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Asteroid (21) Lutetia: Disk-resolved photometric analysis of Baetica region

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ABSTRACT

(21) Lutetia has been visited by Rosetta mission on July 2010 and observed with a phase angle ranging from 0.15° to 156.8°. The Baetica region, located at the north pole has been extensively observed by OSIRIS cameras system. Baetica encompass a region called North Pole Crater Cluster (NPCC), shows a cluster of superposed craters which presents signs of variegation at the small phase angle images. For studying the location, we used 187 images distributed throughout 14 filter recorded by the NAC (Narrow Angle Camera) and WAC (Wide Angle Camera) of the OSIRIS system on-board Rosetta taken during the fly-by. Then, we photometrically modeled the region using Minnaert disk-function and Akimov phase function to obtain a resolved spectral slope map at phase angles of 5° and 20°. We observed a dichotomy between Gallicum and Danuvius-Sarnus Labes in the NPCC, but no significant phase reddening ($-0.04 \pm 0.045\%\ \mu m^{-1}\ deg^{-1}$). In the next step, we applied the Hapke (Hapke, B. [2008]. Icarus 195, 918–926; Hapke, B. [2012]. Theory of Reflectance and Emittance Spectroscopy, second ed. Cambridge University Press) model for the NAC F82+F22 (649.2 nm), WAC F13 (375 nm) and WAC F17 (631.6 nm) and we obtained normal albedo maps and Hapke parameter maps for NAC F82+F22. On Baetica, at 649.2 nm, the geometric albedo is 0.205 ± 0.005, the average single-scattering albedo is 0.181 ± 0.005, the average asymmetric factor is -0.342 ± 0.003, the average shadow-hiding opposition effect amplitude and width are 0.824 ± 0.002 and 0.040 ± 0.0007, the average roughness slope is $11.45^\circ \pm 3^\circ$ and the average porosity is 0.85 ± 0.002. We are unable to confirm the presence of coherent-backscattering mechanism. In the NPCC, the normal albedo variegation among the craters walls reach 8% brighter for Gallicum Labes and 2% fainter for Danuvius Labes. The Hapke parameter maps also show a dichotomy at the opposition effect coefficients, single-scattering albedo and asymmetric factor, that may be attributed to the maturation degree of the regolith or to compositonal variation. In addition, we compared the Hapke (Hapke, B. [2008]. Icarus 195, 918–926; Hapke, B. [2012]. Theory of Reflectance and Emittance Spectroscopy, second ed. Cambridge University Press) and Hapke (Hapke, B. [1993]. Theory of Reflectance and Emittance Spectroscopy) parameters with laboratory samples and other small Solar System bodies visited by space missions.

1. Introduction

The Asteroid (21) Lutetia was observed during a flyby by Rosetta mission on July 10th, 2010. Rosetta is an ESA cornerstone mission, launched on March 2nd, 2004, composed of two elements: the Orbiter and the lander Philae, with the aim to visit the Comet 67P/Churyumov-Gerasimenko. Rosetta spacecraft reached the comet from the heliocentric distance of about 4 AU to start the characterization of the nucleus prior to the delivery of the Philae lander (November 12, 2014) and followed it until its perihelion passage in August 2015 with the end of extended mission on September 2016.

The final choice of the targets (21) Lutetia and (2867) Steins (Barucci et al., 2005) was made only after the launch of the mission and the first orbital correction manoeuvre. The two asteroids have been selected for their high scientific return and Lutetia in particular because of its large size which was expected to lead to accurate mass and density determinations.

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Several instruments were active, resulting into acquiring images and spectrometric observations from the ultraviolet (70 nm, by ALICE UV spectrometer) through the visible (by OSIRIS imaging system) and infrared (by the VIRTIS imaging spectrometer) to the millimeter range (0.5–1.3 mm by the MIRO microwave spectrometer), and the radio science investigation (see Barucci et al., 2015, for detailed results).

The Rosetta spacecraft flew by (21) Lutetia obtaining resolved images for about 10 h before the closest approach and revealing an object with a highly complex history. The OSIRIS camera systems (Keller et al., 2007) composed of two cameras (NAC, Narrow Angle Camera and WAC, Wide Angle Camera) observed the asteroid (Sierks et al., 2011) in 21 broad and narrow band filters covering more than 50% of the surface with spatial scales up to 60 m/pixel. The rotational period of 8.168 h and direction of the pole axis were improved (Carry et al., 2010). The global shape with principal axes dimensions of 121 ± 1 km $\times$ 101 ± 1 km $\times$ 75 ± 13 km was determined (Sierks et al., 2011), even if a large fraction of the asteroid's southern hemisphere was not visible during the fly-by and consequently the shortest semi-major dimension is not well constrained. From the shape model, an estimation of volume of $(5.0 \pm 0.4) \cdot 10^5$ km^3 has been derived and combining it with the mass obtained by the Radio science investigation $1.7 \cdot 10^{18}$ kg $\pm$ 1 by Pätzold et al. (2011) a bulk density of 3.4 ± 0.3 g cm^{-3} has been computed.

The north pole is located near a depression that has been produced by multiple impacts called NPCC (North Polar Crater Clusters). The north rotational pole was roughly pointed towards the Sun at the time of the Rosetta encounter and hence high-resolution imaging was restricted by the illumination to one hemisphere. (21) Lutetia shows to have geological complex surface dominate by impact craters, landslides and a diversity set of lineaments (see Thomas et al., 2012, for detailed description). The largest visible depression is the Massilia structure, which is a highly degraded crater-like structure of 57 km diameter. The surface shows a remarkable structure with boulders and landslides. Its rim appears to have been modified by subsequent impacts. Another dominant feature is the NPCC itself, which forms the most striking structure within the Baetica region. This appears to be one of the youngest surfaces on the object and results of several impacts of varying size, which have overlapped each other.

