Impact crater experiment
Protocol

University of Bern
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1 Introduction

All bodies are affected by impact cratering since the formation of the Solar System 4.5 Gy ago. Planetary bodies are formed in a protoplanetary disk around a star. In this disk, gases condense into dust that are though to accrete into larger grains through a process that is still not well understood. One theory is that grains grow by colliding into one another and sticking together, forming one entity with a bigger mass than previous individual ones. These pieces get larger and agglomerate to form so-called planetesimals, and later planets. Impact cratering is therefore an incessant and a ubiquitous geological process that acts on all planetary bodies with a solid surface (Fig. 1), such as telluric planets, moons (telluric or icy), asteroids and comets. The flux of impact in our Solar System was much higher in the first billion years of Solar System history, but is currently nearly constant. The violent collisions between projectiles and planetary objects can form an impact crater. For example, tons of particles hit the Earth every day at speed between 10 and 70 km s^{-1}. But few can reach the surface because they are destroyed by friction with the terrestrial atmosphere, which acts as a sort of shield. Projectiles that are at least tens of centimetres in size can reach the surface of the Earth, and only bodies that are larger than tens of meters can form impact craters. Numerous impact craters can be observed at the surface of bodies, especially on planetary bodies that have no atmosphere and/or experience very little resurfacing processes (e.g. water erosion, volcanism, plate tectonics...) such as the ones presented in Figure 1. On Earth, most of the impact craters have been erased by erosive processes and plates tectonics (at present about 170 existing impact craters have been identified). This is why impact crater counting is a convenient to evaluate surface age and geologic activity on planetary bodies.

In the twentieth century, scientists realized that impact cratering and bomb cratering presented similarities. Regardless of the angles of impact of the projectile (either a meteor or a bomb), the crater formed always had a circular shape. The reason for this is that the process that drives the formation of the crater is not actually the impact itself, but the explosion due to the impact. The energy released by this explosion is the same in all directions resulting in a circular crater. In the case of a meteor, the impact velocity is so high (at least the escape velocity of the planet, which is 11.2 km s^{-1} for the Earth), that when the projectile hits the ground it penetrates the surface before exploding, which is when the kinetic energy is converted into thermal energy. This explosion then destroy the projectile and the ground in the area, forming the circular pattern of the impact crater.

From experimental investigations and numerical modeling, scaling laws have been established allowing the comparison of different craters. The aim of the present "impact crater" experiment is to reproduce an impact crater formation to study the relation between the energy of the projectile and the size of the impact crater by determining the parameters of scaling laws and comparing your results with the established theory in the literature. The results from the experiment should be presented in a comprehensive report.

2 Theory

Impact crater formation is complex, and depends on the material properties of both target and projectile, the parameters of the impact, the gravity and the atmosphere. However, the main parameter that drives the shape of the crater is the energy input of the impact and the explosion of the projectile. The morphology of impact craters can be most simply divided into two categories: simple craters and complex. The diameter at which craters become complex depends on the surface gravity of the planet; the greater the gravity, the smaller the diameter of the complex structure. On Earth, simple craters are usually less than 2 to 4 km in diameter depending on the properties of the rock at the site of impact. On the Moon, at one-sixth Earth's gravity, simple craters are less than 15 to 20 km in diameter.

The experimental apparatus allows only the formation of simple craters characterized by a bowl-shaped. The crater formed by the explosion of a projectile of radius a (m), has a radius R (m) and is surrounded by a crater rim of a radius R_{rim} (m) (Fig. 2).

The dimension of crater is linked to the energy of the impact. The more energy there is, the larger the crater will be. However, experiments have established that the relationship is not linear, but follows a power law:

$$D = k * E^n \tag{1}$$

With D (m), the diameter of the crater, E (J), the energy of the projectile, k, an unknown constant and n, an unknown factor.

This experiment is small scale and low energy compared to a meteor impact or bomb explosion. It is not possible to directly compare results with the case of a real meteoritic impact. In order to compare experimental results with different parameters and scales, it is necessary to introduce dimensionless parameters. Then, different scaling laws can be established to study the influence of specific parameters when others are kept constant. This helps to understand the physics that drive crater formation. A widely used method to derived the scaling laws is the so called π-group scaling (Holsapple and Schmidt, 1982; Melosh, 1989; Badertscher, 2003):

$$\pi_1 = C\pi_2^{-\alpha}\pi_3^{-\beta}\pi_4^{-\gamma} \tag{2}$$

Where C is a constant parameter. The π groups are presented in table 1 and α, β and γ are unknown factors.

