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Properties of craters on the Achaia region of Asteroid (21) Lutetia

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ABSTRACT

We report on the physical properties of the craters of Achaia region of the main-belt Asteroid (21) Lutetia, based on images obtained with the OSIRIS instrument during the Rosetta flyby that took place on 10 July 2010. Images of the surface were acquired with its Narrow Angle Camera, from which Digital Terrain Models (DTM) of the surface were constructed. These DTMs give access to the geometrical properties of the craters of the asteroid. On a complex asteroid shape, slopes and depth-to-diameter ratios (d/D) of craters should be carefully measured taking into account the local topography to obtain a value that is physically related to the work of forces resisting to mass displacement (associated with gravity and/or material strength) occurring in either excavation or degradation processes. We present new measurements of d/D and internal slopes of impact craters of the Achaia region, which offers optimal conditions of observations and a large population of craters. We find that d/D values for Achaia craters differ from previous works on Lutetia and are consistent with the values found on other asteroids such as (243) Ida or (951) Gaspra. The Achaia region may be divided into three units based on geomorphological analysis. The mean d/D values of the three units are different, revealing differences in resurfacing history by impact-related ejecta blanketing and seismic shaking. Some of these geological events may be recent compared to the age of the region since several lineaments intersect most craters of one of the three units. Independent evidence for ejecta blanket have been given for the unit associated with low d/D values confirming the contribution of this process to crater modification. Moreover, we suggest that displacements along faults identified as surface lineaments may have been responsible for the erasure of small craters. Our results are finally integrated into a chronology sequence of events explaining the present characteristics of the Achaia region.

1. Introduction

Since the visit of (951) Gaspra by Galileo (NASA spacecraft) in 1991, ten asteroids have been imaged by a spacecraft, the last one being (4) Vesta in 2011. Asteroid (21) Lutetia is one of them, visited in July 2010 by Rosetta ESA spacecraft on its way to Comet 67P/Churyumov–Gerasimenko. With a mean diameter of about 100 km, Lutetia is more than two times larger than the previously imaged asteroids (Table 1). The global shape of Lutetia was reconstructed from the images (Gaskell et al., 2008; Jorda et al., 2011; Preusker et al., 2012; Capanna et al., 2013) and different surface features such as lineaments, landslides, boulders and impact craters were identified (Küppers et al., 2012; Thomas et al., 2012). Impact cratering is a fundamental process in the Solar System and the main process by which asteroid surfaces are shaped. The morphological properties of these impact craters are the main topic of this paper.

The morphological properties of fresh craters are driven by the impactor and target properties (density, strength, porosity, composition, gravity) and by the impact parameters (impact angle, velocity) (see for instance Melosh, 1989; Holsapple, 1993). However, once created, fresh craters evolve depending upon the events and processes occurring at the asteroid surface. Degradation of impact crater morphologies is associated with mass displacement at the surface due to micro-impacting or seismic shaking, or infilling by ejecta deposits resulting from a neighboring impact (Carr et al., 1994; Richardson et al., 2005; Jutzi et al., 2013). These processes generally lead to a reduction of the depth to diameter ratio,

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hereafter called d/D ratio. This ratio therefore offers an excellent way to quantify the morphological degradation of impact craters. The d/D ratios based on large numbers of impact craters have been systematically calculated for all asteroids where high-resolution images are available (Table 1). The d/D values appear to vary from one asteroid to another but generally remain lower than 0.25, with a lowest mean value of 0.08 for Asteroid (25143) Itokawa (Hirata et al., 2009).

In this paper, we focus on d/D ratios and internal slopes of impact craters of the Achaia region of asteroid Lutetia, with the objective to determine the chronology of events responsible for its present characteristics. This region is considered as the oldest region of Lutetia (Marchi et al., 2012) and as a consequence, presents a high density of craters that gives access to a variety of crater sizes, slopes, and d/D ratios. The images, the Digital Terrain Model (hereafter DTM) and methods are presented in the next section. Results on the morphological properties of craters are presented in Section 3 for the entire Achaia region. Geomorphological units are then defined and crater retention ages for each of these units are given in Section 4. A discussion on the origin of crater degradation is given in Section 5 and is followed by a scenario for the formation of the Achaia region (Section 6).

2. Data and methods

2.1. Images from the Osiris NAC camera and Digital Terrain Model (DTM)

On 10 July 2010, the OSIRIS instrument (Keller et al., 2007) of the Rosetta spacecraft acquired images of the northern hemisphere of (21) Lutetia (Fig. 1). The highest spatial resolution of 60 m/pixel was reached for the images of the Narrow Angle Camera (NAC) obtained from a distance of about 3170 km, at closest approach (Sierks et al., 2011). Geological units have been defined based on density of craters, presence of linear features as well as overlapping and crosscutting relationships (Massironi et al., 2012; Thomas et al., 2012). We study here one of these regions, Achaia, which is the most heavily cratered of all units. The Achaia region is roughly planar and therefore presents the advantage of being uniformly illuminated at a given time (Sierks et al., 2011).

