8.1 Sample return space missions to small bodies: Hayabusa 2 (JAXA), OSIRIS-REx (NASA)

A. Context and state of the art

Members of C4PO are involved as Co-Investigators (Co-Is) and core members of working groups in two sample return space missions: Hayabusa-2 and the Origins Spectral Interpretation Resource Identification and Security-Regolith Explorer (OSIRIS-Rex). These missions will visit their respective asteroid targets at nearly the same time, in 2018-2019, which promises a high media exposure and will offer a great visibility to C4PO.

The Japan Aerospace Exploration Agency's (JAXA) Hayabusa-2 mission, launched successfully on December 3, 2014, will arrive at the primitive carbonaceous Near-Earth Asteroid (NEA) Ryugu in mid-2018. It will orbit the body for approximately one year before returning a sample to Earth in 2020. A small lander designed by DLR and CNES, the Mobile Asteroid Surface Scout (MASCOT), will perform in situ investigations. A Small Carry-on Impactor (SCI) will also perform a 2 km/s impact and will create a crater on the asteroid's surface, allowing us to test our theoretical and numerical impact model predictions on a real asteroid. The plan is also to take a sample inside the crater produced by the impact, in addition to the one collected on the surface elsewhere. The counterpart of Hayabusa-2, NASA's OSIRIS-REx mission, will be launched in September 2016 and will arrive at the primitive carbonaceous NEA Bennu in fall 2018. It will also orbit its target for nearly a year before collecting a sample. The samples will then arrive on Earth in 2023.

As described in Sec. B, thanks to the numerical tools that we are developing and adapting to this mission, we are actively involved in the numerical studies of various aspects, such as the efficiency of the sampling mechanisms on board these two missions, as a function of the assumed (unknown) surface properties of the asteroid, the bouncing efficiency of the lander MASCOT, the outcome of the Small Carry-on Impactor, … Moreover, for OSIRIS-REx we have the responsibility for the thermal modeling, which consists in calculating the surface temperatures on Bennu as a function of the latitude and time of the day, the physical parameters of the surface such as the thermal inertia, and geometric parameters such as the position of the body along its orbit. Surface temperatures are fundamental for the selection of the sampling site (e.g. the sampling instrument, TAGSAM, can operate safely at temperature below 75°C) and for the thermal design of the mission instruments (including visible and infrared cameras, and other instruments requiring thermal radiators).
Another reason to model asteroid surface temperatures is that they affect the orbital and spin state evolution via the Yarkovsky and YORP effects, respectively. The former is a force and the latter a torque due to the emission of thermal photons by the warm asteroid. In particular, thermal inertia dictates the strength of the asteroid Yarkovsky effect. The latter is partly responsible for the dispersion in space of the members of asteroid families, influences the orbital evolution of small potentially hazardous asteroids, and the delivery asteroids and meteoroids from the main belt into dynamical resonance zones capable of transporting them to Earth-crossing orbits. Next, the temperature and its evolution through the entire life of an asteroid can alter its surface composition and nature of the regolith. For example, when the temperature rises above a certain threshold for a sustained period, certain volatiles can be lost via different processes such as sublimation, dehydration, and desiccation. An important issue related to sample return missions to primitive asteroids is to determine the likelihood that the target candidate originates from a source region of primitive material in the solar system and to assess whether the surface (and the subsurface) of the object has been preserved from weathering processes active in space, such as high temperature excursion, which is crucial in the interpretation of the results of the sample analysis.

All these studies are extremely important for instance to help in the choice of the sampling sites, to interpret the sampling outcome and the analysis of the samples. Furthermore, we will have access to samples (this is guaranteed for OSIRIS-Rex while it will require a response to an international call for Hayabusa-II), which will allow experts in C4PO to be among the firsts to contribute to the sample analysis and to the big steps in our knowledge that are expected from this activity. Thus, our planned activities in the data interpretation of these two missions will allow us to make huge strides in our understanding of primitive asteroids while also helping us to place into context our knowledge of certain types of carbonaceous chondrite meteorites. It will also be novel to compare and contrast the physical nature and compositional properties of two different C-complex asteroids (or see if they are from the same parent family).