"Mass set"	$\pi_1 = \frac{V\rho}{m}$	$\pi_2 = \frac{g}{U^2}\left[\frac{m}{\delta}\right]^{1/3}$	$\pi_3 = \frac{Y}{\delta U^2}$	$\pi_4 = \frac{\rho}{\delta}$
"Energy set"	$\pi_1 = \frac{V\delta U^2}{E}$	$\pi_2 = \rho g\left[\frac{E}{\delta^2 U^8}\right]^{1/3}$	$\pi_3 = \frac{Y}{\delta U^2}$	$\pi_4 = \frac{\rho}{\delta}$
"Gravity set"	$\pi_1^* = V\left[\frac{\rho g}{E}\right]^{3/4}$	$\pi_2^* = \frac{1}{U^2}\left[\frac{g^3 E}{\delta}\right]^{1/4}$	$\pi_3^* = \frac{Y}{\delta U^2}$	$\pi_4^* = \frac{\rho}{\delta}$
"Momentum Energy set"	$\pi_1' = \frac{V\delta E}{M^2}$	$\pi_2' = \rho g\left[\frac{M^8}{\delta^4 E^7}\right]^{1/3}$	$\pi_3' = \frac{Y}{\delta E^2}$	$\pi_4' = \frac{\rho}{\delta}$

Table 1: Different combinations of the π sets determined for the crater scaling laws. V (m^3), the volume of the crater, ρ (kg m^{-3}), the density of the target, Y (N m^{-2}) the strength of the target, g (m s^{-2}) the gravity, m (kg) the mass of the projectile, δ (kg m^{-3}), the density of the projectile, U (m s^{-1}), the speed of the projectile, E (J), the energy and M (kg m s^{-1}), the momentum.

Several scaling laws can be derived from this method. One of them links the π_1 member to the π_2 member of the "Mass set".
Another well known scqling laws links the size of the crater to the energy of the impact:

$$\frac{D}{D_0} = \left(\frac{E}{E_0}\right)^n \tag{3}$$

Where D_0 (m) and E_0 (J) are the diameter and energy associated to one particular crater, respectively. These are different than D (m) and E (J), which are the diameter and energy associated to any crater, respectively.

As you can see, these experiments are performed in order to retrieve the values of the unknown parameters in the scaling laws, and establish your own power laws.

3 Apparatus

The experimental set-up (Fig. 3) is designed to reproduce high velocity impact of a projectile into a granular medium. It was developed by Tobias Badertscher during his PhD Badertscher (2003). A vacuum pump system at the top of the set-up permits to hold a projectile above the target. The pump is controlled via an interface box that links the pump to the computer. The software controls the pump is LabView. The projectiles used in the experiments are marbles of different materials (glass, plastic and steel) and diameters (from 7 mm to 22 mm). The target is set in a plastic tray, and is filled with granular material. There are two types of granular media available, fine and coarse sand. The projectile is released by switching off the pump with the interface box. The marble is then accelerated by passing between 2 wheels that can rotate from 6 to 60 rpm. When the projectile impacts the sand surface it ejects material from the target and forms a crater.

In order to determine the dimension of the crater formed we use an optical device. A high-speed camera is used to measure the impact speed of the projectile by analyzing successive photo frames. The geomorphology of the impact crater is analyzed using stereo-photogrammetry of the test-bed surface. Photos of the test bed are taken after the impact. Then, the images are compiled in a stereo-photogrammetry software (Agisoft Photoscan) that produces 3D models from which one can extract the dimension of the crater a GIS software (Geographic Information System) (QGIS (free), ArcGIS...).

4 Experimental protocol

The following section describes the different steps in the experiment:
- Turn on the Windows computer, user name: "Tobias" - password: no password.
- Place the tray filled with sand below the projectile holder.
- Program and calibrate the high speed camera in order to be able to catch the projectile on a least 2 successive frames.
- Turn on the interface box (on the back of the box).
- Open the LabView program "demo_release.vi" on the Desktop. This program controls the vacuum pump. Click on the white arrows "RUN CONTINUOUSLY" (top left). Click on the button to either "suck" to hold the marble or "release" to release the marble.
- Place the marble on the projectile holder.
- Start the wheels.
- Start the camera recording.

- Release the marble by switching the button on the software interface.
- Stop the camera.
- Take pictures of the test bed.

5 Data analysis and tasks

- Determine the projectile velocity. You can compare that speed to the theoretical speed obtained from the rotation speed of the wheels.
– Extract topographic profiles of impact craters and determine their diameters.
– Present all your measurements in tables, and your results in plots that help you and the reader to understand the different relationships you have obtained.
- Retrieve the constant parameters to establish your scaling laws (π_1 vs π_2, D vs E...).
- Explain what are the conditions and/or assumption required to use these scaling laws.
- Calculate the uncertainty in your measurements.
– Vary the marble speed, material and size, and the sand grain size of the target medium.
- Compare your results with values in the literature.
- Complete the application exercise.
– Display all your work, calculations, results and interpretations in a comprehensive report. Don't forget to explain your experimental choices and procedures, assumptions on calculations, and your interpretation of pictures, graphics and results.
– Feel free to test and/or propose potential improvements to the experiment.