The shape of the northern hemisphere of Lutetia has been reconstructed using a technique called ‘‘stereophotoclinometry’’ (Gaskell et al., 2008; Jorda et al., 2011). The model has a vertical accuracy of about 20 m, i.e., about one-third of the spatial resolution at closest approach. The extraction of local DTMs is performed in three steps: (a) the triangular facets included in a squared region are selected, (b) the coordinates of the vertices are translated and rotated to a local reference frame centered at the center of gravity of the extracted vertices and having its Z-axis parallel to the mean normal of the extracted facets, and (c) the coordinates of the vertices are interpolated on a regular grid using a B-spline interpolation (Renka, 1996). In this study, we use a grid step of 90 m during the extraction, which corresponds to the horizontal sampling of the input shape model.

We selected two squared areas in the Achaia region, labeled ‘‘A’’ and ‘‘B’’, which cover about two-third of its surface (Fig. 1). Note that the method used to select the two regions produced a small overlap between them. An image acquired at closest approach has been projected onto the DTMs of the two areas A and B in order to produce ortho-rectified sub-images of the surface.

2.2. Determination of crater morphological properties: diameter, depth and slopes

On a complex asteroid shape, depth-to-diameter ratios (d/D) and slopes of craters should be carefully measured taking into account the local topography to correctly estimate the work of forces resisting to mass displacement (associated with gravity and/or material strength) occurring in either excavation or degradation processes. A clear description of how these measurements have been undertaken is necessary for comparing results from various authors. Ideally, for a crater excavated in the gravity regime, the depth of the crater should be measured along a direction perpendicular to the plane that is locally tangential to the equipotential surface of gravity. For a crater excavated in the strength regime, the measured depth is related to the volume of material excavated. Depth measurements made perpendicular to a local plane defined by the rim provide a good approximation to these theoretical situations and offers the best conditions for comparing measurements performed by various authors. Craters form on Lutetia most likely in the strength regime (Vincent et al., 2012) so that the above method is the most robust. Therefore, for each crater visually identified on the NAC images, two topographic profiles are extracted: one parallel and one perpendicular to the local topographic slope defined by the crater rim. A rotation of each profile is performed such that the rim endpoints lie on a horizontal line (Fig. 2). In this reference frame, the measured depth is minimal and the rim-to-rim length is maximal. We note that a similar approach has been recently implement in the different context of the larger asteroid Vesta (Vincent et al., in press). The crater diameter is given by $D = \sqrt{ab}$, with a and b the lengths of the two rotated profiles. We first determine the maximum depth independently for the two profiles (Fig. 2) and finally retain the largest of the values.

Finally, we are also interested in the maximum slope inside the crater, which is diagnostic of its state of degradation (Bouley and Baratoux, 2011). We calculate slopes between two successive data points, i.e. every 50 m (Fig. 2), for the two profiles, and retain the maximal value for the crater.

Table 1
Depth-to-diameter ratios (d/D) of craters for several asteroids and the Moon.

Object (dimensions)	d/D	References
Moon	0.2 (fresh craters)	Pike (1974)
Phobos ($27 \times 21 \times 19$ km^3)	0.2 (fresh craters)	Veverka (1978); Shingareva et al. (2008)
(4) Vesta ($560 \times 544 \times 454$ km^3)	0.05–0.35	Vincent et al. (in press)
(21) Lutetia ($126 \times 103 \times 95$ km^3)	0.12 (mean)	Vincent et al. (2012)
	0.15 (mean–Achaia)	Thomas et al. (2012)
(951) Gaspra ($18.2 \times 10.5 \times 8.9$ km^3)	0.14 (freshest craters)	Carr et al. (1994)
(243) Ida ($29.9 \times 12.7 \times 9.3$ km^3)	0.15 (freshest craters)	Sullivan et al. (1996)
(253) Mathilde ($66 \times 48 \times 46$ km^3)	0.12–0.25	Veverka et al. (1999)
(433) Eros ($33 \times 11 \times 11$ km^3)	0.13 ± 0.03 (mean)	Robinson et al. (2002)
	0.16 (mean)	Ernst et al. (2012)
(2867) Steins ($5.7 \times 5 \times 4.6$ km^3)	0.04–0.25	Besse et al. (2012)
(25143) Itokawa ($535 \times 294 \times 209$ m^3)	0.08 ± 0.03 (mean)	Hirata et al. (2009)