8.2 The space mission AIDA: Asteroid Impact and Deflection Assessment

A. Context and state of the art

AIDA is a joint ESA-NASA project in cooperation with the Observatoire de la Côte d'Azur (OCA)[1], the German space agency (DLR) and the Applied Physics Laboratory (APL) of the Johns Hopkins University. A member of C4PO from OCA leads the European science team of this mission (Michel et al. 2016) and co-leads the US-European joint team. AIDA aims to be the first kinetic impactor test for launch in 2020, if approved by the ESA Ministerial of December 2016. The characterization of its target — the secondary of the binary NEA (65803) Didymos — by the Asteroid Impact Mission (AIM) from ESA and the kinetic impact test by the Double Asteroid Redirection Test (DART) by NASA (Cheng et al. 2016) would take place in 2022 (Fig. 1). AIDA would allow us to have, for the first time, a direct measurement of an asteroid internal structure by radar tomography and an asteroid's response to an impact at a scale that is inaccessible in laboratory (see A11.4). Moreover, AIM will demonstrate, at a low cost for a deep-space mission, technologies related to autonomous navigation, optical communication, on-board resources management, close proximity operations, asteroid microlanders, and deep-space intersatellite networks.

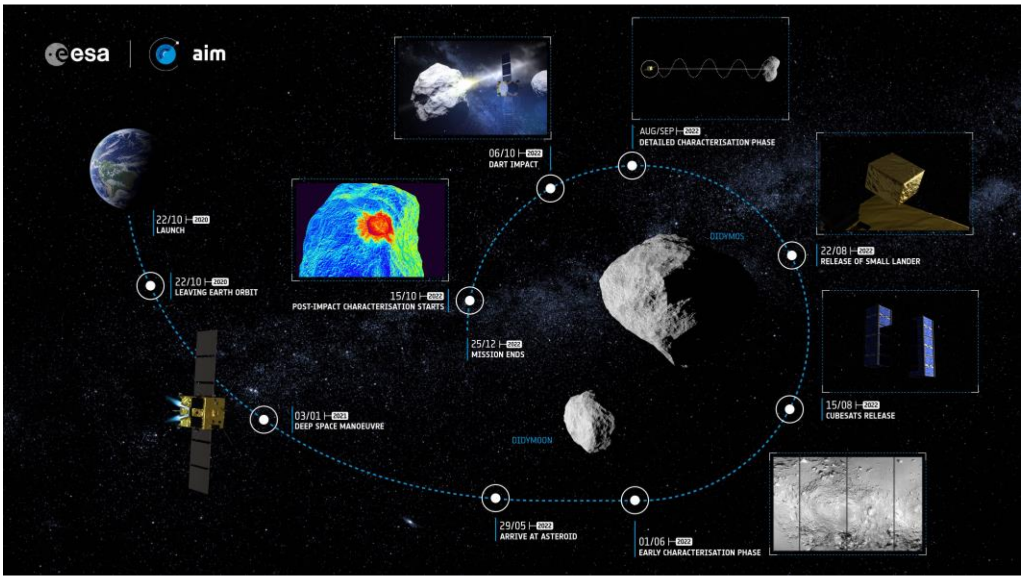

Figure 1: mission scenario of the European component (AIM) of AIDA

ESA and NASA are currently performing a Phase A/B1 study of AIDA until fall 2016. The B2 phase is planed in 2017. Several working groups have been defined to support the mission study, development and data interpretation. Members of C4PO from OCA chair some of these working groups, which activities will require several numerical developments and simulations in the coming years, specially if the mission is approved for launch.

