11.4 Impact disruption and cratering

A. Context and state of the art

The scales of the phenomena that are involved in planetary and small body impacts are larger by far than those reached in laboratory impact experiments. Extrapolations by 15 orders of magnitude in mass are necessary to achieve ranges that are relevant to asteroids and planetesimals. Theoretical models of impact cratering and catastrophic collisions try to fill this gap by establishing non-dimensional relationships between the projectile's size, the impact velocity, the target's strength, its density, etc., that are supposed to be valid at all scales, and which are regrouped in scaling laws (see e.g. Holsapple, 1993). These scaling laws are quite successful at relating projectile size to crater size in the cratering regime, so long as the analogy with a point-source-like explosion holds. Nevertheless, such relationships are necessarily idealized, as they assume a uniformity of the process as well as a structural continuity. Consequently, they cannot predict large-scale impact outcomes with a high degree of reliability. Nor can they provide information on the crater formation process itself and on the ejecta evolutions and fates.

In addition to planets, asteroids and planetesimals are also complex entities whose impact response may have little to do with the physical behavior of rock material in the laboratory (dominated by their mechanical strength) or large fluidized spheres (dominated by gravity). Moreover, some of them are metallic, which requires adapted models to determine how they disrupt and the outcome of a cratering impact.

Numerical simulations are another approach to studying the collisional process, with some notable successes. Various impact codes have been developed, relying on different fracture and porosity models and numerical techniques (Lagrangian versus Eulerian). It is now possible to simulate an impact with a certain degree of sophistication thanks to dedicated numerical codes (see, e.g., Jutzi et al., 2015, for a review) accompanied by improvements in computer performance. However, code-benchmarking activities indicate that differences arise in the impact outcome computed by different codes, for same initial conditions, which implies that big efforts remain necessary to be confident that both our understanding of the physical process and our numerical implementations are robust.

Two collisional regimes are usually considered: the cratering regime and the disruption regime. The cratering regime corresponds to impact events leading to a crater, which means that the mass of the largest remnant of the collision contains typically more than 90% of the original mass. In this regime, in numerical simulations, it is usual to model only a portion of the target, which corresponds to the region where most of the event takes place, which needs to define appropriately the boundary conditions. Scaling laws can also be used to get a first estimate of the crater's size and volume, as long as the underlying assumptions are satisfied.

The disruptive regime corresponds to impact events leading to a family of fragments, in which the largest mass contains less than 90% of the original mass. It is usual to define the catastrophic disruption impact energy threshold as that leading to a largest remnant containing 50% of the original mass, but we can easily demonstrate that even a largest remnant containing up to 90% of the original mass may come from a disruption event (see below).

Another regime is the accretion regime, which corresponds to impact energies that are so low that the two involved bodies in the collision accrete instead of being disrupted. Although this regime is not explicitly included in this text, we plan to study it in CP4O in order to refine the impact energy limit for accretion as a function of all relevant parameters, which is needed in models of planetary formation.

One important aspect of the disruption process is that at large scales (typically objects with sizes about 200 meters, according to our current understanding; see e.g. Benz and Asphaug 1999, Jutzi et al. 2010), it involves two phases: the first phase is the fragmentation phase, during which cracks propagate in the impacted object as a result of the impact of a small projectile; the second phase is the gravitational phase during which the generated fragments start their evolutions and interact due to their mutual gravitational attractions. These attractions can be strong enough to cause reaccumulations, leading to the formation of gravitational aggregates, which are obviously not occurring at laboratory scales where this phase can be ignored. Simulations of asteroid disruptions, accounting for both the fragmentation phase and the gravitational phase, were performed for the first time by Michel et al. (2001) and showed the influence of the reaccumulation process in the outcome.

We compute the outcome of the fragmentation phase with a three-dimensional smooth particle hydrodynamics (SPH) code (Benz and Asphaug 1994). This code solves in a Lagrangian framework the usual conservation equations (mass, momentum, and energy) in which the stress tensor has a nondiagonal part, associated with an appropriate equation of state. Plasticity is introduced by modifying the stresses beyond the elastic limit. A von Mises or a Drukker-Prager yielding criterion is used, depending on needs. For the lower tensile stresses associated with brittle failure, a fracture model based on the nucleation of incipient flaws, whose number density is given by a Weibull distribution (Weibull 1939), is generally used. A porosity model, based on the P-alpha model (Jutzi et al. 2008) or the epsilon-alpha model (Wünneman et al. 2006) is used to account for the dissipation of energy in pore crushing when a material is porous. For metals, appropriate fracture and damage models still need to be developed and implemented (A11.1, A11.2). Once the collision is over and fractures cease to propagate, the hydrodynamic simulations are stopped and intact fragments are identified. These fragments and their corresponding velocity distributions are fed into a gravitational N-body code, which computes the gravitational evolution of the system over the following few hours or days. Because we are dealing with a large number of fragments, up to millions, that we want to follow over a few days after the impact, we use the parallel N-body hierarchical tree code *pkdgrav*, which we also use to model the interaction of various tools with a small body granular surface and the dynamics of granular materials (see Themes 8 and 11.6), to compute the dynamics of these fragments and their potential reaccumulations.