Direct interaction, such as those in these current space missions and potential future ones, assisted with numerical simulations, as planed in C4PO, is the only way to determine the detailed mechanical properties of an asteroid surface and to measure how it responds to an external force. Our knowledge of asteroid geophysics and of aggregate mechanics in micro-gravity environments is still very restricted. Improving this knowledge will allow us to trace back Solar System history from the accretion of these bodies to their current internal and surface properties. Moreover, an understanding of the mechanical properties of an asteroid and its response to external actions is also crucial for the design of mitigation technologies to deflect hazardous asteroids as well as to prepare future human exploration of asteroids or mining projects. Thus, the planed activities have both potentially great scientific return (see A11.4, 11.5 and 11.6) as well as high technology returns.

In the following, we describe some of the activities (non-exhaustive list) devoted to these two sample return space missions, which are already taking place and that already led to some results, showing the feasibility of the proposed plans for the next steps. We also indicate our plans in each mentioned topics in the framework of C4PO.

B. Current activity and future steps

B.1. Numerical investigation of small body's surfaces and application to space mission designs

The following subsections show applications of our numerical simulations to space mission designs. Other applications to the goal of C4PO are presented in Themes 11.4 and 11.6. This activity is very important in the preparation of these missions until the arrival to the asteroid and in the data interpretation during and well after their visit. Moreover, the developed tools and new understanding of asteroid surface responses to various forces/processes will serve other scientific and technical purposes.

B. 1.1. Numerical modeling of the sampling mechanism (asteroid response to the spacecraft) of OSIRIS-REx and Hayabusa-2

B.1.1.1. OSIRIS-REx

The company Lockheed Martin develops the Touch-And-Go SAmpling Mechanism (TAGSAM) and the re-entry capsule of OSIRIS-REx. The sampling mechanism is designed for collecting regolith at the surface of the asteroid. The regolith is fluidized by high-pressure annular N2 flow. A Mylar check valve retains the regolith, and the goal is to collect a minimum of 60 g of regolith for analysis in terrestrial laboratories: 11.5 g are used for immediate analysis after Earth return, 3.5 g are kept for margin, and 45 g are archived for future generations. The possibility to test the efficiency of the TAGSAM of OSIRIS-REx over a wider range of possible regolith kinds, using different grain sizes and material types, is an important activity in the preparation of the mission. In effect, once we will be at the asteroid, the choice of the sampling site will rely on our assessment that the TAGSAM can collect enough material (goal: 60 g) based on the observed surface properties. However, because the parameter space is too large to be tested fully experimentally, the possibility to model numerically the sampling tool was investigated, using a numerical code that we developed at the Observatoire de la Côte d'Azur and the University of Maryland. This code is adapted from the N-body code *pkdgrav*, in which the Soft Sphere Discrete Element Method was introduced and tested by comparison with experiments (Schwartz et al. 2012). It is thus capable of modeling the dynamics of granular materials in a wide range of conditions and gravitational environments (including the low gravity of asteroid's surfaces; see Themes 11.5 and 11.6). First simulations of the OSIRIS-Rex TAGSAM with a new adaptation of the code were performed using the same gravity level as on the asteroid. In particular, we included an accurate numerical model of the geometry of the TAGSAM based on indications by Lockheed Martin and of its reaction force to the regolith. So far, we studied the effect of various regolith properties (characterized by various rolling, twisting and sliding frictions of the particles, as well as their size distribution; see Fig. 1) as well as surface slopes on the compliance of the TAGSAM with the surface and compared the results with experimental data and other code results to validate our approach.