The knowledge obtained by AIDA will have great implications for our understanding of the history of the Solar System. Having direct information on the surface and internal properties of small asteroids will allow us to understand how the various processes they undergo work and transform these small bodies (see A11.4, 11.5 and 11.6) as well as, for this particular case, how a binary system forms. Making these measurements from up close and comparing them with ground-based data from telescopes will also allow us to calibrate remote observations and improve our data interpretation of other systems. With DART, thanks to the characterization of the target by AIM, the mission will be the first fully documented impact experiment at asteroid scale, which will include the characterization

[1] http://www.oca.eu/michel/AIDA/

of the target's properties and the outcome of the impact. AIDA will thus offer a great opportunity to test and refine our understanding and models of the impact process at the actual scale of an asteroid (see A11.4), and to check whether the current extrapolations of material strength from laboratory-scale targets to the scale of AIDA's target are valid. Moreover, it will offer a first check of the validity of the kinetic impactor concept to deflect a small body and lead to improved efficiency for future kinetic impactor designs.

In the following, we describe some of the activities (non-exhaustive list) devoted to AIDA and to kinetic impact concepts in general, in which members of CP4O participate and which will continue independently on the fate of this project.

B. Current activity and future steps

B.1. Numerical simulations of impacts of a kinetic impactor

In support of the AIDA mission concept, an international working group was formed to better understand the range of possible outcomes of the DART impact (Stickle et al. 2016). Impact modeling is one of the primary tools to be used to interpret the results of the kinetic impact deflection, to infer the physical properties of the target asteroid, and to advance our understanding of impact processes on asteroids (see A11.4). Several types of numerical methods can be used to model the DART impact, all of which differ in their fundamental approach to solving flow equations as well as modeling of material properties and responses to impact stresses.

The momentum enhancement of a target from a kinetic impactor spacecraft is parameterized by the factor β, which depends on the initial spacecraft momentum ($p_{spacecraft}$) and the momentum of ejecta excavated during crater formation (p_{ejecta}): $\beta = 1 + (p_{ejecta}/p_{spacecraft})$, with momenta tracked in the direction of intended deflection. If there are no ejecta sent in the opposite direction to the projectile's one, β =1. Obviously, β depends on the impact conditions and physical properties of the target.

Jutzi and Michel (2014) presented results of code calculations of the β factor for porous targets, using a SPH hydrocode that includes a model of porosity (see A11.4). The results of our study using a large range of impact conditions indicated that β is small for porous targets even for very high impact velocities ($\beta < 2$ for v_{imp}=6 to15 km/s), which is consistent with published scaling laws and results of laboratory experiments (Holsapple & Housen 2012, 2013). Our simulations showed that both porosity and strength have a large effect on the scaling of β with impact velocity.

This first numerical study and the motivation offered by AIDA to investigate deeper this issue opened the way to a vast campaign of numerical simulations, using the different existing impact codes (hydrocodes) that rely on different numerical techniques and fracture models. An initial benchmarking campaign was established, which is currently on its way, to compare the results of simplified test cases across a variety of hydrocodes.

To enable comparison between codes, five initial test cases have been sent to each team performing simulations. These cases cover impacts into both aluminum and basalt targets and were designed to isolate the effects of geometry (impacts into a half-space versus a sphere), material strength, and porosity. Comparisons between models include metrics such as crater size, ejecta velocity and damage growth as well as measurements of β. Figure 2 shows preliminary results provided by two different impact codes for one of the considered cases.