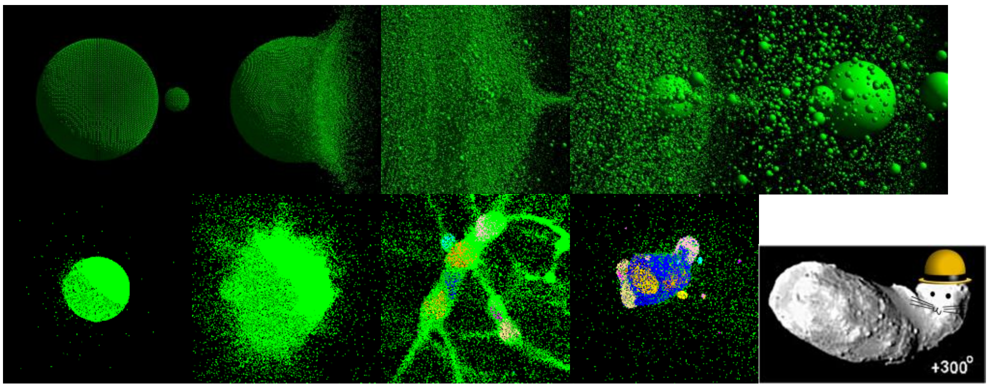

Figure 1: Top: Snapshots of the time evolution of one of our N-body simulations of the gravitational phase of a disruption. Each particle is shown to scale, assuming spherical shapes. First frame (left): initial condition, soon after the disruption of the parent body. The view size of this frame is 200 km. Other frames (at times t=0.55, 0.84, 1.68, and 8.38 hours) are 50 km in size. The rapid growth of a large remnant and of a complete hierarchy of fragment sizes is clearly apparent. While the largest remnant accretes fragments that are gravitationally bound, other bodies of different sizes diffuse in the surrounding space. In this simulation, when particles reaccumulate, they are replaced by a spherical particle with consistent mass and momentum. Bottom: same simulation, but a new model of reaccumulation is used, accounting for the shape of the reaccumulated body: reaccumulated particles do not merge into spheres and are allowed to stick at contact, bounce (depending on the impact speed and assuming a coefficient of restitution), or break depending on a strength criterion (see Michel and Richardson, 2013, for details).

A first application, which also helped to validate our approach of a two-phase modeling, was to reproduce some well-characterized asteroid families (Michel et al. 2001, 2003). More than 20 asteroid families have been identified, each corresponding to groups of bodies concentrated in proper orbital element space and sharing similar spectral properties. Until our simulations, the theory of the collisional origin of asteroid families rested entirely on these similarities in dynamical and spectral properties and not on the understanding of the collisional physics itself. In Michel et al. (2001, 2003), we explicitly simulate both the fragmentation of a parent body and the evolution of the debris cloud to late times, typically several days after fragmentation, using our hybrid approach combining an SPH hydrocode and a gravitational N-body code. We showed that gravitational interactions between fragments result in reaccumulations (Fig. 1) and lead to the formation of a family of bound aggregates. This cluster, composed of well-dispersed "rubble piles"' of all sizes, eventually evolves into one of today's asteroid families. Thus, the reason why asteroid family members can both be big and constituting a dispersed cloud is that they are not generated as single fragments, which would be too small, given the impact energy required to disperse them, but rather they grow in size thanks to the reaccumulation process occurring during the gravitational phase. The fact that they are rubble piles is consistent with the measured bulk density of some of them, which indicates a fraction of porosity that is bigger than that expected in monolithic rocks (Britt and Consolmagno 2000).

The influence of porosity was also studied by comparing the impact energy threshold for disruption of non-porous and porous targets for different sizes and impact velocities (Jutzi et al. 2010).

In the cratering regime, so far, we used scaling laws (Holsapple 1993) to predict the outcome of a cratering impact, except for the applications to space missions (see A8), and to estimate the age of a body based on the crater density on its surface (e.g. Michel et al. 2009). However, given the number of space missions that will observe planetary and small body surfaces in the coming years, the need for numerical simulations of the process to interpret the data, to estimate the surface chronologies and to improve the understanding of the process itself is very high. The current benchmarking activities in the framework of the AIDA mission (A8.2) is a good demonstration of this need.

