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Hydrocode simulations of the largest crater on asteroid Lutetia

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ABSTRACT

The flyby of the Main Belt asteroid Lutetia by the Rosetta spacecraft allows the camera OSIRIS to obtain very good images of about half of the body at the maximum resolution of 60 m per pixel. From the images and radio-science experiment, a density of about $(3.4 \pm 0.3)\,\mathrm{g/cm^3}$ has been inferred for the asteroid.

Many impact craters have been observed on the surface of Lutetia and the largest, named Massilia, has a diameter of about 55 km. Relative to the size of Lutetia (the longest axis is approximately 126 km) the crater represents one of the dominating features on its surface. Whether or not the impact that formed Massilia affected the entire asteroid can be only evaluated via numerical modeling, with hydrocodes, of the impact process. The results of a suite of iSALE simulations are compared with the crater profile derived from the Digital Terrain Model of the observed surface. The best match to the DTM of the crater with hydrocode simulations has allowed to determine a value of 7.5 km for the impactor diameter, which suggests a primordial origin of Lutetia due to the low probability of such an impact event.

A second interesting impact structure has been identified nearby Massilia within the North Pole Crater Cluster. The crater has a diameter of 24 km and it lies over a larger crater of the North Pole Crater Cluster. This is strongly suggestive of a very young structure on Lutetia. The numerical simulations of this feature constrain the impactor to be 3.8 km in diameter, assuming the same material properties for target and impactor as in the model of the formation of Massilia.

1. Introduction

Rocky planets, satellites and asteroids all exhibit surfaces with impact craters as the most common landforms. In spite of their ubiquitous presence, craters still represent a scientific challenge in terms of interpreting their origin, shape and morphology. The current understanding of impact cratering processes is derived in part from observational data and in part from computer simulations. Extensive small-scale laboratory impact experiments and high energy explosions have been performed to derive empirical scaling laws that enable to predict the approximate size of a crater for a given impact energy, gravity and material properties (e.g. Holsapple, 1993). In this context, a single but relevant data point is represented by the collisional experiment performed on comet Tempel 1 by the Deep Impact space mission (e.g., A'Hearn et al., 2005; Richardson et al., 2005; Wünnemann et al., 2005a, 2005b).

Hydrocodes are valuable tools to study craters on asteroids. The cratering record provides important scientific clues on the history and structure of a given body. Crater counting, a methodology allowing to evaluate the age of the asteroid's surface, significantly benefits from specific and reliable scaling laws that relate crater sizes and depths to the impactor diameter and velocity (impact energy), and gravity. Such scaling laws that were originally derived empirically from laboratory impact experiments (Holsapple, 1993; Schmidt and Housen, 1987) strongly depend on the properties of the

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target material and may be refined by hydrocode modeling (Wünnemann et al., in press). Hydrocode modeling of impact processes can also be used to determine the amount of damage caused by the impact on the body (e.g. Collins et al., 2004; Asphaug et al., 2002; Ivanov et al., 1997; Melosh et al., 1992). From the morphology of the specific craters it may be possible to infer some of the petrophyiscal and structural properties of the asteroid surface.

The ROSETTA mission had a close flyby to asteroid Lutetia on July 10th, 2010, and the imaging system OSIRIS on board the spacecraft took high resolution images of the asteroid surface revealing a very complex object, endowed with a variety of both small scale and major features, pointing to a long and highly complex history (Sierks et al., in press).

The surface morphology is dominated by different populations of impact craters, whose dimensions span from few hundreds of meters to a few tens of kilometers (Vincent et al., 2012). In particular, one impact structure, named *Massilia*, with its 55 km of diameter has a size comparable to the radius of the asteroid (50 km). This crater, located near the terminator of the high resolution images, is deformed by grooves and pit-chains, indicating modifications that took place after its initial formation (Thomas et al., 2012). Adjacent to Massilia's rim, a cluster of craters, named *North Pole Craters Cluster* (NPCC), stands out for the presence of a possibly young crater (marked in Fig. 1 and referred hereafter as *NPCC-d*) with remarkable dimensions ($\sim$24 km in diameter). This crater also appears to be asymmetric, possibly because it originated on the wall of a pre-existing larger crater (Thomas et al., 2012), while its interior is dominated by a great variety of deposits, among which smooth and fine deposits with boulders, produced by the excavation of the shattered bedrock. The main reasons of interest for this crater are related to its possible young age, the vast number of features of interest Thomas et al., 2012 and the many boulders observed in images (up to 300 m in dimension) as it is described in Küppers et al. (2012).

