High–velocity impact experiments on meter–sized targets

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Partners

The following partners have already shown interest in this project: Centre d'Essai des Landes (CEL), Centre Technique d'Arcueil (CTA), Pr. Willy Benz (Berne University, Switzerland), Dr. Mario Di Martino (Torino Observatory, Italy). They are actively participating in designing the technical setup of the experiments, and preparing the post–analysis.

Other industrial partners are forseen to provide the targets, the projectiles, and the measurement equipments: Bouygues, Aerospatiale, CEA among others.

Proposed experiments

We plan to perform experiments of high–velocity impacts on meter–sized solid targets. The range of projectile velocities we are interested in goes from several hundred of meters per second to several kilometers per second, allowing those to exceed the sound speed inside the material. The main objective of these experiments is to improve our knowledge of a wide variety of phenomena occuring during collisions: fragmentation modes, the size and shape of the fragments, their rotational and ejection velocity fields, the fraction of impact energy transfered into fragment kinetic energy. Up to now laboratory experiments have been performed on targets at most 20 centimeters in size. It has been realized that it is impossible to simply extrapolate the outcome characteristics of the collisions to larger target size. Already the different extrapolations, based on several assumptions on the collisional physics, differ from one to the other by an order of magnitude in their predictions at sizes of a few meters. The new experiments we are proposing will help to constrain the available models, and will allow for the first time to measure physical quantities (pressure, displacement, temperature, ...) during the fragmentation process, thus improving our knowledge of the physical processes at work.

Scientific Rationale

The role of collisions is fundamental in different astrophysical fields such as the origin of our Solar System and the formation of planets, the evolution of small bodies in the Solar System, and even in the fate of the human kind, since a collision of a dangerous asteroid on the Earth is a threat that cannot be neglected.

Several evidence of the occurence of collisions have been shown up thanks to recent space missions and even ground–based observations. The recent impact of the comet Shoemaker Levy 9 on Jupiter in 1994, observed from the Earth in real time, is just an example among others showing that small bodies and planets are continuously the targets of such events. Space probes devoted to the observation of asteroids have also shown that the surface of these bodies is altered by a large number of impact craters. Most of Earth–approaching objects are also fragments of larger bodies, resulting from a collision between asteroids evolving in the Mars to Jupiter region or between comets from the Kuiper belt, located outside Neptune's orbit. These fragments are then injected in some dynamical routes leading to the terrestrial planet region. Note that the typical impact velocities between asteroids are of the order of a few kilometers per second, whereas those between comets are of the order of a few hundred meters per second. To build a coherent model of collisional and dynamical evolution of our Solar System, and to be able to face the potential threat of an asteroid coming to the Earth, a good knowledge of the collisional process is required. In particular, the size distribution and ejection velocity distribution of the fragments, the fraction of the impact energy transmitted to the kinetic energy of the fragments, their shape, their rotational velocities, all these properties are important to estimate as a function of the initial conditions of the impact.

Despite this determinant role, our knowledge on the collisional process is still very poor. This is due to the fact that the laboratory experiments have been made with targets having sizes less than a few tens of centimeters, whereas the asteroids are objects having sizes up to several hundreds of kilometers. Different extrapolations have been attempted based on some assumptions on the collisional physics. They have resulted in several so–called *Scaling Laws*, which differ from one to the other by at least an order of magnitude in their predictions for meter–sized targets. These scaling laws provide an estimate of the critical specific energy Q^* required to break a target so that the largest fragment is half the mass of the parent body (see Figure 1). Two regimes have been identified depending on the size of the target: the *Strength regime* for small enough targets, where the cohesion of the target is only due to the mechanical strength, and the *Gravity regime* for large targets, in which the self– gravity of the target comes also into play and becomes dominant. Classical gravitation is theoretically fairly well known, and its effects can be implemented in numerical simulations. In both regimes however, the crucial process of failure and propagation of damage or crack inside the target is still poorly understood. This process by itself can be explored in the strength regime with meter–sized targets.