The relatively low density of smaller impact craters within the NPCC contrasts sharply with the high crater density seen in other regions. Marchi et al. (2012) studied the crater distribution and estimate the age for different regions on Lutetia. Significant amounts of ejecta were also observed on the far side of the impact crater. Detailed results on Lutetia surface characterization are reported and discussed by Barucci et al. (2015).

In this paper we analyze the Baetica region (Fig. 1.1) as observed by the OSIRIS camera. We apply empirical and theoretical photometric analysis to derive the spectral slope map and semi-physical parameters of the surface. All analysis is done in disk-resolved scale. The region is our main focus of interest due to the identification of some talus of bright material coming down though one of the walls of the NPCC at the small phase angle images (Schulz et al., 2012; Magrin et al., 2012; Thomas et al., 2012), moreover it is the only one to be most extensively covered during all fly-by. Therefore, we are interest to investigate possible space weathering processes (Gaffey, 2010), and for this purpose, we analyze real variegation and parametric variations among Gades, Corduba and surrounding areas.

(21) Lutetia has been observed with a phase angle ranging from 0.15° to 156.85°, a varying resolution of 0.375 km/pixel to 0.059 km/pixel and limited incidence angle conditions due the fast fly-by of about 15 km/s. Only a photometric modeling covering all

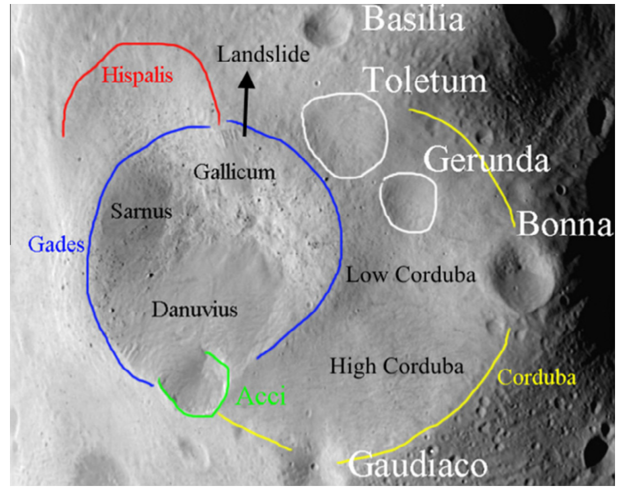

Fig. 1.1. The geomorphological units of the Baetica Region reproduced from Thomas et al. (2012). Sarnus Labes, Gallicum Labes, Danuvius Labes are the major landslides on NPCC. Gades has diameter 21 km, Corduba – 34 km, Hispalis – 14 km, and Acci – 6 km. On Corduba, we have separated the labeling in the Lowland and Highland according to the topographical slope (we reference Fig. 4 in Marchi et al., 2012 for a topographical map).

aspects of the phase curve of an atmosphereless body may provide complete analysis of the (21) Lutetia surface. The main aspect is the opposition effect, a non-linear increase in brightness when the phase angles approaches zero degrees, observed in asteroids for the first time by Gehrels (1956). This has been studied for the connection with two important optical mechanisms of particulate media: The shadow-hiding (e.g., Hapke, 1981; Lumme et al., 1990; Stankevich et al., 1999) and the coherent-backscattering enhancement (e.g., Muinonen, 1994,; Mishchenko et al., 2009). The former is related to the disappearance of mutual shadows among the regolith particles when opposition is near. The latter happens when the multiple scattered electromagnetic waves constructively interfere at near zero phase angle. Those mechanisms are intrinsically connected to regolith packing, size distribution, particle shape, inclusions and transparency in a complex relation that it is still subject of on-going research (e.g., Muinonen et al., 2012; Déau et al., 2013). Other aspect is the macroscopic shadowing, a mechanism often significant when a surface is observed at phase angle larger than about 30° and when illumination azimuth is higher. Generally, boulders, micro-craters or micro-irregularities are evoked to explain the hindering of brightness due to the casting of large shadows (Hapke, 1984; Goguen et al., 2010; Shkuratov et al., 2012).

Previous studies on disk-resolved small Solar System bodies have basically relied on a class of models based on Radiative Transfer Equation (RTE) to retrieve semi-physical parameters related to those mechanisms. The Hapke (1981, 1993, 2002, 2008, 2012) models have been the most widespread among the treatment of spacecraft data of atmosphereless bodies of the Solar System. (433) Eros, orbited by NEAR Shoemaker (Clark et al., 2002), Phobos and Deimos, visited by Viking Orbiter (Thomas et al., 1996; Simonelli et al., 1998) and (25143) Itokawa, orbited by Hayabusa (Kitazato et al., 2008) and (4) Vesta, orbited by Dawn (Li et al., 2013b), are examples of small bodies which had their global Hapke parameters obtained. However, only recently, efforts have been taken to derive a spatially resolved Hapke parameters out of disk-resolved data (Spjuth et al., 2012; Sato et al., 2014).

Moving further from the RTE models, there is a class of empirical models that decouples the reflectance dependence of phase angles, the phase function, from the gradient behavior due to local