022\)](#), demonstrating the need for high flexibility and capacity to adapt to an unexpected environment. Hayabusa2 deployed several surface packages on Ryugu’s surface, starting in September 2018 with the Minerva hoppers, which revealed from the surface itself the extreme roughness of Ryugu’s landscape, followed in October 2018 by the MASCOT lander developed by DLR and CNES ([Ho et al., 2017, 2021](#)). After bouncing off a cliff, MASCOT landed at 17 meters distance and started its operations ([Garmier et al., 2021](#)). The first in-situ thermal infrared observations of a boulder on a C-type asteroid were then performed by the infrared radiometer MARA, indicating that the boulder’s thermal inertia was very low. This low thermal inertia implies that boulders on Ryugu exhibit low thermal conductivity, which in turn reflects a high porosity and a low tensile strength in the range of a few hundred kPa ([Grott et al., 2019](#)). Thus, a low thermal inertia does not necessarily imply the presence of fine grains, as was commonly assumed ([Gundlach and Blum, 2013](#)), but can be due to the high porosity of meter-sized boulders.

The biggest surprise occurred after the first successful touch-down and sampling operation that was performed in February 2019, when the Small Carry-on Impactor (SCI) experiment was carried out on April 5, 2019. This impact experiment was the first to be performed on an asteroid’s surface. It involved a projectile of 2 kg launched at 2 km/s towards the surface of Ryugu ([Arakawa et al., 2017](#)). While a crater of a few meters in diameter was expected if the surface had some strength, the real crater was much bigger, of about 17 meters in diameter. The only way to explain such a large size is by considering the surface as cohesionless or with a cohesion less than 1.2 Pa ([Arakawa et al., 2020](#)). This was a big surprise, as the impact occurred on a surface that is rich in boulders, as shown by pre-impact images. The presence of apparently solid boulders suggested that there is some material with perceptible strength on the

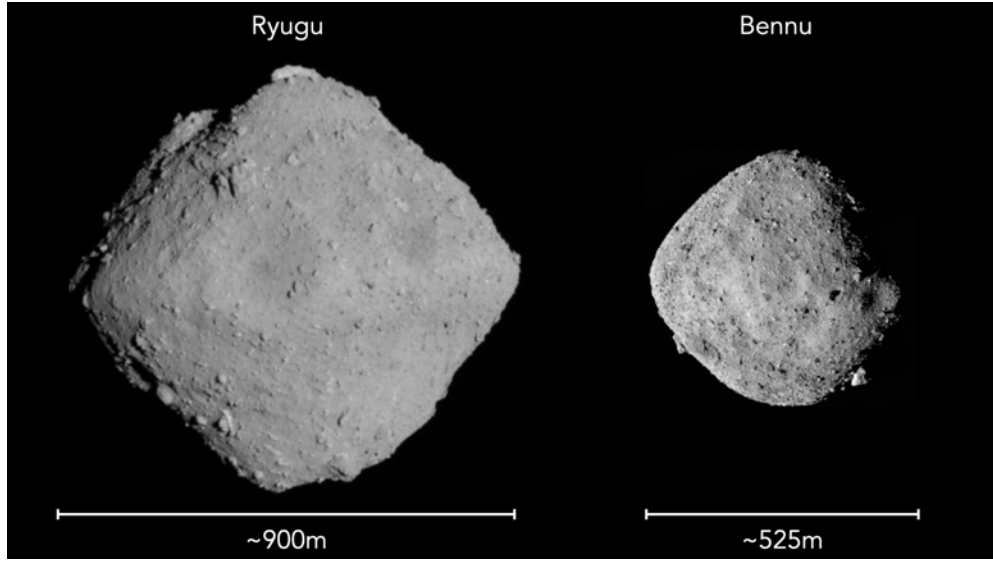


Fig. 5 The asteroids Ryugu and Bennu were visited by the JAXA Hayabusa2 and NASA OSIRIS-REx missions. Image credit for Ryugu: JAXA, University of Tokyo, Kochi University, Rikkyo University, Nagoya University, Chiba Institute of Technology, Meiji University, University of Aizu, and AIST. Image credit for Bennu: NASA/Goddard/University of Arizona.

