Planetary science

DART's data verify its smashing success

Coralie D. Adam

A strategy for deflecting asteroids on a path towards Earth has passed its first test. The results confirm predictions about how asteroids respond to impact — and offer useful insights.

See p.443, p.448, p.452, p.457 & p.461

On 26 September 2022, a spacecraft the size of a refrigerator collided with the moon of an asteroid. The Double Asteroid Redirection Test (DART) was the first planetary-defence experiment designed to test the viability of re-routing an asteroid through kinetic impact. Viewers worldwide were captivated by images transmitted by the DART spacecraft as it approached the asteroid moon known as Dimorphos. Five papers[1–5] in this issue characterize the impact and its dusty aftermath, which were captured by space- and Earth-based telescopes. The authors' findings advance our understanding of asteroid-impact geophysics and planetary defence.

Dimorphos is the natural satellite of the subkilometre-sized asteroid Didymos, and together the pair form a binary system that poses no threat to Earth (Fig. 1). The system was chosen for the DART experiment because it would be possible to measure the degree to which the impact changed Dimorphos's orbit of Didymos — a key observable parameter — using telescopes on Earth. And with an average diameter of roughly 150 metres, Dimorphos also happens to be in a size category that is relevant to planetary defence because an asteroid the size of Dimorphos could cause substantial regional damage on Earth. Only one-third of the population of asteroids larger than 140 metres in diameter has so far been detected and tracked[6].

The spacecraft navigated and manoeuvred autonomously during its final 4 hours before smashing into the surface of Dimorphos at 6.1 kilometres per second. The camera that the spacecraft used to perform this navigation couldn't distinguish between Dimorphos and Didymos until 73 minutes before the collision[2].

The Italian Space Agency's LICIACube spacecraft (Cheng *et al.*[1]; page 457) was released from DART 15 days before the impact and performed a close fly-by of Dimorphos 168 seconds after impact, catching a glimpse of the complex structure of the ejected material. Earth- and space-based telescopes observed radiation from the impact at visible and radio frequencies for more than 18 days after the collision, witnessing a plume of dust shoot away from Dimorphos at high velocity and then change slowly into a complex, tail-like structure.

Daly and colleagues[2] (page 443) provide estimates of the timing, velocity, energy, location and angle of the impact, as well as geophysical properties of Dimorphos and Didymos. The reported measurements offer preliminary models for the shapes of both bodies, putting limits on their sizes and providing valuable characterization of the terrain at the impact site. The authors determined to metre-level certainty that DART hit the surface only 25 metres from the geometric centre of Dimorphos. This precision allowed them to pinpoint the exact location of the spacecraft's impact with respect to their digital model of the moon's terrain. The team identified two large boulders that the spacecraft's solar panels probably touched first, before its more massive main body collided with the terrain between them. These results establish a frame of reference for the companion studies published in this issue, as well as for future work.

Measuring the change in Dimorphos's orbital period allowed an estimation of the momentum transferred to the asteroid by the spacecraft. Thomas *et al.*[5] (page 448) found that this period change was −33 minutes. The change was much more than the 7 minutes that was expected of the impact[7], but is still within the range of expected possibilities. The authors measured pre- and post-impact orbital periods with radar and with light-curve measurements (which quantify a celestial body's brightness) from various ground-based telescopes. Two independent numerical methods, one based solely on light-curve data and the other combining light-curve and radar data, yielded statistically identical results.

Cheng and colleagues estimated the change in orbital velocity, and confirmed the degree to which the impact was expected to enhance Dimorphos's momentum[7] as a result of recoil from the ejecta streams it produced. The authors used extensive computer simulations to perform their calculations, because the coupled dynamics of the binary system are complicated, and several of the parameters used to model the possible impact scenarios are subject to uncertainties. Their findings show that the DART impact was highly effective at deflecting Dimorphos. However, with a sample size of one, this does not necessarily mean that the technology used would be as

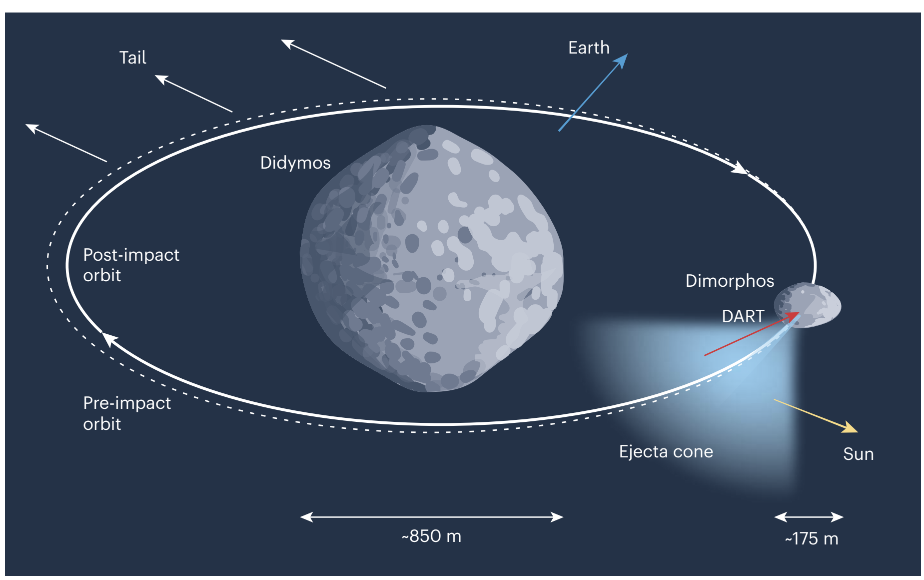

Figure 1 | Deflecting the asteroid moon, Dimorphos. The Double Asteroid Redirection Test (DART) assessed the viability of re-routing an asteroid by directing a spacecraft to collide with Dimorphos, the moon of an asteroid called Didymos, along the direction of the red arrow. The mission was a success, and the impact reduced the period of Dimorphos around Didymos by 33 minutes. Five papers[1–5] now report findings derived from space- and Earth-based observations of the event and its aftermath, including the wide ejecta cone and the tail of dust that the impact caused.

effective at diverting other asteroids.

