Icarus 226 (2013) 89–100

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

The influence of recent major crater impacts on the surrounding surfaces of (21) Lutetia

M. Jutzi [a], N. Thomas [a,*], W. Benz [a], M.R. El Maarry [a], L. Jorda [b], E. Kührt [c], F. Preusker [c]

[a] Physikalisches Institut, University of Bern, Sidlerstr. 5, CH-3012 Bern, Switzerland
[b] Laboratoire d'Astrophysique de Marseille, 38 rue Frédéric Joliot-Curie, 13388 Marseille, France
[c] DLR, Institute of Planetary Research, Rutherfordstr. 4, Berlin-Adlershof, Germany

ARTICLE INFO

Article history:
Received 7 January 2013
Revised 4 April 2013
Accepted 14 May 2013
Available online 2 June 2013

Keyword:
Asteroids, surfaces
Impact processes
Cratering
Collisional physics

ABSTRACT

We present 3-D simulations of impacts into Asteroid 21 Lutetia, the subject of a fly-by by the European Space Agency's Rosetta mission to Comet 67P/Churyumov-Gerasimenko. Using a 3-D shape model of the asteroid, impacts of sizes sufficient to reproduce the observed craters in Lutetia's North Polar Crater Cluster (NPCC) as observed by the OSIRIS experiment have been simulated using the Smoothed Particle Hydrodynamics technique. The asteroid itself has been modelled both as a homogeneous body and as a body with an iron core.

Crater erasure in the vicinity of the NPCC has been observed by OSIRIS. The results show that this erasure has most probably been caused by ejecta deposition following the impact of a 2.3 km diameter projectile impacting at a velocity of 5 km s^{-1} (or an impact with similar energy). This would produce a crater of roughly 34 km in diameter comparable to the largest (and oldest) member of the NPCC. Erasure of craters via the shock associated with such an impact is shown to be less significant and does not reproduce the observed spatial distribution of erased craters or "ghost" craters.

Time series of the surface velocity fields resulting from the simulated impacts are also presented. It is suggested that the surface velocity field and velocity shear may play a role in the generation of lineaments. Our model calculations show that the velocity field lines around 50 s after impact exhibit a reasonable qualitative correlation with the orientation of lineaments observed on the entire visible surface of Lutetia. It is also shown that incorporation of a core of 25–30 km in diameter does not modify the velocity field evolution with time and, as such, the presence or otherwise of such a core cannot be inferred from lineament observations if this concept for their formation is valid.

1. Introduction

The European Space Agency's Rosetta spacecraft completed a flyby of the main-belt Asteroid (21) Lutetia on 10 July 2010 at a heliocentric distance of 2.72 AU (Schulz et al., 2012). Lutetia is in the inner main-belt with an orbital semi-major axis of 2.43 AU and an eccentricity of 0.1634 (Keihm et al., 2012). It was originally classified as M-class although its spectral properties are now known to be unusual with some characteristics being more similar to chondritic material (Belskaya et al., 2010; Tosi et al., 2012).

The main imaging system on Rosetta, OSIRIS (Optical, Spectroscopic, and Infrared Remote Imaging System; Keller et al., 2007), acquired a remarkable series of images during the encounter at scales down to 60 m/px. The images have been used to re-construct the global shape models of Lutetia (Preusker et al., 2012; Jorda et al., 2012). These models show a highly irregular shape ($(126 \pm 1) \times (103 \pm 1) \times (95 \pm 13)$ km^3). Using the density derived with the support of the radio science instrument (Pätzold et al., 2007, 2011), the magnitude of the surface gravitational acceleration can be calculated to be $\sim$0.05 m s^{-2} but varies strongly over the surface. The north pole (Carry et al., 2010) is located near a depression which has been produced by multiple impacts – the North Polar Crater Cluster or NPCC (Thomas et al., 2012). Its approximate position is indicated in Fig. 1 together with the prime meridian and the position of the 270°E longitude according to the IAU definition. As a consequence of the high obliquity of Lutetia (96.35°), the sub-solar point was at 47°N at the time of the fly-by (Keihm et al., 2012). Fig. 1 also illustrates the basic regions on Lutetia as defined in Massironi et al. (2012) and Thomas et al. (2012). The reader should note that having a copy of Thomas et al. (2012) available to refer to while reading this paper will probably be necessary because of the frequent references to figures therein.