surface (Fig. 6). In fact, some boulders were displaced from their original position by the impact, showing that some materials with strength were present at the impact region. However, globally, the surface behaved as if it was cohesionless, which was confirmed by images of the impact obtained by the small camera DCAM3 (Kikuchi et al., 2024). The camera showed a fair amount of ejecta falling back onto the surface, despite the low gravity of the asteroid. Such low-speed ejecta are also characteristic of a crater produced in the gravity regime where cohesion is negligible. This new finding required numerical models to be revised to be able to capture the impact physics in such low-gravity regimes (Jutzi et al., 2022). Hayabusa2 successfully performed two sampling operations, and eventually, 5.4 grams of sample were returned to Earth in December 2020. Their isotopic composition and their average bulk density ($1.79 \pm 0.31 \text{ g/cm}^3$ (Miyazaki et al., 2023)) match that of CI carbonaceous chondrites. Since the bulk density of Ryugu is about 1.2 g/cm^3 , the interior of the asteroid must contain a fraction of porosity that could be a mixture of microporosity, as measured in the

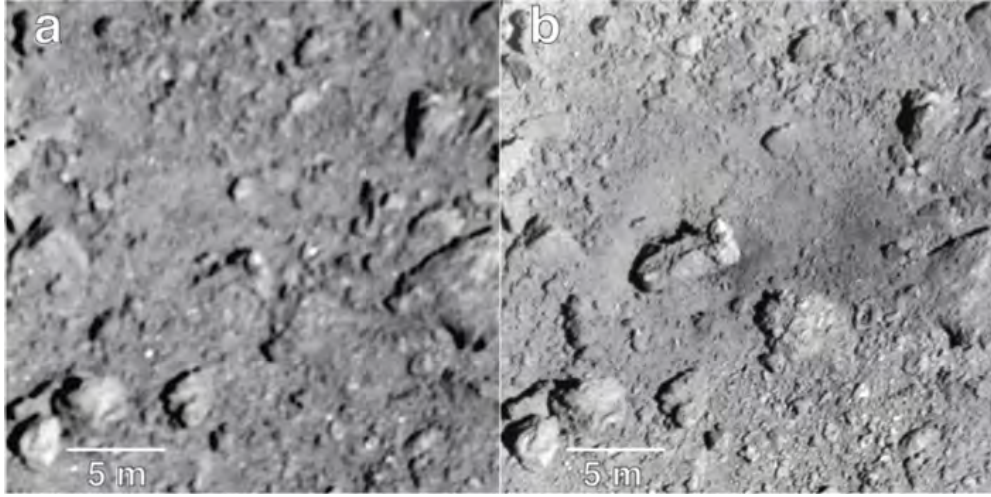


Fig. 6 Images taken by the ONC camera onboard Hayabusa2 before (a) and after (b) the SCI impact. Both images are registered in an ONC latitude-longitude mosaic map. Credit: JAXA, The University of Tokyo, Kochi University, Rikkyo University, Chiba Institute of Technology, Meiji University, The University of Aizu, AIST.

samples (26-31%), and macroporosity. However, the exact distribution is not known since there was no instrument devoted to the probing of the internal properties, as planned on Hera. Therefore, we are left with open questions regarding the detailed rubble structure of Ryugu, with implications on its formation through the catastrophic disruption of a larger parent body ([Michel et al., 2020](#)).

3 Lessons learned from NASA OSIRIS-REx

OSIRIS-REx was launched on September 8, 2016, from Cape Canaveral with an Atlas V rocket. It reached the asteroid (101955) Bennu, 500 meters in diameter, on December 3, 2018 ([Lauretta et al., 2015](#)). Like Ryugu, Bennu belongs to the C-complex taxonomic class ([Clark et al., 2011](#); [de León et al., 2012](#)), with CM carbonaceous chondrites as the best meteorite analogues. Based on radar observations ([Nolan et al., 2013](#)), its shape was already expected to resemble a spinning top. This was confirmed with actual images sent by OSIRIS-REx at arrival ([Barnouin et al., 2019](#)). As for