6 Application

One of the most famous and well preserved crater on Earth is the "Meteor Crater" in Arizona (see cover photo). Its diameter is about 1.2 km and its depth is 190 m. Use the results of your experiment to answer the following questions:
Question 1: How much kinetic energy did the asteroid that formed "Meteor Crater" have when it hit the Earth?
Question 2: If we assume that the velocity of this asteroid when it hit the

Earth was about 15 km s^{-1}, what was the mass of the asteroid?
Question 3: Assuming a spherical shape, what was the radius of the asteroid which created this crater?

7 Future developments

Feel free to propose and test potential improvements for the experiment. We are interested in several aspects, such as:
- Studying the trajectory of the sand grains ejected. This can be performed with particle-tracking softwares, e.g.:
"https://perso.univ-rennes1.fr/joris.heyman/trac.html" or
"https://www.compadre.org/osp/webdocs/Tools.cfm?t=Tracker"
- Control the pump with a program (MatLab or other) without the need of the LabView interface and software.

8 Appendix

8.1 Safety

- The projectile can reach high speeds, up to 25 m s^{-1}. Do not stand too close to the set-up when you release the projectile. Use the lateral protection and wear goggles.
- Do not remove the tap on the wheels. If it starts to become loose, inform the experiment supervisor.
- Switch off the wheels after each experiment and when you put a projectile back on the sample holder.
- The previous version of this experiment and data analyses required a laser sheet. This laser has not been removed yet but you don't need it. You could use it as an indication of the position of the impact on the target if you so choose. Be careful to not look directly into the plane of the laser.

8.2 Potential issues

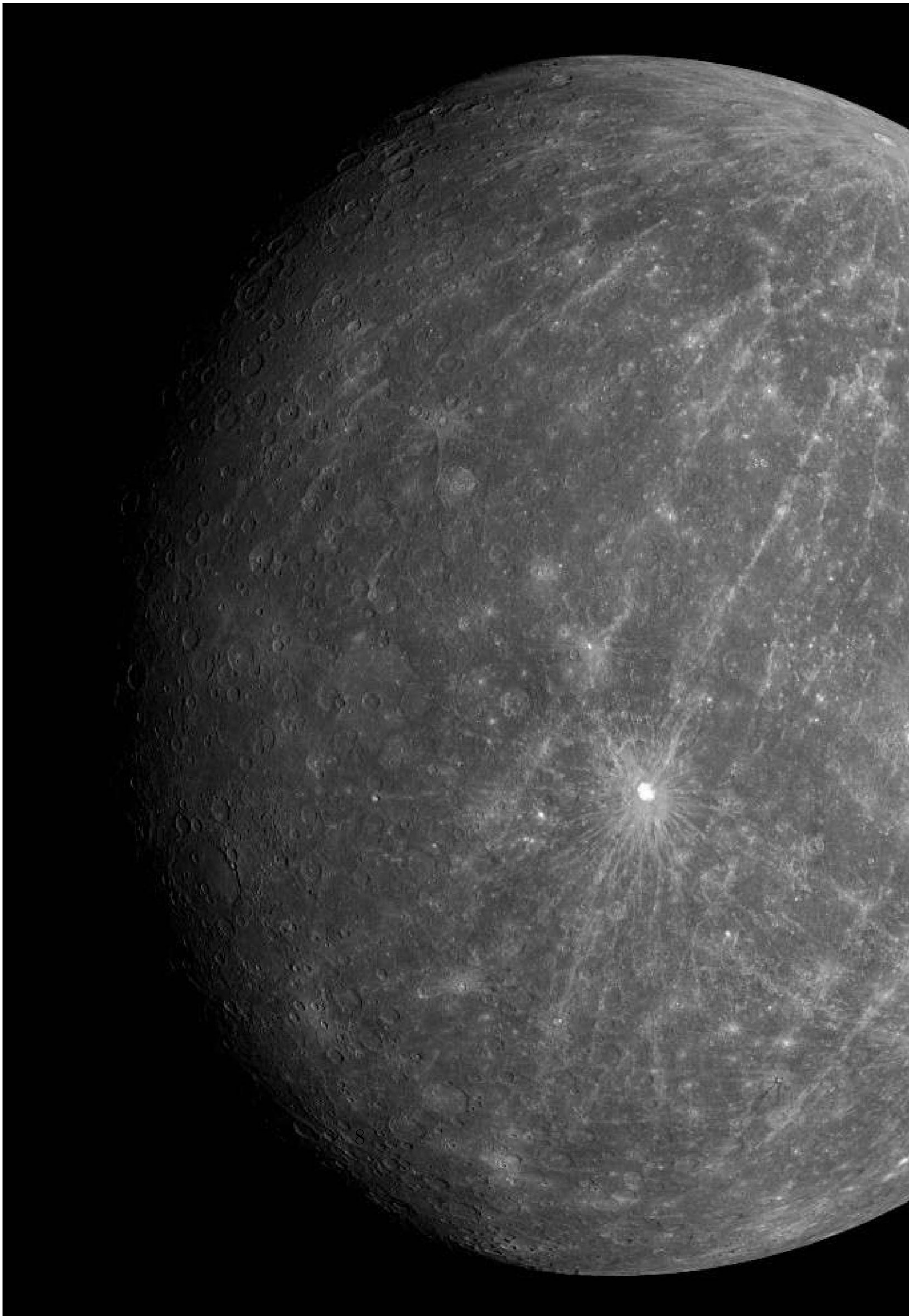
Please communicate any issues to the experiment supervisor.