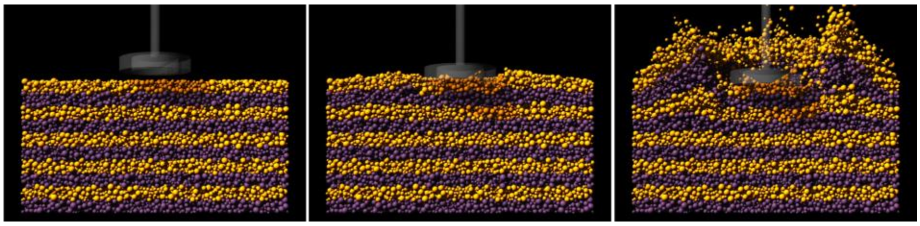

Figure 1: A model TAGSAM (visualized with some slight transparency) penetrates a bed of about 100,000 particles (seen in cross-section) with an initial downward vertical speed of 10 cm/s in the microgravity environment of Bennu (g = 20 μm s^{-2}). The regolith is composed of a power-law distribution of spherical particles (power-law index = -1) with minimum and maximum radius R_{min} = 0.5 cm and R_{max} = 1.5 cm, respectively. The cylindrical container has a height and radius of 60 cm. The colored layers aid the viewer to discern the penetration depth (each layer is about 6 cm in height). The particles were assigned friction parameters similar to those of gravel as determined by physical experiments (Yu et al. 2014).

Future steps

Our goal is to construct a library of TAGSAM touchdown outcomes as a function of the observable regolith properties (local slope, size distribution, and minimum and maximum particle sizes) and to perform the studies defined in agreement with the mission's plans (such as comparison of numerical models using defined tests/exercises, etc. and other studies that may be asked during the project). Furthermore, we will study the effect of varying the regolith's material properties (cohesive, frictional, and dissipative parameters) in order to place limits on the range of possible outcomes. The library will be useful for sample site selection based on available observables, and, upon sampling, may aid in interpreting the physical properties of the regolith by comparing measurements from on-board accelerometers and gyroscopes with simulation data. The main task of the proposed work will be to complete these TAGSAM simulations with the goal of obtaining the highest possible simulation fidelity. In a further phase, we will implement angular particle shapes to represent real granular material more accurately. This will require the largest coding efforts. Finally, these developments, as well as those below for Hayabusa-2, in particular concerning the numerical treatment of the interaction of a tool with a given geometry with a granular material in low-gravity conditions, will benefit to future space mission studies aimed at interacting with the surface of a small body.

B.1.1.2. Hayabusa-2

We also adapted our numerical tools (Schwartz et al. 2012) to simulate the Hayabusa 2 sampling mechanism over a range of surface properties that cannot be considered in experiments. The same approach is used as that for the OSIRIS-REx sampling tool modeling with the same objective, but the sampling tools of both missions are very different. Therefore for each case, our numerical model requires a specific (and complex) adaptation. The Hayabusa 2 sampling mechanism consists of a small projectile impacting at low velocity on the surface; the aim is then to collect the ejecta resulting from the impact. A first paper has been published in Planetary and Space Science (Schwartz et al. 2014) exposing the comparison of our numerical simulations with experiments of the sampling mechanism performed in Earth's gravity. In addition to a successful comparison with experiments, our modeling could also indicate the sensitivity of the outcome (amount of ejected material) on surface material properties characterized by, e.g., the normal coefficient of restitution of the grains, static friction, grain sizes etc. We also made a preliminary demonstration of our Hayabusa 2 sample mechanism modeling capability in a microgravity environment. As expected, a reduction in gravity increases both the amount of ejected mass and the timescale of the impact process.

Future steps

We started a dedicated quantitative study of the sampling process in the low gravity environment of the asteroid Ryugu. One important difficulty is that the time-step required to perform simulations of the impact of the projectile used as a sampling tool in low-g is extremely small and every run requires a very long CPU time (several months using a few hundreds of cores). Therefore, we plan to find a technical solution to this problem by modifying our code. The goal is to construct a full database before the arrival of the spacecraft to Ryugu in 2018. Moreover so far, we looked at the amount of material ejected by the sampling projectile from the surface, but not all this material may be captured by the sampling horn due to its geometry. Our plan is to code the exact design of the horn in our modeling, so that we will be able to run simulations accounting for this geometry effect and check how much of the material ejected from the surface is actually sampled by the sampling tool.