Ryugu, the first real surprise was the incredible richness of boulders on the surface of Bennu (DellaGiustina et al., 2019), which also required a revision of the sampling operation strategy (Lauretta et al., 2021). In fact, although they have different levels of gravity due to their difference in size and mass, the two asteroids show a few common characteristics, which is interesting (Fig. 5). Their shape, density, and albedo are similar, as well as the presence of craters at the equator. If one looks more into details however, there are also some differences, like the equatorial ridge that is much more circular on Ryugu than on Bennu (Roberts et al., 2021). Spectrally, while the material of Ryugu becomes redder with time due to space weathering (Morota et al., 2020), an opposite and more complex trend is found on Bennu (Lantz et al., 2017). The asteroid has a moderately blue average color. Unweathered material is first redder, but thanks to space weathering, it brightens in the near-ultraviolet (becoming bluer at shorter wavelengths) and then brightens in the visible to near-infrared (DellaGiustina et al., 2020). The spectral variability is associated with a diversity of geologic features, which include boulders and craters, as well as areas where rocks are moved down geopotential slopes (Jawin et al., 2022). While the Hayabusa2 spacecraft mostly hovered at a home position 20 km distant from Ryugu, OSIRIS-REx performed a series of complex trajectories, which included orbiting around Bennu and performing flybys at close distances to choose and characterize appropriate sampling sites (Lauretta et al., 2021). This operational strategy enabled acquisition of a large number of detailed images of the surface. One additional challenge for the operations is that Bennu was observed to be active, and small particles were regularly ejected naturally from its surface (Lauretta et al., 2019). It was concluded that this activity did not pose any threat to the spacecraft, given the size and speed of ejected particles. However, this is a good example of surprises that may await us, which can question the initial operation plan if any danger is identified. On the positive side, the tracking of the trajectory of these natural ejecta enhanced the determination of the gravity field of the

asteroid (Scheeres et al., 2020). Thanks to these maneuvers, over the almost 2 years of observations of Bennu’s surface by the various instruments onboard the spacecraft, the geological context of Bennu was fully documented. Like on Ryugu, a diversity of boulder types was found, differing in brightness and morphology. Diverse exogenous materials were also identified, some of them having a spectral type matching that of V-type asteroids (DellaGiustina et al., 2021; Tatsumi et al., 2021), while on Ryugu they match that of S-type asteroids (Tatsumi et al., 2021). On both asteroids, an absence of fine grains is apparent on the surface. Thus, although the global cohesion of Bennu was estimated to be rather low, on the order of a few Pa (Barnouin et al., 2019), and the surface cohesion even less, smaller than 0.6 Pa (Barnouin et al., 2022), solid features like boulders and pebbles are apparent on the surface. Such features are also present in the surroundings of the finally chosen sampling site, called Nightingale (Fig. 7). Yet, the surprise that was offered to the team when the sampling operation was performed, was that the surface showed almost no reaction when the sampling device head touched it, as if it consisted of a cohesionless medium (Walsh et al., 2022)! Images are misleading when they are used to assess the mechanical properties of the surface of a small asteroid in its extremely low gravity environment, as the apparent presence of solid features is not diagnostic of a surface with high strength. As for the Hayabusa2 SCI experiment, the surface behaved globally as an almost cohesionless one. But some pebbles were also moved by the sampling operation, which shows that material with strength also exists while not influencing the global behavior. Furthermore, Ballouz et al. (2020) derived from the identification of craters on some boulders that the strength of boulders on Bennu is in the range 0.5–1.7 MPa. This demonstrates the complexity of small body reactions that need to be accounted for in the interpretation of Hera data. In fact, Hera will allow us to understand the response of a small asteroid to a hypervelocity impact, thanks to the DART impact, and to a low-speed landing, thanks to Juventas and Milani landings, allowing us to explore the mechanics of asteroids under two different kinds of interactions.

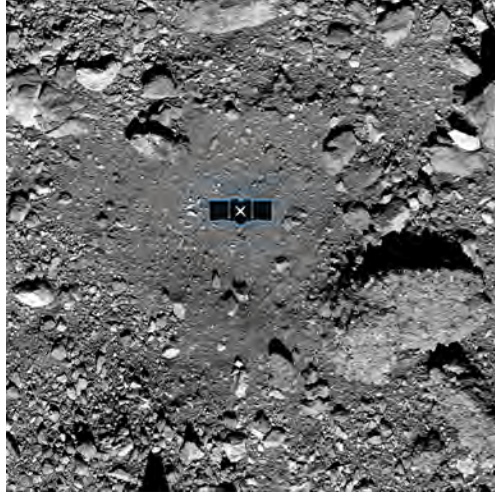


Fig. 7 The sample site Nightingale of the OSIRIS-REx mission on Bennu. The image is overlaid with a graphic of the OSIRIS-REx spacecraft to illustrate the small scale of the site. Credit: NASA/Goddard/University of Arizona; source: www.asteroidmission.org