The relative surface ages of units on the visible surface have been discussed in Marchi et al. (2012), Massironi et al. (2012) and Thomas et al. (2012). The observations show that the NPCC

* Corresponding author. Fax: +41 31 631 4405.
E-mail address: nicolas.thomas@space.unibe.ch (N. Thomas).

0019-1035/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.05.022

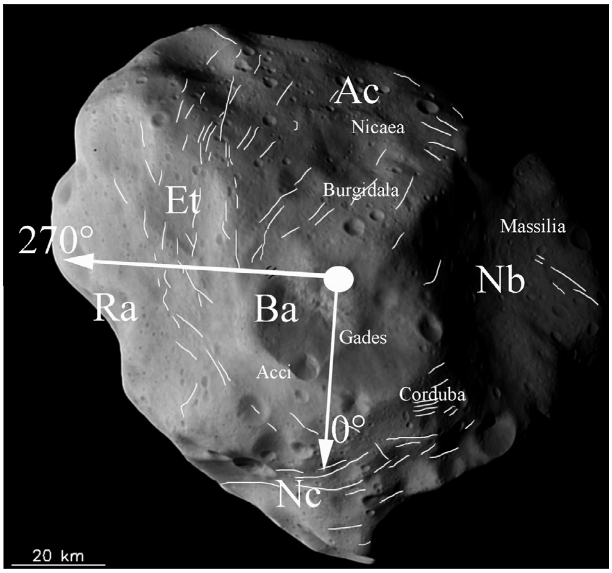

Fig. 1. Image NAC_2010-07-10T15.40.47.674Z_ID30_1251276001_F22 showing the prime meridian, the 270°E longitude, the main regions observed (Ac = Achaia, Nb = Narbonensis, Nc = Noricum, Et = Etruria, Ra = Raetia, Ba = Baetica. Superimposed on the image are lines tracing a few of the visible lineaments. At high resolution, the lineaments are far more numerous, but those shown give a basic impression of their orientation.

must be geologically young. Estimates from the prevalence of boulders within and in the vicinity of the NPCC (Küppers et al., 2012) suggest an age of <300 Ma. The crater statistics suggest even younger ages (<245 Ma; Marchi et al., 2012; their Fig. 8). The NPCC is however composed of several discrete impacts, four of which, named Corduba, Hispalis, Gades and Acci (see Thomas et al., 2012), define the appearance of the NPCC. While the 6 km Acci and 21 km Gades impacts (see Fig. 1) may have been the most recent, the Corduba (34 km) impact was obviously larger and also earlier as witnessed by both the later impact events and evidence of other, now buried, craters within its rim.

One of the most striking features of the OSIRIS images of Lutetia is the prevalence and diversity of lineaments on the surface. Some of the observed lineaments are more than 10 km long but they are very narrow and their depths are mostly below the resolution limit of the digital terrain model (<∼100 m). Lineaments have been observed on several other objects, most notably on the martian moon, Phobos (Thomas et al., 1979), 433 Eros (e.g. Buczkowski et al., 2008), 243 Ida (Sullivan et al., 1996; Asphaug et al., 1996) and 951 Gaspra (Veverka et al., 1994) but were not observed on 253 Mathilde (Veverka et al., 1997). Cassini observations indicate the presence of "grooves" on some small saturnian satellites (Morrison et al., 2009).