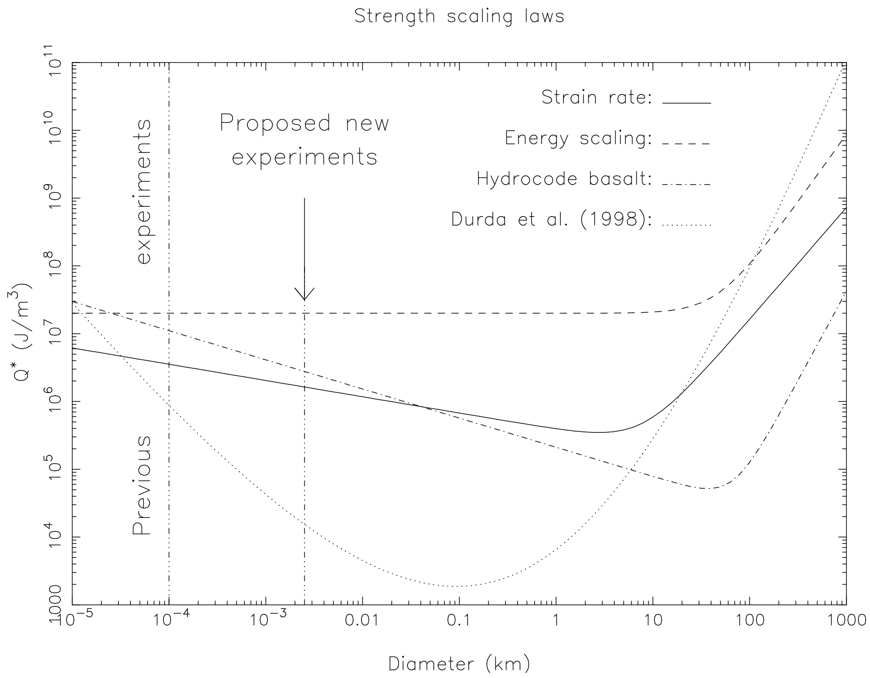

Figure 1: Critical impact energy Q^* (J/m^3) as a function of target diameter (km). Different scaling laws currently used are shown. They have been obtained assuming different physical processes.

Experimental strategy

Our project is thus to perform high–velocity impact experiments using targets in the size range $1 - 1.5$ meters in radius, for which the scaling laws are not reliable anymore. The development of these experiments will be done in relation with a tridimensional hydrocode developed by our collaborator Pr. Willy Benz, using the concept of Smooth Particle Hydrodynamics (SPH). Currently, several kinds of numerical codes have been developed to determine the outcome of collisions. The most complex and ambitious remain the hydrocodes, which use the hydrodynamical equations, sometimes coupled with a model of brittle failure, to calculate the propagation of the shock wave and the resulting propagation of cracks inside the target. The aim of the hydrocodes is to represent in the most reliable way the evolution of stress and strains inside the material. Important physical quantities such as the internal energy of the target and the evolution of the damage coefficient can be recorded. Among the hydrocodes, the SPH codes are the only ones that allow to simulate the projectile along with the target, that are stable at the points of large deformations and that can reproduce individual fragments.

Simulations with our SPH code will allow first to guide the choice of the experimental parameters and to estimate the order of magnitudes of the different measurable quantities. In turn, the experimental results will allow to calibrate the free parameters of the numerical models, and thus to constrain the set of plausible scaling laws. Besides the increase by an order of magnitude of the size of the target, the great novelty of these experiments, compared to previous ones, will be the possibility of measuring physical quantities during the fragmentation process: pressure at different points of the target, surface displacements, temperature close to the impact point, ... In addition to the already mentioned quantity Q^*, which characterizes the outcome of the whole event, these quantities will allow us to ensure the correct modelization of the physics in our numerical simulations.

The first set of experiments to be performed will consist in 6 impacts at two different velocities and variable projectile masses. The first three impacts will be performed with a projectile velocity of 400 meters per second, and using projectiles with mass ranging from about 40 to 100 kilograms. This range was estimated from the numerical simulations with our SPH code for basalt–like targets, to be able to measure from the experiments the actual value of Q^*. To test the dependence of Q^* on the impact velocity, we will then perform three other impacts, with a projectile velocity of 800 meters per second and masses deduced from the first 3 experiments.