4 Results from the DART mission

The DART mission successfully reduced the orbital period of Dimorphos around Didymos by 33 minutes from an original period of 11h 55m (Thomas et al., 2023). Here, we briefly expose some of the many results that were obtained thanks to intense and fruitful activities to analyze the data. Assuming a reasonable range for the mass of Dimorphos, which could not be measured, the decrease by 33 minutes of the orbital period of Dimorphos implies an enhancement by a factor 2 to 5 of DART’s momentum transferred to the asteroid (Cheng et al., 2023). Thanks to images provided by the DRACO camera onboard the DART spacecraft, the initial properties of both Didymos and Dimorphos could be investigated, although only one side of each of the two bodies could be observed (Fig. 8), as the images cover only the last tens of minutes before impact (Daly et al., 2023). Nevertheless, these investigations allowed documentation of the impact site on Dimorphos as well as performing estimates of various properties, such as surface ages, the bearing capacity, which is the capacity of a soil to support the loads that are applied to the ground above, the angle of internal friction and the role

of thermal fracturing (Lucchetti et al., 2024; Barnouin et al., 2024; Bigot et al., 2024; Pajola et al., 2024; Robin et al., 2024; Vincent et al., 2024). Post-impact dynamical analyses and predictions were also performed (Richardson et al., 2024; Meyer et al., 2023; Nakano et al., 2024). Moreover, accounting for images of early ejecta by the LICIACube CubeSat (Dotto et al., 2024) and data obtained from space by HST (Li et al., 2023), JWST (Rivkin et al., 2023), the Lucy spacecraft (Weaver et al., 2024) and ground-based telescopes (Bagnulo et al., 2023; Lin et al., 2023; Moreno et al., 2023; Murphy et al., 2023; Opitom et al., 2023; Polishook et al., 2023; Roth et al., 2023; Rožek et al., 2023; Shestakova et al., 2023; Gray et al., 2024; Lister et al., 2024; Ofek et al., 2024) numerical impact models were also used to predict what should be the final state of Dimorphos. Accounting for all data at hand, one prediction is that Dimorphos is very weak and that the DART impact entirely reshaped it (Raducan et al., 2024). In fact, studies of the geology of both Didymos and Dimorphos from DRACO images also suggest that Dimorphos has a surface cohesion smaller than 0.9 Pa (Barnouin et al., 2024), which is consistent with the necessary weak structure to explain the ejecta characteristics by numerical impact models. Furthermore, the boulder-rich surface of Dimorphos (Pajola et al., 2024; Vincent et al., 2024) and binary formation models also suggest that Dimorphos is a rubble pile, formed by mass shedding from its primary (Didymos) and debris reaccumulation (Agrusa et al., 2024). Overall, DART was extremely successful, offering a great amount of detail regarding the original properties of the Didymos system and predictions for the Hera mission to verify (Chabot et al., 2024).

5 What Hera will measure

Although Hera will visit two asteroids for which we already have images, one important thing to keep in mind is that Didymos and Dimorphos, as imaged by the DRACO Camera onboard DART before impact, will be very different when Hera takes images.



Fig. 8 Dimorphos (left) and Didymos (right) oriented with their north poles toward the top of the image and with each asteroid and their distance to each other to scale. Both images correspond to mosaics of DRACO images, assembled by layering the higher-resolution images on top of the lower-resolution ones. The height of Dimorphos is roughly 113 m and the height of Didymos is roughly 607 m. Credit: NASA/Johns Hopkins APL.

In fact, Hera is not going to visit an already known world, but one that will likely have experienced substantial modifications because, between the DART images and those obtained by Hera, something major has happened. A hypervelocity impact was performed with perfectly known initial conditions regarding both the projectile's mass, speed, impact angle as well as the impact site. Therefore, Hera will tell us what transformations may have occurred on a small asteroid that has experienced such an impact, in its almost immediate aftermath. Four years delay is a short enough time to assume that nothing substantial happened between DART and Hera in the asteroid system. In addition to the relevance for planetary defense, this also has high relevance for the scientific understanding of asteroids. In effect, until now, space missions to asteroids showed us craters on their surfaces without the possibility of really knowing when they were produced and in which conditions. With DART and Hera, for the first

time, we can relate a major modification to the event that produced it, including the conditions of this event itself.