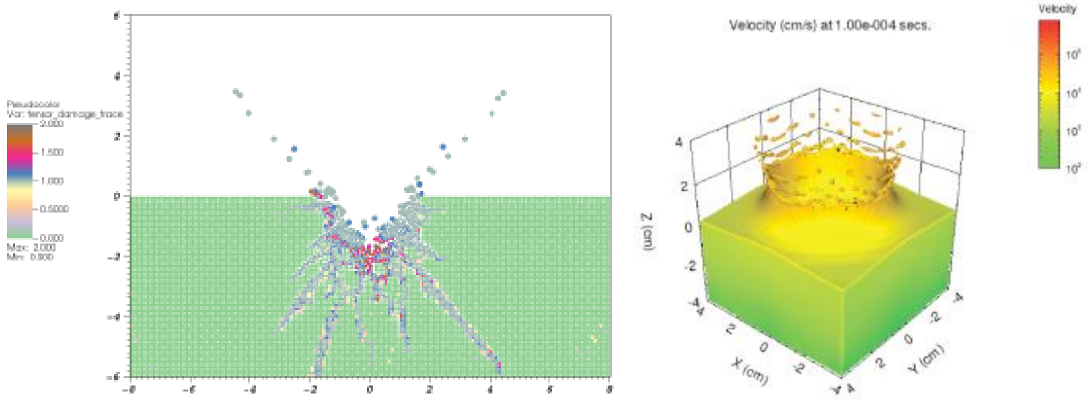

Figure 2: left: simulation results from a calculation by the Spheral ++ SPH code (see Theme 11.5) of a 0.635 cm basalt impactor impacting at 5 km/s onto a basalt half-space. The colored contours show the trace of the damage tensor, where 2 (brown/black is fully damaged. Right: Same from a calculation using the adaptive grid-code CTH. Colors show velocity contours, allowing the velocity of ejecta particles to be tracked and quantified (from Stickle et al. 2016).

Future steps

Comparisons between methods will allow the determination of the variability between different numerical schemes and material models, which will provide confidence for the more complicated numerical simulations required to understand and interpret the DART impact (as well as other kinetic impact concepts and cratering studies) in the coming years. Members of C4PO will participate to these efforts, by contributing to the development, implementation and test of relevant damage and fracture models developed by its members in impact codes (see A11.1, A11.2 and 11.4). The resulting improvement of our understanding of the impact physics and differences between the various approaches (numeric, fracture models), and consequently in the realism of numerical simulations, will also greatly contribute to the study of fundamental science issues related to the impact process in planetary systems (A11.4).

B.2 Dynamical and physical properties of the AIDA target: (65803) Didymos

One important activities in the preparation of a space mission to a small body is the elaboration of the asteroid reference model that is used by industries to design the mission and to interpret the first data sent by the spacecraft, which needs to account for the limited set of actual data obtained from the ground and all uncertainties regarding the asteroid's properties.

The Dynamical and Physical Properties of Didymos Working Group (Richardson et al. 2016), to which members of CP4O belong, is supporting this activity and the AIDA mission by addressing the following broad questions: what is the dynamical state of the Didymos system, how can the consequences of the impact best be measured, and how can the physical properties of the system be inferred based on current knowledge? These activities and resulting understanding will greatly advance our knowledge of binary systems, their origin, and more generally of the geophysical properties of small asteroids.

So far, progresses have been done to constrain the region of origin of Didymos in the main asteroid belt. The current dynamical state has also been constrained based on observations and the system dynamics is under study to determine possible libration modes in the secondary's orbit around the primary and other variations in dynamical parameters with time. The secondary (the target of the AIDA mission), of about 163 m in diameter is assumed to orbit in the equatorial plane of the 780 m-diameter primary. Figure 3 (left image) shows the current shape model from radar and light-curve observations.

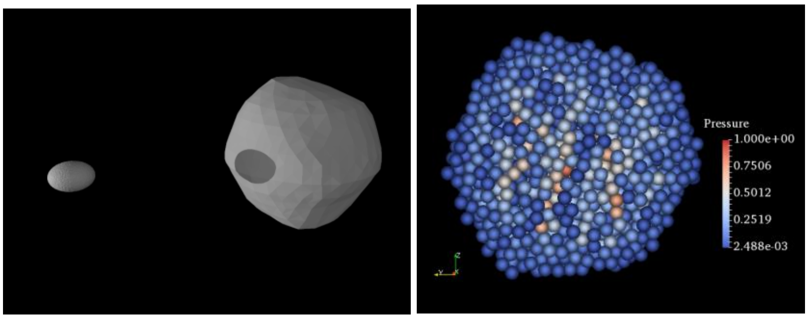

Figure 3: Left: preliminary shape model of the primary from combined radar and light-curve data; diameter ~780 m. The secondary is estimated to be more elongated, although no direct data exist on its shape. Right: Relative pressure distribution in a stable discrete model of the spinning primary (cross section) computed with the Soft-sphere Discrete Element Method N-body code *pkdgrav*. Material repose angle ~37°, packing efficiency ~62%.