The experiments will be performed in open–air in order to follow the complete trajectory of the fragments until they reach the ground. The measure of the fragment size and shape distributions requires a ground as soft as possible, so that the secondary break–up of some fragments is avoided. This ground must also be as clean as possible to ensure the recovery of all the fragments without any contamination by objects not resulting from the target. The measure of the ejection and rotational velocities will be obtained by the analysis and correlation of the images from two, then three of the four cameras recording the event, using pattern–recognition technics. We already have acquired some experience with imaging and analysis technics with fast frame cameras such as NAC E-10 and fast TV CCDs during previous experiments on decimeter–sized targets using contact charges.

Material characteristics

The target will consist in a sphere of radius as large as 1.5 meter. The material itself should be concrete with a bulk density of the order of 2 g/cm^3. The target will be elevated at about 50 centimeters from the ground and released to be in free–fall at the time of impact.

The projectile will consist in a sphere of a material similar to the target. Depending on the experiments its mass will vary from a few tens to a few hundreds kilograms.

Experimental configuration

The projectile will be accelerated on the 2 km railway available at the CEL. The target will be placed at about 30 m after the end of the railway. The projectile will achieve a free flight from the end of the railway to the target. The impact point will be located at about 1.5 m from the ground. A zone of 30 m in radius around the target will be prepared to receive the fragments resulting from the impact. The ground will be soft. The target will be equipped with contact detectors or displacement gauges and pressure gauges. Shortly before the instant of impact, explosive bolts will be fired in order to release it in due time.

Four fast cameras, running at 400 images per second, will be placed at about 50 m, at angles 45°, 135°, 225° and 315° from the shot line.

Industrial developments

Besides a certainly drastic improvement of our knowledge of high–speed impact outcomes (e.g. the propagation of the shock and elastic waves, the mechanics of brittle failure ...) and their astrophysical implications on the evolution of small bodies in the Solar System, these experiments will also lead to industrial developments. These will basically concern three distinct fields: the knowledge of the material behavior, the development of measuring instrumentation, imaging and pattern–recognition technics.

First, the experiments will provide precious information on the behavior of the used material during energetic impacts. The study of the material behavior under extreme conditions is precisely the field in which the CTA is an expert. The results should strongly interest potential industrial who could then find a motivation to build and provide the targets. These data will bring an important contribution to the study of the protection of sensitive infrastructures, by giving new constraints on the material strength and reaction to impacts.

One of the innovative aspects of the proposed experiments is the possibility to place several captors on and around the target, allowing to measure different physical quantities during the impact and along the fragmentation phase. The timescales of the whole process are of order of several milliseconds, with some transient regimes spreading over several microseconds. Within these timespans, the dynamics of the quantities to be measured is very large. For the pressures, expected values rise up to 1 GPa. For the surface deformations, the displacements to be measured are of a few hundreds μm, varying with velocities of a few m/s and accelerations of a few 10^4 m/s^2. The temperature in the surrouding of the impact point is the most delicate quantity to be measured. It will require some research, and it will thus lead to a precious industrial development. Temperatures of several thousands of degres, reached in a few milliseconds will have to be measured, while the material will be partly in vapor phase. The greatest difficulties will then be related to the captor strength and inertia and to its coupling with the medium to be measured.

After the shock, the created fragments have different ejection velocities before falling on the collecting surface. This phase of the experiment will be filmed by four fast cameras. The images will be digitalized, and each individual fragment will have to be automatically detected and identified. The fragments will thus have to be related from one camera to the other, and from one image to the next for each camera. This will allow us to define automatically the three–dimensional trajectory of the fragments. The problems of pattern–recognition, of the determination of topography, and of the following of objects during their motion are still *hot topics* in the imaging research field. The necessary developments for the data analysis of our experiments will require the writing of new softwares which could then be applied to the study of automatic control of autonomous mobile engines.

The results of these experiments will be published in specialized journals. Industrial ownership of data or technics will however be preserved. The experiments are available to be used for advertisement by our partners as they see fit.

Estimated total budget: $\sim$ 1.7 M Euro ($\sim$ 11 MFr).

- Cost of individual launch (excluding the development studies and the price of the target): $\sim$ 0.15 M Euro ($\sim$ 1 MFr).
- Estimated supplementary expenses (development studies, targets, post–analysis, publications): $\sim$ 0.8 M Euro ($\sim$ 5 MFr).