Predictions of the outcome of the DART impact do not lead to a unique solution (Raducan et al., 2024). Therefore, we can expect big surprises and that the new images of Dimorphos and Didymos will correspond to real discoveries, showing us the reality of a wide range of possibilities. For instance, we can say with certainty that the images provided by Hera of the impact site will be very different from the last image of this site by DART before impact (Fig. 9). All boulders at the impact site do not exist anymore and a new geological environment waits to be discovered. In fact, we cannot rule out that a few small pebbles left from the DART impact will still be present in the environment of Didymos when Hera arrives, which has to be accounted for in the close proximity operations. However, if they exist, they are expected to fly at very low relative speeds and therefore pose no threat to the Hera spacecraft. It may also be that small particles are naturally ejected from the two components, like for Bennu (see Sec. 3). This could be the case if the observed activity on Bennu is simply due to micrometeorite impacts, which occurs on all small bodies and which can then be detected and analyzed by the VISTA instrument onboard the Milani CubeSat. Note that they did not pose any threat to the OSIRIS-REx spacecraft and the ESA operation team had to deal with such complexity during the ROSETTA mission on an even more active body (Prez-Aycar et al., 2018).

As illustrated in more detail in Michel et al. (2022), one of the main measurements Hera will obtain is the mass of Dimorphos (see Tortora et al., this issue, and Gramigna et al. (2024) for more details on this multi-instrument measurement including radio science). The measurement of the mass will allow us to determine by what factor the momentum of DART was enhanced, which is currently estimated to be between 2 and 5 (Cheng et al., 2023). Although the post-impact mass is less than the initial mass due to the production of ejecta, the difference is only thought to be of the order of



Fig. 9 The last complete image of Dimorphos, taken by the DRACO imager from ≈ 12 kilometers from the asteroid and 2 seconds before the impact of the DART spacecraft. The image shows a patch of the asteroid that is 31 meters across. Credit: NASA/Johns Hopkins APL.

1% and, therefore, will not affect the evaluation of the momentum transfer efficiency. The gravimeter onboard the Juventas Cubesat, after its landing on Dimorphos, will also contribute to the determination of the gravity field. Then images of Dimorphos will tell us whether it has been globally reshaped and in this case, what is the new shape. If the surface shows a crater as a result of the DART impact, Hera will allow us to measure its size and depth. Spectral imaging from both the Hyperscout-H spectral imager onboard the main spacecraft and the ASPECT near-infrared imager onboard the Milani Cubesat will reveal the extent of fresh material exhumation, resurfacing, and ejecta deposition on both Dimorphos and Didymos. These observations are what the numerical impact models must succeed in reproducing to be validated. However, these models also need to know which asteroid structure they need to consider as a target, i.e., whether they need to start with a large solid core surrounded by boulders and gravel as originally seen on the surface, or whether they need to consider a rubble pile with a similar boulder size distribution in and out! Hera will thus feed the models by measuring the internal properties of Dimorphos, as never done before, thanks to the low-frequency radar, JuRa, onboard the Juventas Cubesat (Herique et al., this

issue). The high-resolution images of Dimorphos from the AFC (Vincent et al., this issue) will also allow improved constraints to be placed on the asteroid’s physical properties such as density, friction, cohesion (e.g., Barnouin et al., 2024; Robin et al., 2024). Data by TIRI, the Thermal Infrared Imager onboard the spacecraft, will also provide information on the thermal properties and surface roughness. Thus, thanks to this wealth of data, numerical models will have as inputs a precise knowledge of the initial conditions of the simulations, which include the impact conditions given by DART and the target’s physical, compositional and internal properties given by Hera, as well as the final ones in terms of the crater’s size and depth or global reshaping of the asteroid that they must reproduce for their validation. DART and Hera thus offer a fully documented deflection experiment relying on a hypervelocity impact at asteroid scale with great applications to planetary defense and solar system science. Furthermore, the response to a low-speed impact will also be explored with the landing of the two Cubesats. We will then obtain valuable information on the mechanical properties of small asteroids with implications on the design of surface packages or tools aimed at interacting with their surfaces for various purposes.

6 Hera in the context of other and future missions

Hera takes place in the context of what we can call the golden age of asteroid exploration. There is a great number of missions that are either already flying or in development to visit the main belt, Trojan or near-Earth asteroids. As we focus on near-Earth asteroids (NEAs), we mention but do not describe those devoted to other kinds of asteroids: Lucy (Levison et al., 2021) and Psyche (Elkins-Tanton, 2018) by NASA, and EMA by UAE space agency (AlMazmi et al., 2023), which includes the landing of a surface package. These missions will reveal new and important knowledge about a multitude of asteroids, either through flybys, rendezvous or even landing operations, which will also allow us to better assess their diversity.