B. Current activity

There are at least four major projects that we are currently investigating (those related to space missions are indicated in Theme 8).

B.1. Database of catastrophic disruptions of porous parent bodies

As explained in the previous section, in recent years, we have shown by numerical impact simulations that collisions and gravitational reaccumulation together can explain the formation of asteroid families and satellites. We also found that the presence of microporosity influences the outcome of a catastrophic disruption (Jutzi et al. 2010). consisting of either monolithic non-porous basalt or non-porous basalt blocks held together by gravity (termed rubble piles by the investigators) has already been investigated (Durda et al. 2007, Benavidez et al. 2012). Using a wide range of collision speeds, impact angles, and impactor sizes, we are performing more than 175 simulations of the disruption of porous targets (represented by pumice material) with sizes greater than 100 km in order to build a database of resulting fragment Size-Frequency Distributions (SFD). Dark-type asteroid families, such as C-type, are often considered to contain a high fraction of porosity (including microporosity; Britt and Consomagno 2000). To determine the impact conditions for dark-type asteroid family formation, a comparison is needed between the actual family SFD and that of impact disruptions of porous bodies. Our database will also allow us to better understand how porosity influences the outcome in various conditions, and to possibly explain dark asteroid family histories and properties.

B.2. Original location of reaccumulated fragments within the parent body before its disruption

In Michel et al. (2015), we simulated numerically the catastrophic disruption of a 250 km-diameter asteroid and the subsequent reaccumulation of fragments as a result of their mutual gravitational attractions. We then investigated the original location within the parent body of the small pieces that eventually reaccumulate to form the largest remnants of the disruption as a function of the internal structure of the parent body, ranging from fully molten to fully solid. We found that the extent of the original region where the small pieces come from within the parent body varies considerably depending on the internal structure of the parent (Fig. 2). This investigation showed that such modeling has the potential to test the degree to which a group of meteorites is a selective sample of their original parent body, and to test competing petrogenetic models that predict their original depths of formation. This is particularly useful to understand the origin of ureilites and of the Almahatta Sitta meteorites, whose origins are still a mystery.

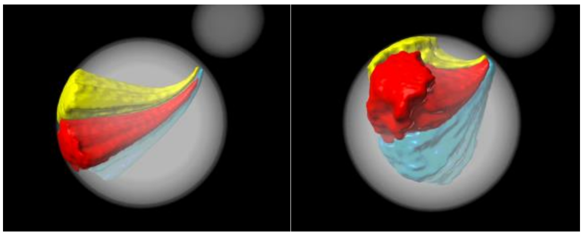

Figure 2: 3D image of the original positions of particles that will reaccumulate and form the largest, second, and third largest fragments in blue, yellow and red, respectively, from a molten parent body (left) and a solid parent body (right). The impactor is shown at the top right and moves vertically down. In the investigated greatly disruptive regimes, all the material that is in not in these largest fragments (i.e., the largest fraction of the parent body) is blown away, i.e., it will not reaccumulate (or only in very small fragments).

We are now extending this study to larger targets in order to check whether our results apply to the ureilite parent body, which is estimated to be 428 km diameter (max) in some models, as well as test a wider range of impact parameters to better understand the types of selective sampling that can occur during large impacts in the disruptive regime and in an intermediate regime between cratering and disruption.

B.3 Chemical fractionation resulting from the hypervelocity impact process on metallic targets

The study of impact disruption of metallic objects need an appropriate model of fracture and damage of metallic materials, which will be an important topic of interdisciplinary work between members of CP4O belonging to OCA and Ecole des Mines de Paris (see Theme 11.1).

Another aspect of the impact disruption process which is not yet well understood is the chemistry of the process, in particular, the chemical fractionation during impacts, accounting for the projectile's, target's and ejecta's material. In high impact energy regimes, internal energy deposited in the target + projectile region can be large enough to melt and/or vaporize the material, which expands rapidly away from the impact site. The vapor initially forms a hot, high-pressure supercritical gas that expands in an approximately adiabatic fashion into open space above the impact site. Less highly shocked material follows this early, fast, vapor expansion and forms an ejecta curtain (Fig. 3).