The internal structures of binary components pose constraints on the origin of the system and can help to discriminate between the different proposed scenarios (Walsh and Jacobson, 2015). So far, we have only studied the possible internal structure of the primary, as there is no real data on the secondary's shape. Given its rotation period of 2.26 h, the Didymos primary is close to if not beyond the limit for loose material to remain on the surface at the equator. Weak cohesion (< 100 Pa) may be implied, although there is sufficient uncertainty in the shape model that zero cohesion cannot yet be ruled out. Two approaches are used to constrain the internal structure, which will also be used and compared in the framework of CP4O for this case as well as in general studies of the dynamics of granular materials on small bodies (see A11.6).

Continuum analysis. Failure modes have been established of the primary (indicating the degree of cohesion needed to maintain its shape as a function of spin period), based on a continuum analysis, assuming uniform internal structure and the assumed bulk density. A Drucker-Prager model was used for the yield condition, and the internal friction angle was fixed at 35°. We found two distinct failure modes, if there is insufficient cohesion/friction. If Didymos fails at a spin period longer than 3.0 h, only the equatorial region fails. Otherwise, the internal structure should fail first.

Discrete-element analysis. Using our Soft-Sphere Discrete Element N-body code *pkdgrav* (Schwartz et al. 2012; see A8.1 and 11.6), we are exploring the conditions needed for a rubble-pile model of the primary made up of mono-disperse spheres to hold its shape. We find that gravel-like material properties (friction angle 40°) together with a spring-dashpot rolling friction model give a stable outcome without cohesion for bulk density > 2500 kg/m^3 when the spheres are packed randomly, and at even lower densities for hexagonal close- pack configurations. The relative internal pressure distribution for a stable random-packed case is shown in Fig. 3 (right image). Analysis of this case shows that it is everywhere below the Drucker-Prager yield condition.

The thermal properties of the surface (e.g. thermal inertia) will not be known before AIM rendezvous with Didymos. A modeled temperature map of the far side of Didymoon for nominal and extreme (high and low) possible thermal properties have been obtained assuming a spherical shape for the body (Michel et al. 2016) and is currently improved to account for the actual shape, shadows etc.

Future steps

We will continue to study the possible internal, surface, thermal and dynamical state of Didymos based on the observed properties and numerical modeling (with continuum and discrete approaches). For instance, we will use different packing models and check the consequences in terms of stability and cohesion, and will also consider various size distributions of the particles composing the bodies. The plan is to have a complete database of possible states before the arrival of AIDA to its target, so that we can check which is the closest to the real one, and help in the interpretation of the observations.

As for Hayabusa 2 (see A8.1), we are also developing numerical simulations and experiments in the drop tower of ISAE-SupAero of the deployment of the small lander at the surface of the secondary. Here, the challenge is that the surface gravity of the secondary, whose size is about 163 m, is much smaller than on the target of Hayabusa 2 whose size is about 800 m. It is thus important to check the bouncing conditions as a function of assumed regolith properties and landing site latitude on the secondary.

B.3 Numerical modeling of the fate of ejecta produced by the DART impact

In the framework of AIDA, and possibly of any kinetic impactor mission consisting of a projectile and an observing spacecraft, it is important to characterize safe regions for the observing spacecraft during and after the impact (Schwartz et al. 2016). A good understanding of the fate of the ejecta from an impact must thus be achieved, which is also an interesting purely scientific topic, as what happens to ejecta from a cratering impact has implications on the target's surface properties and environment (see A11.4 and 11.5).