There is no accepted mechanism for producing these features on asteroids or small moons although some relationship to impact is widely assumed. In the case of Phobos, for example, the grooves and lineaments are assumed to be the result of the impact which produced Stickney crater (Thomas et al., 1979; Thomas and Veverka, 1979; Prockter et al., 2002) although an alternative view has been presented by Murray et al. (1994). Furthermore, the grooves of Pola Regio on 243 Ida have been linked to the impact that formed Vienna Regio (Asphaug et al., 1996). Hence, it is reasonable to suppose that the observed lineaments on Lutetia may have a similar impact-related origin.

The aim of this paper is two-fold. Firstly, can the relative absence of craters surrounding the NPCC (except for the Noricum region) be explained by an impact which formed one of the elements of the NPCC? Can the ejecta pattern be modelled and can parameters be selected which lead to a reproduction of the basic features of the ejecta blanket seen on Lutetia. In addition, can the more recent units within the Massilia crater be explained by the same phenomenon?

Secondly, can the orientations of lineaments, which are seen over most of the visible surface of Lutetia (Thomas et al., 2012), be a consequence of the same impact? Does the irregular shape of the body naturally lead to the different orientations of the lineaments seen in different regions? We use recent advances in Smoothed Particle Hydrodynamics (SPH) modelling to investigate this possibility.

In Section 2, we review the principal observations that we are seeking to model. In Section 3, we describe the model itself and the basic assumptions we use to construct and initialise the model runs. This is followed by a description of the cases run and the results obtained. This section is split into sub-sections describing the ejecta pattern, the propagation of the shock wave from an impact, and the velocity field. We shall see that many aspects of the observations can indeed be explained by a simple impact. The results also point to possible means of lineament production which we consider to be of major significance for future studies of small bodies.

2. Pertinent observations

Areas surrounding the NPCC appear to be covered (to a greater or lesser extent) with ejecta (Massironi et al., 2012; Thomas et al., 2012). The non-negligible gravitational attraction of Lutetia (Pätzold et al., 2011) implies an escape velocity of $\sim$70 m s^{-1}. Hence, using simple scaling laws (see e.g. http://keith.aa.washington.edu/craterdata/scaling/index.htm; retrieved 18 February 2013), around 75–80% of material excavated in a hyper-velocity impact will fall back onto the surface.

The observed deposition blanket is not symmetric about the impact site – probably because of the irregular shape and gravity field of the object and, possibly, the angle of impact. The boundary between the NPCC (called Baetica in the unit definitions) and the Noricum region is very abrupt (see Thomas et al., 2012; Fig. 6) suggesting that little or no ejecta from any of the NPCC impacts exited in the direction towards 0–40°E. The ejecta are most evident in the direction towards the oldest region, Achaia. In particular, Massironi et al. (2012) have illustrated that the ejecta from the NPCC partially covers the crater Burdigala. In Fig. 2, the area marked 'a' indicates this ejecta deposit although the exact definition of its margin is open to interpretation. The degree of burial of the older Achaia unit by this ejecta led to the inclusion of this region within the Baetica unit by Massironi et al.

As pointed out in Thomas et al. (2012), the Etruria region seems to be devoid of larger craters (Fig. 2). The appearance in general seems very different qualitatively from Achaia. Hence, some resurfacing by ejecta or other processes may well have occurred here too as part of one of the NPCC impact events.

The Nicaea depression forms a younger sub-unit within Achaia (Fig. 1). The structure is not of a regular crater and the depression has an unusual internal crater distribution (Thomas et al., 2012; Fig. 36). Massironi et al. (2012) infer from this that Nicaea is younger than the rest of the Achaia unit but that it is older than the oldest NPCC event. However, an alternative interpretation might be that, although Nicaea formed around the time of the Achaia unit or slightly later, it received a partial coating of ejecta, roughly conforming to the area marked out as region 'b' in Fig. 2, from the NPCC events. A similar explanation may apply to Burgidala (which is suggested to be of similar age; Massironi et al., 2012).

Thomas et al. (2012) noted that there were areas of different surface age within the Massilia crater in the Narbonensis region.