References

Badertscher, T. (2003). *Einschlagexperimente in granularen Medien bei tiefen Geschwindigkeiten.* University of Bern.

Holsapple, K. and R. Schmidt (1982). On the scaling of crater dimensions, 2. impact processes. *Journal of Geophysical Research 87*(B3), 1849–1870.

Melosh, H. (1989). *Impact Cratering: A Geologic Process*. Oxford University Press.



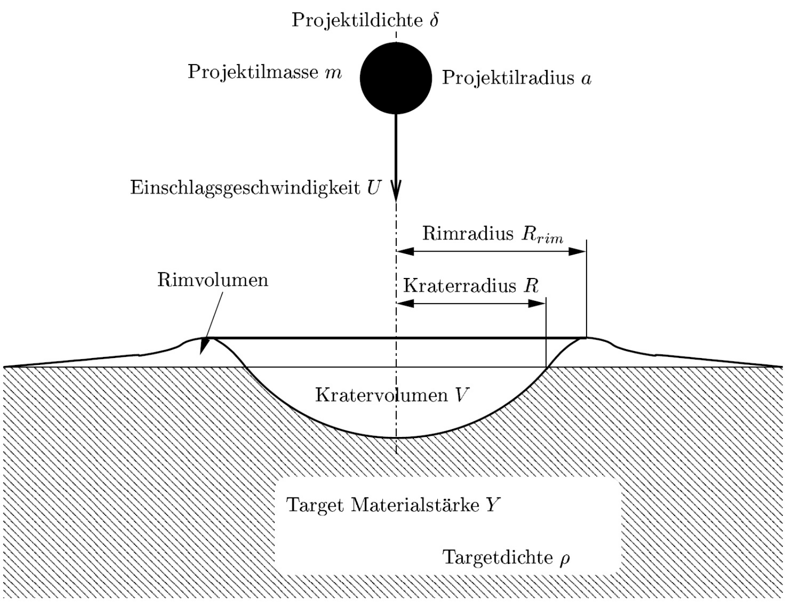


Figure 2: Parameters associated to the formation of a simple crater (from Badertscher (2003)).

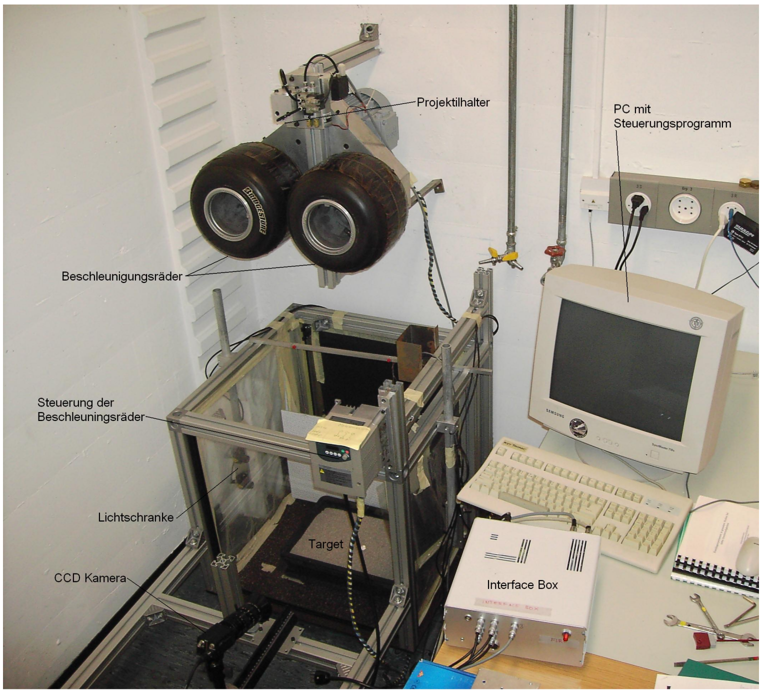


Figure 3: Experimental apparatus.