We performed a first study of the evolution of ejecta produced by the DART impact on the secondary of Didymos in 2022 (Yu et al. 2016). For this, we developed a detailed dynamical model for the simulation of an ejecta cloud from a binary asteroid that synthesizes all relevant forces based on the analysis of the mechanical environment. We applied our method to the AIDA impact (accounting for the Didymos reference model mentioned n Sec. B.2; see Michel et al. 2016), including the subsequent evolution of debris and dust around Didymos. In this first study, we used crater scaling relations from laboratory experiments to approximate the initial distributions of ejecta mass and launching speeds. The size distribution of ejecta was modeled with a power-law fitted from observations of real asteroid surfaces. A first full-scale simulation has then been performed using parameters specified by the AIDA mission (e.g. mass and speed of the projectile). In Yu et al. (2016), we report the results of the simulation, including the computed spreading of the ejecta cloud as a function of time and the recorded history of ejecta accretions on the binary components and escapes from the system. The first violent period of the ejecta evolution is found to be short, and is followed by a stage where the remaining ejecta are gradually cleared. Solar radiation pressure proves to be efficient in cleaning dust-size ejecta, and the simulation results after two weeks show that large debris on polar orbits (perpendicular to the binary orbital plane) have a survival advantage over smaller ejecta and ejecta that remain at low latitudes.

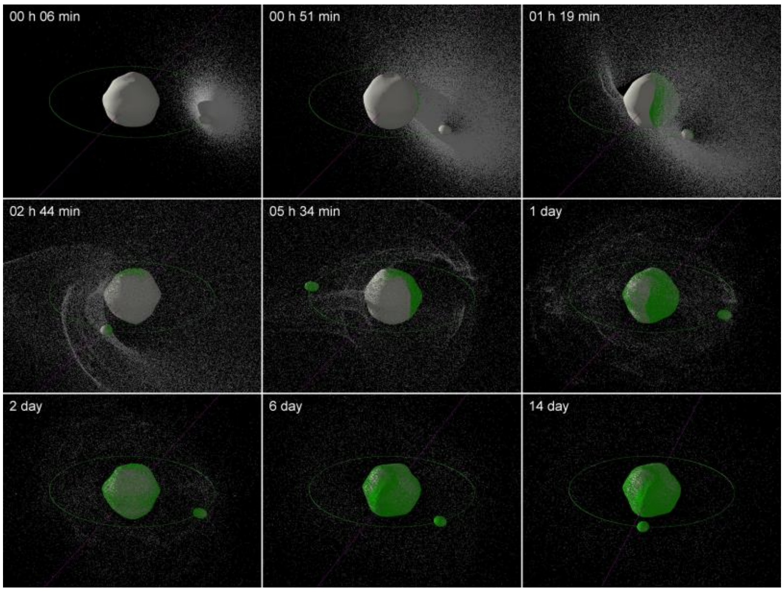

Figure 5: Snapshots of the time evolution of the ejecta cloud near Didymos (view size ~ 4.6 km). The binary and heliocentric orbits are marked with solid lines of green and purple color, respectively. Fictitious large particle sizes are adopted for visual enhancement, and the accreted particles onto Didymos are colored in green (from Yu et al. 2016).

Future steps

In this first study, which serves as a demonstration of principle, we did not explore the parameter space of the system, but only one of the many possible outcomes of the impact. An extensive investigation over a large portion of the parameter space (impact outcomes) is currently under way. In particular, in addition to the use of scaling laws to define the initial conditions of the ejecta, we will study possible ways to use the outcome of hydrocode simulations (Sec. B.1). We will also analyse the dynamics of the ejecta, using chaos theories and celestial mechanics in order to identify possible classes of trajectories. We will develop visualization tools in order to present our results in the most relevant ways for the industry studies (e.g. mass or kinetic energy density plots in space and time, ejecta trajectories, etc). Finally, our methodology will be applied to other studies of cratering impact, for instance, those performed to understand the possible contribution of such impacts in the origin of regolith on the surface (see A11.5).

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Schwartz, S.R., Asphaug, E., Cheng, A., Housen, K.R., Michel, P., Miller, P., Stickle, A., Tancredi, G., Vincent, J.-B., Wünnemann, K., Yu, Y. and The AIDA Impact Simulation Working Group 2016. Asteroid Impact and Deflection Assessment (AIDA) mission: modeling and simulation of impact outcomes - ejecta properties and evolution. Abstract 3002, 47th Lunar and Planetary Science Conference.