B.1.2 Interaction of a lander with a low-gravity asteroid surface

Hayabusa-2 will deploy the lander MASCOT (DLR/CNES cooperation) on the surface of Ryugu. One important uncertainty, as we have seen with the lander of Philae (Rosetta mission), is the outcome of the first interaction of the lander with the surface, which depends on the surface properties and the surfce response to the lander geometry and speed at impact. With our numerical code *pkdgrav* and the Soft-Sphere Discrete Element Method, we started a study on the bouncing of MASCOT with Ryugu's surface, assuming various impact geometries, speeds, and surface properties. The lander design (e.g. moments of inertia) was provided by DLR and was coded in our numerical tool. As a demonstration of principle, we performed a first study, assuming that the surface consists of spheres of unique size (centimeter), and varying the orientation of the lander at contact (see Fig. 2).

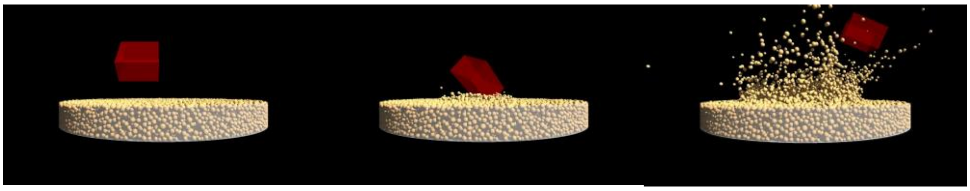

Figure 2: Snapshots from a simulation of MASCOT landing and bouncing on a surface composed of mono-size spherical particles (1 cm in diameter) in the gravity conditions of the asteroid Ryugu. In this run, the lander rotates on itself (1 rotation/mn) and impacts on an edge, before bouncing. Such a simulation allows measuring the coefficient of restitution as a function of the impact geometry and assumed surface properties. Here, MASCOT is modeled as a box with its actual moment of inertia.

Future steps

Our plans are to continue the development of the numerical tool, including the account for some portions of the MASCOT design that are not yet implemented, and to study its interaction with different kinds of possible surfaces, so that we can provide a measurement of the coefficient of restitution, which is an important input in the mission analysis, and information on how much time is needed before MASCOT settles down on the surface, as well as how much area of the asteroid's surface is covered before this happens. As a by-product, this study will contribute to characterize the real surface properties of Ryugu and response to MASCOT, based on observed traces by Hayabusa-2, which in turn will allow us to better understand how the surface of this type of asteroid's surface evolves with time, knowing its mechanical properties and response.

B.1.3 Small Carry-on Impactor (SCI) on board Hayabusa-2

The SCI consists of a small half-sphere projectile of 2 kg launched at 2 km/s on the asteroid's surface.

The objectives of the SCI are:

- to sample the interior (subsurface) of the asteroid;
- to produce a fresh surface, which is expected to not have experienced significantly space weathering;

- to investigate the sub-surface structure and physical properties;
- to test, improve or revise crater scaling laws and numerical simulations.

The third item requires information on the original depth of the exposed material and on the ejecta properties (size and ejection speed distributions). This can be studied by numerical simulations of the impact event that provide an estimate of the original location of the ejected material and the one exposed on the surface.

We performed a first series of simulations of the cratering experiment by the SCI with a numerical SPH impact hydrocode that includes a model of porosity (Jutzi et al. 2008). This code was validated by confrontation to laboratory experiments (Jutzi et al. 2009) and contributed to various studies that we performed on asteroid disruptions (e.g. Michel et al. 2001, 2003, 2015; see Theme 11.4). Our primary objective is to estimate the range of possible crater's sizes, as a function of assumed surface properties, as well as the original depth of the exposed material and ejecta.