The ejected material was observed by LICIACube, the Hubble Space Telescope and a network of ground-based telescopes. Li and colleagues[4] (page 452) used 3D numerical modelling and the Hubble data to characterize the ejecta over the course of the 18 days during which Hubble observed it. Gravity and solar-radiation pressure sorted the material naturally by particle size during this period, enabling the authors to identify micrometre- to centimetre-sized dust populations. They estimated the ejecta cone to be wider than that produced by impacts performed in laboratory experiments, but found its dust tail to be consistent with the shape of asteroid tails that are thought to have been produced by natural impacts[8,9]. Several days after impact, a secondary tail appeared, pointing 4° off-axis from the original tail, but the mechanisms underlying this tail remain to be explored.

A network of citizen scientists observed the Didymos system during the days before and after the impact event to help set limits on the mass, velocity and kinetic energy of the ejecta plume and tail. Their efforts are reported by Graykowski and colleagues[3] (page 461), who estimate that the fast-moving plume carried away 3–30% of the kinetic energy, with a total mass of hundreds to thousands of kilograms. The slower-moving tail material moved 150–250 kilometres towards the Sun before solar-radiation pressure imparted enough force to turn the plume around. The authors found that the mass of this material was around 13 million kilograms, with an average particle size of around 2 millimetres.

The team also report the detection of a brief but pronounced reddening of the light emitted by the binary system at the time of impact. This reddening phenomenon was observed previously when NASA's OSIRIS-REx mission made contact with an asteroid called Bennu[10]. Many interpretations of the possible cause remain[3].

One limitation of the experiment is that Dimorphos's mass could not be measured directly by DART, leading to large uncertainties in the densities of the binary parent and satellite. Density and porosity are key to understanding the impact dynamics, as well as how the properties of this binary system relate to those of the meteorites catalogued so far[11]. The European Space Agency's Hera mission is planning a close-up reconnaissance of Didymos and Dimorphos by 2027 that promises valuable context and refined understanding of the DART experiment. Likewise, the sample returning this September from asteroid Bennu will provide more insight into how the properties of asteroid material relate to the contact dynamics measured by OSIRIS-REx[12].

NASA's Near-Earth Object Surveyor mission is also expected to come online by the end of this decade. The mission will detect and track the remaining population of potentially hazardous asteroids that are larger than Dimorphos. This will give scientists a more complete view of any would-be threats to our planet that could require follow-up characterization or possibly a controlled deflection. The DART mission was a crucial first test of how such a deflection might be carried out, and the data reported in these five papers will inform our understanding of other asteroid impact events that have been observed previously[13], as well as those still to be detected.

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The author declares competing interests. See go.nature.com/4ttyqgf for details.

Inorganic chemistry

Metal-oxide cage traps radioactive element

May Nyman & Gauthier Deblonde

The ability to separate the radioactive element americium from spent nuclear fuel would lower the long-term hazards of nuclear waste. An inorganic molecular cage that selectively binds to americium opens up a separation strategy. **See p.482**

On page 482, Zhang *et al.*[1] provide a rare atomic-level glimpse of a notoriously dangerous radioactive element, americium (Am), in its highest oxidation state. The authors used a water-soluble metal-oxide cage, known as a polyoxometalate (POM), to facilitate the isolation of americium from chemically similar elements found in nuclear waste. Such a POM-mediated separation could solve a long-standing problem in reprocessing spent fuel from civilian nuclear reactors, thereby enhancing the efficiency and safety of the nuclear industry.

Lowering the greenhouse-gas emissions generated by energy production is one of the most urgent challenges of the twenty-first century, and nuclear energy has a key role in achieving this goal. A considerable hurdle to the widespread use of civilian nuclear reactors is finding a way to deal with radioactive waste, which currently requires long-term storage. Spent fuel rods can be processed to recycle uranium (U) and plutonium (Pu), but other elements in the waste remain radioactive for thousands of years and need to be managed accordingly.

Fission reactions in nuclear reactors split uranium atoms to release energy, but also generate various products consisting of lighter elements from across most of the periodic table. Among them, a family of 15 elements — the lanthanides — must not be recycled into new fuel because they hinder energy-producing nuclear reactions by capturing neutrons. A fraction of the uranium atoms in nuclear fuels also absorbs neutrons and produces heavier radioactive elements, including americium. Several isotopes of americium are particularly problematic because of their toxicity and long-lived radioisotopes, and because their decay contributes substantially to the residual heat produced by nuclear waste.

Typical civilian nuclear fuel yields about 10–20 kilograms of lanthanides and 0.5–2.0 kg of americium per tonne of uranium[2]. Americium separated from these complex waste mixtures could be used in next-generation reactors, thereby greatly decreasing the long-term toxicity of nuclear waste and facilitating its storage. However, lanthanides and americium are chemically very similar, having the same predominant oxidation state (+III) and similarly sized ions. Organic ligand molecules designed to bind to trivalent americium ions (Am^{3+}) therefore typically also bind to the analogous lanthanide ions (Fig. 1a).

Since the 1960s, scientists have researched various processes to separate americium from lanthanide fission products[3]. Most are based on solvent extraction (the selective

Correction
Figure 1 in the original version of the News & Views article 'DART's data verify its smashing success' showed Dimorphos orbiting in the opposite direction around Didymos.

Corrected 26 April 2023