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Yu, Y., Michel, P., Schwartz, S.R., Naidu, S.P., Benner, L. 2016. Dynamics of the ejecta cloud produced by a kinetic impact on the secondary of the binary asteroid Didymos: a contribution to the AIDA space project. Abstract 2140, 47th Lunar and Planetary Science Conference.

D. International collaborations

A member of C4PO is leading the European team of AIM (and a few members of C4PO belong to the team) and co-leads the US-European team of AIDA. Thus a great number of European countries and US institutions are involved and collaborate in this project, which also involves a few industries and main space agencies (NASA, ESA, DLR etc).

The code *pkdgrav* that includes the Soft-Sphere Discrete Element Methods, which is used to simulate the dynamics of granular materials and the interaction of sampling tools and landers with a granular surface in gravity conditions adapted to the considered body is developed in collaboration with Prof. D.C. Richardson at the University of Maryland (UMD) in USA. OCA and UMD have signed Memorandum Of Understanding for a cooperation in fields of common interest (including planetary science), the development joint projects in these fields, the exchange of faculty and students for research, teaching and study, and of scholars for seminars, conferences and other academic meetings.

The code Spheral++, which is used for our simulations of the impact process was originally developed at the Lawrence Livermore National Laboratory in California and is maintained there. A collaboration is taking place with members of C4PO to use this code and to include and test different models of damage and equations of state. Some impact simulations are also done in collaboration with the University of Bern in Switzerland.

E. List of people involved in the project

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F. Most significant publications of the team

Cheng, A., Michel, P., Jutzi, M., Rivkin, A.S., Stickle, A., Barnouin, O., Ernst, C., Atchison, J., Pravec, P., Richardson, D.C., AIDA team, AIM team 2016. Asteroid Impact & Deflection Assessment mission: Kinetic impactor. Planetary and Space Science 121, 27-35.

Cheng, A., Atchison, J., Kantsiper, B, Rivkin, A.S., Stickle, A., Reed, C., Galvez, A., Carnelli, I., Michel, P., Ulamec, S. 2015. Asteroid Impact and Deflection Assessment mission. Acta Astronautica 115, 262-269.

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

Michel, P., Cheng, A., Küppers, M., Pravec, P., Blum, J., Delbo, M., Green, S.F., Rosenblatt, P., Tsiganis, K., Vincent, J.B., Biele, J., Ciarletti, V., Hérique, A., Ulamec, S., Carnelli, I., Galvez, A., Benner, L., Naidu, S.P., Barnouin, O.S., Richardson, D.C., Rivkin, A., Scheirich, P., Moskovitz, N., Thirouin, A., Schwartz, S.R., Campo Bagatin, A., Yu, Y. 2016. Science case of the Asteroid Impact & Deflection Assessment (AIDA) Mission. Advances in Space Research, in press.

Short CV of participants

Patrick Michel, CNRS research director, leader of the team Theory and Observations in Planetology of the Lagrange Laboratory at OCA, expert in the impact process, granular material dynamics and asteroid physical properties, Co-I of Hayabusa-2 and OSIRIS-REx, science team leader of the space project AIDA (ESA-NASA collaboration), member of the Science Program Committee of CNES, Carl Sagan Medal of the Division of Planetary Science of the American Astronomical Society (2012), Prize Paolo Farinella in Planetary Science (2013), Prize Young Researcher of the French Society of Astronomy and Astrophysics (2006), asteroid (7561) PatrickMichel, more than 90 refereed publications, H-index = 27.

Marco Delbo, CNRS research scientist, expert of the physical characterisation and modelling of asteroids, ground- and space-based astronomical observations, and laboratory experiments on meteorites. He is CoI of space missions ESA's Gaia (responsibility of asteroid spectroscopy) and NASA's asteroid sample return OSIRIS-REx mission. Author of 80 reviewed publications, ~1,000 citations and an H-index = 19 (ADS). Asteroid (16250) was named after "Delbo".