Our first simulations were performed at a very high resolution, up to ~ 15 million particles. Our modeling of the SCI impact considered for the asteroid surface: a varying tensile strength (0 - 0.1 MPa), a varying porosity (50-75 %), a flat surface. The impactor was 2 kg in mass, had 2 km/s impact speed, and two different shapes were assumed (homogeneous sphere, hemispherical shell). Fig. 2 presents an example showing the influence of the projectile's shape and asteroid's porosity on the crater's size and depth.

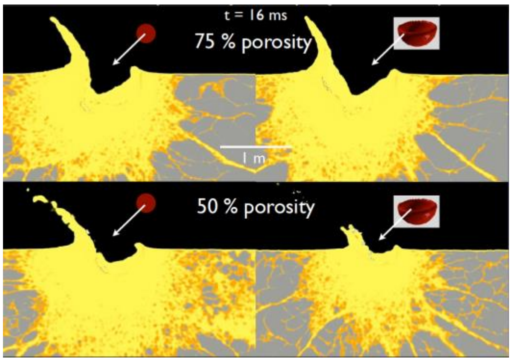

Figure 3: Snapshot of a SPH simulation of the hypervelocity impact performed by the SCI on the asteroid's surface as a function of porosity and projectile's shape (left : spherical projectile, right : shell). One can easily see the influence of those parameters on the cratert's size/mophology and depth. The yellow zones correspond to damaged zones (from Michel et al. 2016).

However, these preliminary simulations did not lead yet to an accurate measurement of the crater's size, and ejecta fate. The final crater dimensions are difficult to determine for various numerical reasons.

Future steps

Our plans are to support the SCI studies by continuing this investigation over a wide parameter space for the possible surface properties and impact conditions. This will be done with our past SPH impact code developed in collaboration with the University of Bern and another SPH impact code (Spheral++) originally developed at Lawrence Livermore National Laboratory in which we are introducing/testing new fragmentation models (see Themes 8.2 and 11.4), and which is continuously maintained and updated by this laboratory, justifying its choice with respect to our past code. Such a code development and testing is also part of the plans.

We also plan to develop a method to compute accurately the final crater and initial depth of exposed material. This work will also greatly contribute to better understand the relation between carter's size and impact conditions (projectile's properties), on which the various studies of surface ages and chronologies in the Solar system rely. Applications of impact simulations for other scientific purposes are described in Theme 11.2.. We also plan to continue our development of a method to compute the evolution of the ejecta under the influence of the asteroid's gravity, Solar tides and Solar Radiation Pressure. A first study of ejecta fate has been performed in the framework of the AIDA mission (see Theme 8.2) and the developed methodology will be applied to the SCI experiment on

Hayabusa-2. This study is extremely important to determine safe positions of the Hayabusa-2 spacecraft during and after the impact event.

B. 1.4. Numerical modeling of the surface temperatures of Bennu for OSIRIS-REx

In collaboration with US-based colleagues we developed the so-called Preliminary Thermal Model (PTM). The PTM was used by engineers for the thermal analysis during the mission design phase. In a second phase we produced a refined thermal model, which will also be used for a preliminary analysis of the data from OSIRIS-REx Thermal Emission Spectrometer (OTES). During several phases of the mission, OTES measures the energy emitted by Bennu over wavelengths of approximately 5 – 50 microns. At these wavelengths, virtually all minerals have unique spectral signatures that are like fingerprints, which will help the science team to understand what minerals are present on the surface of Bennu and search for minerals of particular interest, such as those that contain water. Additionally, the emitted heat energy (temperature) at these wavelengths can tell the science team about physical properties of the surface, such as the mean particle size.