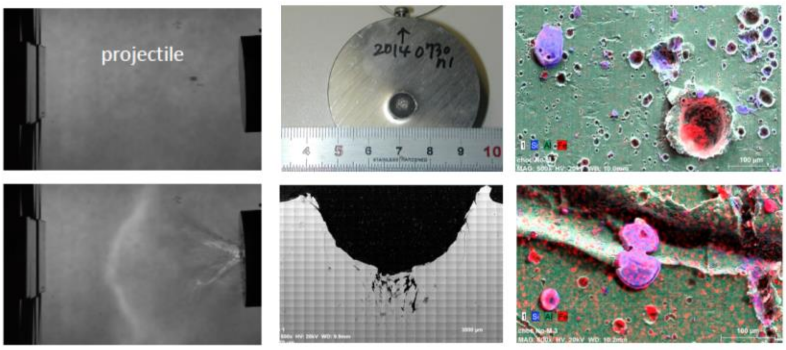

Figure 3: High velocity impact experiments on a metallic target with millimeter–sized basalt projectiles (left) using a two stages light gas gun (coll. Prof. A. Nakamura at the University of Kobe , Japan). In collaboration with CEMEF, target (center) and ejecta (left) are analyzed *post-mortem* for their microstructure and chemical composition. The ejecta (right), collected in an aluminium catcher were analysed for minor and trace elements using EDX-SEM and LA-ICPMS techniques.

High velocity ejecta create a distal layer of (tektite-like) molten droplets. Fast and energetic impact processes have therefore important chemical consequences on the projectile and target rock transformations. Several physical and chemical processes occurred indeed in the short duration of our impact experiments (e.g., melting, coating, mixing, condensation, crystallization, redox reactions, quenching, etc); all concurring to alter both projectile and target composition in an irreversible way.

In order to document such overlooked hypervelocity impact chemical fractionation, we just started to investigate this problem by impact experiments with Prof. Nakamura (Univ. of Kobe, Japan) on metallic target with millimeter–sized basalt projectiles (Fig. 3). With a range of impact speeds from 0.25 to 7 km.s^{-1}, these experiments are aimed i) to characterize all the post-mortem materials (e.g., target, crater, impact melt, condensates, and ejecta), in order ii) to make a chemical mass balance budget of the process, and iii) to relate it to the kinetic energy involved in hypervelocity impacts for scaling law purpose. Irrespective of the incident velocities, our preliminary results (Ganino et al., 2015) show the importance of redox processes, the significant changes in the ejecta composition (e.g., iron enrichment) and the systematic coating of the crater by the impact melt. On the target side, characterizations of the microstructure of the shocked iron alloys to better constrain shielding processes are in progress in collaboration with CEMEF's colleagues and members of C4PO.

B.4 Simulations of reaccumulation using the Soft-Sphere Discrete Element Method

In our first studies of the gravitational phase of a disruption, we replaced reaccumulated particles in a single body by a sphere. In order to access information on the shapes of reaccumulated objects, we then included in our N-body code *pkdgrav* a model of rigid aggregates (Michel and Richardson 2013, Fig. 1). However, this model treats the collisions occurring during reaccumulation as instantaneous between hard spheres (all single particles are spherical): when they stick, reshaping is not allowed, unless they are ejected again from the body (they cannot roll or slide on the surface).

In order to have a more realistic treatment of the interaction between particles that reaccumulate, we are now developing simulations of the gravitational phase, using our implementation of the Soft-Sphere Discrete Element Method in *pkdgrav* (Schwartz et al. 2012), which we also use to model the interaction of various tools with a small body granular surface and the dynamics of granular materials (see Themes 8 and 11.7). This requires a much smaller time step in the numerical simulations, and adds the number of parameters to account for (e.g. the various kinds of particle friction parameters). A first application is currently performed to simulate the possible formation of comet 67P by this process, and to potentially explain the shapes of some asteroids, which we suspect, may come from the reaccumulation process.

C. Future steps

We plan to continue our investigation of the impact disruption process, in all phases of our Solar system history. We will also address the important issue of the formation of planets through collisional accretion, and of crater formation on small body and planet surfaces.

C.1 Fragmentation phase

We plan to investigate the influence of the porosity and fracture models on the impact outcome, among other parameters. This will be done in collaboration with the Ecole des Mines de Paris and the GéoAzur laboratory, which both belong to C4PO and who develop fracture and damage models, as well as material equation of states (see Themes 11.1, 11.2 and 11.3).

For this, we will continue to contribute to the development and testing of the impact code Spheral++ developed at Livermore National Laboratory, which will be used for these various studies. Impact experiments in the laboratory, will be performed with collaborators who have access to impact facilities, to validate new models, as we did in the past in Japan (e.g. Jutzi et al. 2009). Different fracture models will be included and tested in synergie with the partners of C4PO (A11.1, A11.2). We will then use the code for our studies of planet formation, asteroid families, and influence of various parameters on the impact outcome. We will also revisit the cratering process with these new models to check how the outcome may differ from the one of classical scaling laws and previous simulations, and determine whether this may have implications on the current estimate of surface ages.