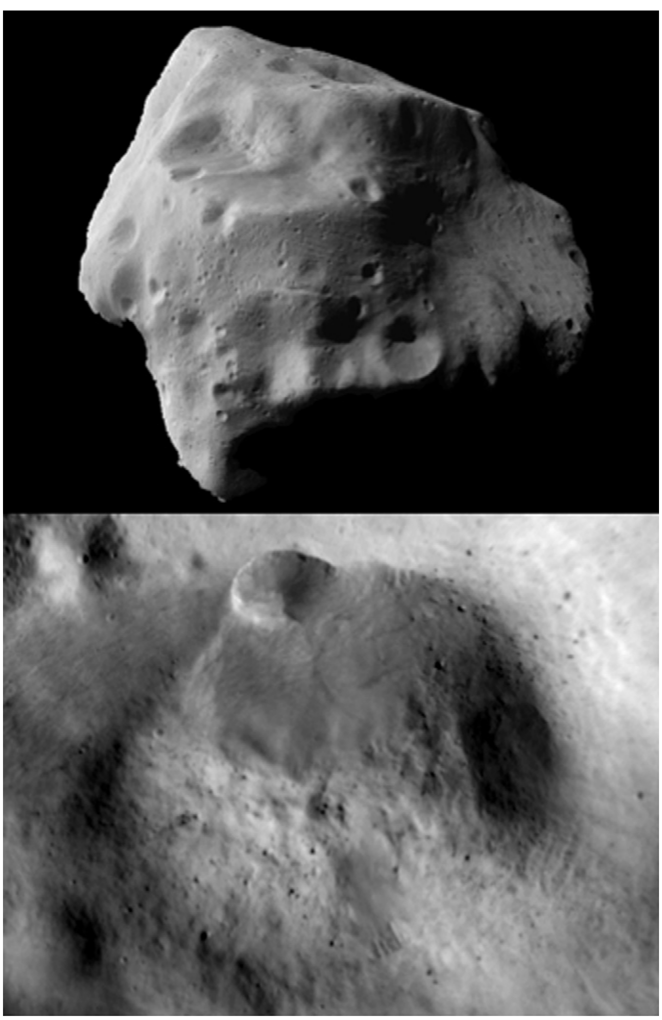

Fig. 1. 3D perspective views of OSIRIS NAC DTM, textured with OSIRIS NAC orthoimage mosaic where is visible the 55 km crater on top and the 24 km crater on bottom.

The large dimensions of these craters pose challenging questions concerning the size of the impactor and the frequency of such events. Determining the projectile size allows to put stringent constraints on the collisional history of Lutetia and its internal structure. By means of the iSALE hydrocode, we modeled the largest crater on Lutetia (Massilia) and the young component of the NPCC having the diameter of 24 km. These two craters, the most prominent features on the surface of the asteroid in terms of impact events (Thomas et al., 2012), will help us to better understand the surficial and internal structure of the asteroid and its collisional history.

2. The iSALE hydrocode: a short description.

Hydrodynamic computer codes, or *hydrocodes*, are sophisticated computer programs that can be used to simulate numerically highly dynamic processes. In particular, they are capable to model the propagation of shock waves as well as the behavior of geologic materials over a broad range of stress states and deformation rates (Anderson, 1987; Pierazzo et al., 2008). They are based on the discretization of the continuous real world medium into elementary pieces, called cells. This leads to the choice of the resolution, in space and time, at which a simulation is carried out. On the one hand, any simulation should be carried out with sufficiently high resolution to resolve all the important flow variations both in space and time. On the other hand, this requirement has to be balanced by the available computer power and the time needed to complete the simulation (e.g., Pierazzo and Collins, 2004).

Over the last few decades, rapid improvement of the computer capabilities has allowed for modeling impact cratering with an increasing degree in complexity and realism in high resolution 2D cylindrically symmetric simulations and make now even full 3D simulations possible (Benz and Asphaug, 1994; Jutzi et al., 2008, 2009; Pierazzo and Collins, 2004).

In contrast to previous approaches using the SPH (Smooth Particle Hydrocode) technique (Benz and Asphaug, 1994; Jutzi et al., 2008, 2009), we adopted the iSALE (Simplified Arbitrary Lagrangian Eulerian) shock physics code (Amsden et al., 1980; Ivanov et al., 1997; Wünnemann et al., 2006). Although there is a 2D and 3D version of the code available we employed the 2D cylindrically symmetric variant, which limits all our analysis to vertical impacts and to a head-on direct impact geometry. The advantage of Lagrangian–Eulerian hydrocodes over the mesh-free SPH technique is the much more advanced implementation of complex brittle and ductile material models. The yield strength, brittle fracturing and dynamic weakening of rocks substantially affect crater size and morphology and, therefore, play important roles in our modeling. We carried out a large number of simulations varying the unknown material properties inside realistic boundaries until we found a good match between the modeling results and the observed crater morphology. Such an attempt is only feasible for 2D simulations with the available computer resources.