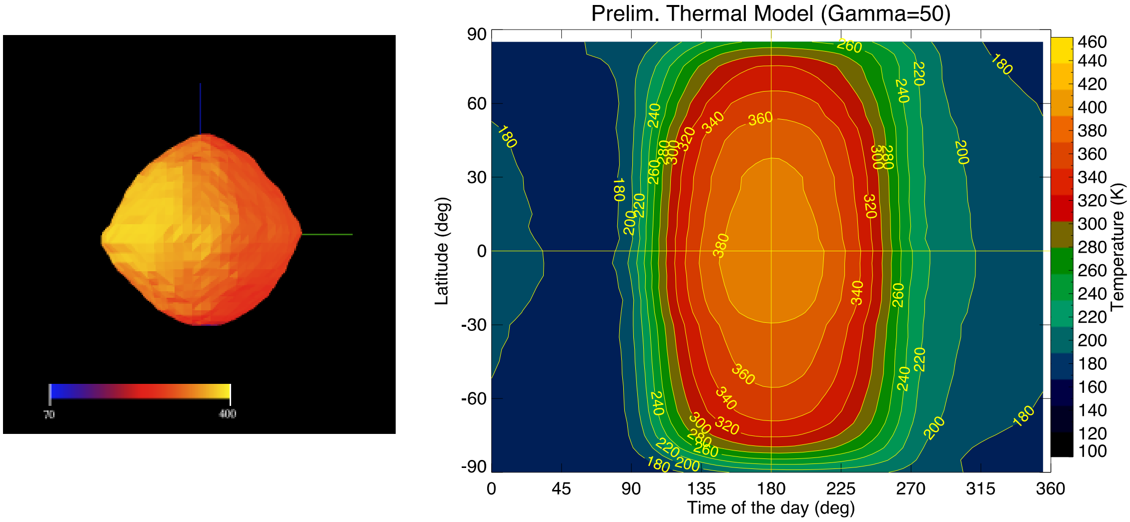

Figure 4: Left: Example of temperatures calculated on the radar shape model of the asteroid Bennu. Right: Average surface temperatures calculated at 1 AU from the Sun assuming a value of the thermal inertia of 50 J m^{-2} $s^{-0.5}$ K^{-1} using the Preliminary Thermal Model developed for the Mission Preliminary Design Review (PDR).

A second activity carried out in the context of thermal modeling is a better understanding of the link between the value of thermal inertia and the regolith grain size. This issue is fundamental for sampling site selection. As the TAGSAM can be safely operated with grain sizes smaller than 2-3 cm, and as thermal inertia is a sensitive indicator of regolith grain size, a big effort is being done to better constrain regolith size from thermal data.

Future steps

A future step consists in the improvement of the asteroid thermophysical model to capture the detailed physical process occurring on the regolith and in the subsurface of the asteroid Bennu. These processes include e.g. the variability of the thermal parameters with depth and temperature, a realistic model of the surface roughness, the effects of mutual heating and shadowing due to the asteroid's complex topography.

Clearly, the most important future step will take place in July/August 2018, during the approach phase and the arrival of OSIRIS-REx at Bennu, when the OTES instrument will acquire thermal infrared data to be analyzed in real time. The themophsyical model will be used to fit the thermal continuum of the OTES spectra. The thermal infrared continuum will give us information about the surface temperature, albedo, roughness, and thermal inertia. The latter will be used to derive information about the regolith grain size, which is a fundamental parameter for the sampling site selection. Indeed, regolith grains bigger than 2-3 cm can clog the OSIRIS-REx sampling mechanism and the presence of boulders represents a hazard for the spacecraft touchdown.

Thanks to collaborations between the CMEF/Mines-Paritech and the Laboratoire Lagrange, a sophisticated thermal model that takes into account the heat transfer within a multi-dispersed regolith bed is being developed. This approach is important to verify the current procedures used to derive the regolith properties of the sampling site for the Hayabusa2 and the OSIRIS-REx space missions, described above. Both missions require substantial fine regolith to successfully sample the asteroid surface. But, the science teams are taking decision of the sample site on the basis of 1D heat conduction models (used to derive the surface thermal inertia from the spacecraft instrument measurements, and from the value of the thermal inertia the effective grain size of the regolith).