Regarding NEAs, while DART was a big success, the two other missions to near-Earth asteroids which we briefly described in previous sections, namely Hayabusa2 by JAXA (Sec. 2) and OSIRIS-REx by NASA (Sec. 3), were also highly successful during their prime mission and have now been extended. The Hayabusa2 mission is now re-named Hayabusa2Sharp (for Small Hazardous Asteroid Reconnaissance Probe). It is targeting a flyby of the 500-meter diameter NEA (98943) Torifune in July 2026. It is then planned to rendezvous in July 2031 with 1998 KY26, an NEA with a diameter of only about 30 meters and a rotation period of only 10 minutes (Mimasu et al., 2022), although a recent study under review decreased the diameter to 11 meters and the spin period to 5.3 minutes (Santana-Ros et al., 2025), which makes it even more challenging for close proximity operations. This rendezvous will allow us to discover the geological properties of a small fast rotator whose size is close to the size of the body that exploded over Chelyabinsk on February 15, 2013. Another fast rotator is the target of the sample return mission Tianwen-2 (Zhang et al., 2019) by China National Space Administration (CNSA), i.e. the asteroid (469219) Kamo'oalewa, which is a quasi-satellite of the Earth probably originating from the Moon (Jiao et al., 2024), whose size is also 40-100 meters and rotation period is only 28 minutes. The launch is planned for 2025 followed by a challenging approach and sampling operation on such a small and fast-rotating body, which will lead to very interesting information regarding the response of asteroids in those conditions to external actions. CNSA also announced a mission to perform a deflection test using the same technique as DART, including also an orbiter, to an NEA of 30 meters diameter (Wei et al., 2024).

Another mission, which is more closely connected to Hera, is the OSIRIS-APEX mission, which is the mission extension of OSIRIS-REx (DellaGiustina et al., 2023). After the successful release of the re-entry capsule containing the samples of Bennu on September 24, 2023, the OSIRIS-REx probe took a new journey and a new name to reach the NEA Apophis in 2029 and visit it for 11 months. Apophis will perform a

close approach at a distance of 32,000 km to the Earth on Friday April 13, 2029. Such a close approach for an asteroid of 340 meters in diameter is estimated to occur only once in a few millennia, which makes this event a unique opportunity for us to investigate its potential consequences on the asteroid’s physical properties. As we have seen in previous sections, the response of small asteroids to external actions is still counter-intuitive and images are not sufficient to predict their physical properties accurately. However, so far, all external actions were artificially produced, through sampling or impact experiments. In the case of Apophis, we have the unique opportunity to observe the action of nature, through the tidal forces of the Earth that will be effective during the passage of Apophis at its closest distance to our planet ([Kim et al., 2023](#)). Because of its close proximity to Earth, its light will be visible to the naked eye by more than 2 billion people in the night sky of April 13, 2029 in Europe, Africa, and parts of Asia, making this event something to remember collectively. The trajectory of OSIRIS-APEX will only allow the start of its detailed investigation a few weeks after the closest approach to Earth of the asteroid. The mission will then measure the potential long-term effects of Earth’s tidal forces and post-encounter physical properties. In order to investigate the immediate change of properties during the closest approach, another mission is needed that can measure the pre-encounter properties and observe how they evolve while tidal forces are in action. The European Space Agency got the authorization of pre-funding to start the development of the RAMSES mission (Rapid Apophis Mission for Space Safety) before a formal approval at the ESA Council at Ministerial Level of November 2025, so that it can launch in April 2028, reach Apophis two months before its closest approach to the Earth and characterize its properties before, during and after the approach, paving the way to OSIRIS-APEX ([Küppers et al., 2024](#); [Michel et al., 2025](#)). Due to the short timescale to develop RAMSES, the chosen approach is to base the mission on a re-built and adaptation of the Hera platform as well as mission architecture with two CubeSats and team structure, with

some adjustment because some payloads are different. Since the development scheme and organizational structure used for Hera demonstrated its ability to develop a space mission in a rapid manner, it is thus natural to use the same approach for an even more rapid development, this time not starting from scratch. Such a fast development is in line with the necessity of being able to develop fast reconnaissance missions in the framework of planetary defense.

7 Conclusion

Hera is now on its way to the Didymos system, which will look like a new world to us. What we know from the system thanks to the pre-impact images obtained by the DRACO Camera onboard the DART spacecraft must have experienced major changes. Yet we do not know what those changes are. Thanks to its architecture, which includes for the first time for deep space exploration of a small body and contribution to a deflection test, two CubeSats in addition to a main spacecraft, new kinds of measurements will be performed as well as technology demonstrations, which promise major advances in our understanding of asteroids and how to protect us from an impact.

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Conflict of interest/Competing interests

Not Applicable

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