We will also continue our investigation of the fragmentation process in metallic targets. In particular, we will develop fragmentation models for metals, in synergie with Ecole des Mines Paris Tech (see A11.1, A11.2), and will also perform deeper investigations of the chemical fractionation that occurs in metallic target impacts. This will allow us to contribute to the important problems of how differentiated bodies (which have a metallic core) disrupt, the history of the observed metallic asteroids, and the survival of metallic projectile materials on terrestrial bodies. We will also study the cratering process in metallic objects, in order to improve our knowledge of the expected crater morphologies on metallic asteroids. This latter aspect will be very useful if a space mission, like the Psyche mission in competition in the NASA Discovery program (of which one of us is co-investigator), is sent to a metallic world.

Finally we will study the conditions for accretion versus disruption, as a function of impact energy, target's material, porosity and other relevant parameters, which are needed in models of planetary formation. Low impact energy regimes (e.g. leading to accretion) need models of material deformation and damage at low strain rates, for which members of Ecole des Mines de Paris and Géoazur are experts. They will nicely feed numerical models developed at OCA, which is another demonstration of the multidisciplinarity of CP4O.

C.2 Gravitational phase

We will continue to increase the realism of the simulations of the reaccumulation process. In particular, we will look at various ways to model different frictions, and at the possibility to model our individual particles as non-spherical ones (e.g. polyhedra). This will allow us to trace back the history of body's with given shapes, densities, rotation properties, such as those that will be visited by space missions. However, a great amount of numerical development and testing is still necessary for a great improvement in the realism of the simulations.

C.3 Geophysical signature of impact craters

Numerical simulations of impact craters that are more than tens of km in diameter often do a good job of predicting the initial stages of the cratering process, but do less well in accounting for the gravitational collapse stage and final crater morphology. We intend to address this problem by comparing the observed geophysical signature of impact craters with the output of our numerical simulations. The key datasets that will be used are the gravity fields and topography of the Moon and Mars, both of which are well known as a result of recent spacecraft missions, in synergies with the multidisciplinary expertise in C4PO. We have used these data previously (summarized in A9) to determine the volume of material excavated by basin formation events, to determine the amount of structural uplift in the centers of peak-ring and multi-ring basins, to determine the amount of fracture induced porosity in the crust, and to highlight the importance of target temperature on the final crater morphology. By comparing simulations and observations, it should be possible to determine the size, velocity, and impact angle of the projectiles that formed the observed craters. Discordances between the morphology of observed and simulated craters will be used to highlight deficiencies with the current state-of-the-art numerical codes.

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D. International collaborations

The code *Spheral++*, which is used for our simulations of the impact process was originally developed at the Lawrence Livermore National Laboratory (USA) 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 with an impact code in collaboration with the University of Bern in Switzerland.

The code *pkdgrav* that includes the Soft-Sphere Discrete Element Method, which is used to simulate the gravitational phase of a disruption 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).

Collaborations are taking places with several institutes that have impact experiment facilities: university of Kobe (Japan; team of Prof. Arakawa and Prof. Nakamura; John Hopkins University (teams of Prof. Ramesh and Prof. Barnouin), University of JKent (team of Prof. Burchell); South West Research Institute (team of D. Durda).

E. List of people involved in the project

Patrick Michel, DR2 CNRS
Guy Libourel, Professor, UNS
Alexandre Chemanda, Professor, UNS
Mark Wieczorek, DR2 CNRS
Clément Ganino, MdC, UNS
Pierre-Olivier Bouchard, Professor, Ecole des Mines de Paris

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F. Most significant publications of the team

Michel, P., Benz, W., Tanga, P., Richardson, D.C. 2001. Collision and gravitational reaccumulation : formating asteroid families and satellites. Science 294, 1696-1700 (+cover of the journal).

Michel, P., Benz, W., Richardson, D.C. 2003. Fragmented parent bodies as the origin of asteroid families. Nature 421, 608-611 (+cover of the journal).

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Short CV of participants

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

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.

Mark Wieczorek (CNRS Director of Research, laboratory Lagrange) specializes in using geophysical data to decipher the interior structure and geologic evolution of the terrestrial planets. He is a co-investigator on NASA's lunar gravity mapping mission GRAIL, NASA's martian geophysical station InSight, and the laser altimeters that will be flown on the ESA BepiColombo and JUICE missions. He is a former editor-in-chief of the *Journal of Geophysical Research Planets*, and has published over 66 scientific papers (H-index 31).