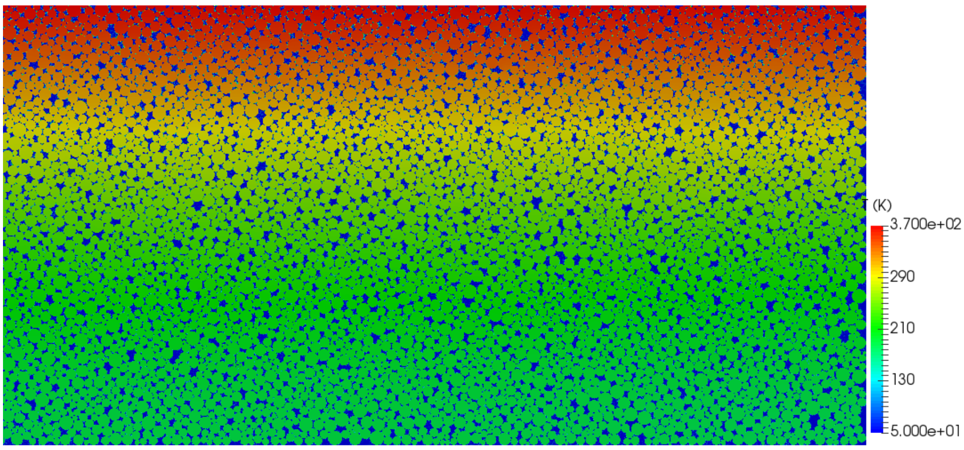

Figure 5: Temperatures in a very compact regolith bed calculated with a finite element thermophysical model that takes into account inter-grain conduction and the presence of voids.

In addition, by removing the thermal infrared continuum from OTES data, we will derive the surface emissivity. The latter is a very sensitive indicator of the mineralogical assembly of the regolith. For these studies, synergies between thermal modelers and experts of material sciences are fundamental. In addition, there will be necessity to measure in the laboratory the thermal emissivity of meteorites and other asteroid analogs, in order to fully interpret the OSIRIS-REx/OTES data.

References (max. 10):

- Jutzi, M., Benz, W. & Michel, P. 2008. Numerical simulations of impacts involving porous bodies I. Implementing sub-resolution porosity in a 3D SPH hydrocode. Icarus 198, 242-255.
- Jutzi, M., Michel, P. , Hiraoka, K., Nakamura, A.M. & Benz W. 2009. Numerical simulations of impacts involving porous bodies II. Confrontation with laboratory experiments. Icarus 201, 802-813.
- Jutzi, M., Michel, P. 2014. Hypervelocity impacts on asteroids and momentum transfer. I. Numerical simulations using porous targets. Icarus 229, 247-253.
- Michel, P., Benz, W., Tanga, P. & Richardson, D.C. 2001. Collisions and Gravitational Reaccumulation: Forming Asteroid Families and Satellites. Science 294, 1696-1700.
- Michel, P., Benz, W. & Richardson, D.C. 2003. Fragmented parent bodies as the origin of asteroid families. Nature 421, 608-611.
- Michel, P., Richardson, D.C., Durda, D.D., Jutzi, M., Asphaug, E. 2015. Collisional formation and modeling of asteroid families. In Asteroids IV (P. Michel et al., eds), the University of Arizona Press, Tucson, pp. 341-354.
- 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, accepted.

- Schwartz, S.R., Richardson, D.C., Michel, P. 2012. An Implementation of the Soft-Sphere Discrete Element Method in a High-Performance Parallel Gravity Tree-Code. Granular Matter, DOI 10.1007/s10035-012-0346-z.
- Schwartz, S.R., Michel, P., Richardson, D.C., Yano, H. 2014. Low-speed Impact Simulations into Regolith in Support of Asteroid Sampling Mechanism Design I.: Comparison with 1-g Experiments. Planetary & Space Sci. 103, 174-183.
- Yu, Y., Richardson, D.C., Michel, P., Schwartz, S.R., Ballouz, R.-L. 2014. Numerical predictions of surface effects during the 2029 close approach of asteroid 99942 Apophis. Icarus 242, 82-96.

D. International collaborations

The NASA space mission OSIRIS-REx A letter from the PI of OSIRIS-REx is included in the proposal of C4PO, which demonstrates the international framework and collaboration taking place within this space mission, although only a few Co-Investigators are non-US researchers, and three are members of C4PO.

In the framework of Hayabusa 2, in which a member of C4PO is a co-I, core member of the Small Carry-on Impactor instrument and lead of the Regolith Science Group, OCA participated to a proposal to the Japanese Society for the Promotion of Science Core-to-Core Program, which was selected in March 2016. This program is intended to promote international exchange of scholars and sustained relationship among multiple countries and Japan in science. The core institute of our proposal is the University of Tokyo. The topic of our Core-to-Core program is planetary science with main emphasis in small-body explorations in the Solar System and exoplanetary science. The ultimate science goal is to advance our understanding of planetary formation processes based on these approaches. Hayabusa 2 is a central part of this program The funding allows sending researchers and students to France to do joint research and meeting there.

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.

Thermophysical modeling is carried out in collaboration with J. Emery of the Dept. of Earth and Planetary Sciences, University of Tennessee in Knoxville, USA.

E. List of people involved in the project

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F. Most significant publications of the team

- Bottke, W.F., Vokrouhlicky, D., Walsh, K.J., Delbo, M., Michel, P., Lauretta, D.S., Campins, H., Connolly, H., Scheeres, D., Chesley, S. 2014. In Search of the Source of Asteroid (101955) Bennu:

Applications of the Stochastic YORP Model. Icarus 247, 191-217.
- Delbo, M., Mueller, M., Emery, J. P., Ben Rozitis & Capria, M. T. in Asteroids IV (eds. Bottke, W. F., DeMeo, F. E. & Michel, P.) 1–21 (2015).
- Michel, P. & Delbo, M. 2010. Orbital and thermal evolutions of four potential targets for a sample return space mission to a primitive Near-Earth Asteroid. Icarus 209, 520-534.
- Schwartz, S.R., Michel, P., Richardson, D.C. 2013. Numerically simulating impact disruptions of cohesive glass bead agglomerates using the soft-sphere discrete element method. Icarus 226, 67-76.
- Schwartz, S.R., Michel, P., Richardson, D.C., Yano, H. 2014. Low-speed Impact Simulations into Regolith in Support of Asteroid Sampling Mechanism Design I.: Comparison with 1-g Experiments. Planetary & Space Sci. 103, 174-183.
- Tardivel, S., Scheeres, D.J., Michel, P., Van wal, S., Sánchez, P. 2014. Contact Motion on Surface of Asteroid. Journal of Spacecraft and Rockets 51, 1857-1871. DOI: 10.2514/1.A32939

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.

Guy Libourel, Professor, Univ. Côte d'Azur (UCA), belonging to Lagrange Laboratory at OCA and affiliated Professor, Hawai'i Institute of Geophysics and Planetology (HIGP), University of Hawaii, USA, expert in cosmochemistry, meteorites, experimental petrology and material science, Co-I on the NASA OSIRIS-REx mission, Humboldt fellow, Bronze CNRS medal, 100 refereed publications.

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".

M. Bernacki, Professor in Numerical Metallurgy at CEMEF MINES-ParisTech. Expert in numerical developments for the simulation of microstructure evolution and damage phenomena. Applicant for an ERC grant in 2016. Head of the "Numerical Materials" committee of the SF2M. Head of research group "MultiScale Modelling".

Pierre-Olivier Bouchard, is Professor at Mines ParisTech and in charge of the Computational Machanics and Physics department at the Center for Material Processing, Sophia-Antipolis. Laureate of the ESAFORM Scientific Prize in 2005. P.-O. Bouchard is expert in damage and fracture modeling at multiple scales. He is the coordinator of the French ANR project COMINSIDE (2014-2018). He is in charge of the MECAMAT association working group dedicated to "Physics and Mechanics of Damage and Fracture". About 50 refereed publications.