Planetary and Space Science 101 (2014) 186–195

Contents lists available at ScienceDirect

Planetary and Space Science

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

Lutetia's lineaments

S. Besse [a,*], M. Küppers [b], O.S. Barnouin [c], N. Thomas [d], J. Benkhoff [a]

[a] ESA/ESTEC, Keplerlaan 1, Noordwijk, The Netherlands
[b] ESA/ESAC, PO Box 78, 28691 Villanueva de la Cañada, Spain
[c] Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA
[d] Physikalisches Institut, Sidlerstrasse 5, University of Bern, CH-3012 Bern, Switzerland

ARTICLE INFO

Article history:
Received 18 April 2014
Received in revised form
10 July 2014
Accepted 14 July 2014
Available online 30 July 2014

Keywords:
(21) Lutetia
Asteroid
Lineaments
Impact crater

ABSTRACT

The European Space Agency's Rosetta spacecraft flew by asteroid (21) Lutetia on July 10, 2010. Observations through the OSIRIS camera have revealed many geological features. Lineaments are identified on the entire observed surface of the asteroid. Many of these features are concentric around the North Pole Crater Cluster (NPCC). As observed on (433) Eros and (4) Vesta, this analysis of Lutetia assesses whether or not some of the lineaments could be created orthogonally to observed impact craters. The results indicate that the orientation of lineaments on Lutetia's surface could be explained by three impact craters: the Massilia and the NPCC craters observed in the northern hemisphere, and candidate crater Suspicio inferred to be in the southern hemisphere. The latter has not been observed during the Rosetta flyby. Of note, is that the inferred location of the Suspicio impact crater derived from lineaments matches locations where hydrated minerals have been detected from Earth-based observations in the southern hemisphere of Lutetia. Although the presence of these minerals has to be confirmed, this analysis shows that the topography may also have a significant contribution in the modification of the spectral shape and its interpretation. The cross-cutting relationships of craters with lineaments, or between lineaments themselves show that Massilia is the oldest of the three impact feature, the NPCC the youngest, and that the Suspicio impact crater is of intermediate age that is likely occurred closer in time to the Massilia event.

1. Introduction

On 10th July 2010, the Rosetta spacecraft of the European Space Agency successfully flew by the main-belt asteroid (21) Lutetia (Schulz et al., 2012). Numerous observations of its surface were made by remote sensing instruments, revealing its surface properties and composition. Of particular interest were the observations of the OSIRIS (Optical Spectroscopic and Infrared Remote Imaging System) camera (Keller et al., 2007), the main imaging system onboard the orbiter, which revealed numerous geological features on its surface (Sierks et al., 2011). Detailed analysis of the images has shown that the asteroid surface is covered by numerous craters (Vincent et al., 2012) with shallow depth-to-diameter ratios, suggesting that Lutetia may have encountered weathering processes on its surface mostly by impact (Besse et al., 2012; Ernst et al., 2012; Michel et al., 2009; Hirata et al., 2009; Richardson et al., 2005). The large impact craters located at the north pole, also named North Polar Crater Cluster (NPCC), is one of the most interesting features of Lutetia's surface. Küppers et al. (2012) have shown that the boulders' distribution on the surface could be explained by ballistic trajectory of the NPCC impact ejecta. It has been also suggested that NPCC is the source of most of the lineaments visible on the observed surface (Jutzi et al., 2013; Thomas et al., 2012), if it is assumed that lineaments are created by large impacts on a surface.

Lineaments are very common features that have been observed on many previously imaged asteroids. The first direct observation of lineaments was obtained by the Viking missions on the moon Phobos (Thomas et al., 1979). These lineaments extend for several kilometers around the surface, and a lot of them start from the crater Stickney, thus suggesting impact as one of the leading formation mechanisms (Thomas et al., 1978). Lineaments were then observed on asteroids (243) Ida (Sullivan et al., 1996), (951) Gaspra (Veverka et al., 1994), (433) Eros (Prockter et al., 2002; Thomas et al., 2002), (4) Vesta (Buczkowski et al., 2012; Jaumann et al., 2012), and one large lineament was proposed on asteroid (2867) Steins (Keller et al., 2010). Lineaments were also suggested on the surface of asteroids (253) Mathilde (Thomas et al., 1999) and (25,143) Itokawa (Barnouin-Jha et al., 2008). Lineaments have been easily spotted on the surface of asteroid (21) Lutetia given their wide distribution on the surface (Sierks et al., 2011; Thomas et al., 2012).

---

* Corresponding author.
E-mail address: sbesse@rssd.esa.int (S. Besse).

http://dx.doi.org/10.1016/j.pss.2014.07.007
0032-0633/© 2014 Elsevier Ltd. All rights reserved.

The observation of lineaments on asteroids has led to various possible mechanisms explaining their origin. These mechanisms are grouped into 5 main categories: (1) formation by impact (Asphaug et al., 1996; Thomas et al., 1979; Buczkowski et al., 2008) is one of the most accepted scenario for most of the asteroids including Lutetia and consistent with most observations, (2) ejecta coming from impact craters on Mars, as originally proposed by Murray et al. (1994) for Phobos, although this hypothesis has been recently debated (Ramsley and Head, 2013), (3) thermal stress was proposed on Eros to explain the multiple orientation of lineaments (Dombard and Freed, 2002), (4) parent body inherited fabric (Buczkowski et al., 2008; Thomas et al., 2002) also proposed as a viable explanation for the multiple orientations of the lineaments on Eros, and (5) down slope scouring by boulders coming from an impact crater on the object itself was also proposed in the case of Phobos and the Stickney impact (Head and Cintala, 1979). Nevertheless, impact craters are likely the source of most lineaments on asteroids, as seen in many cases. Other mechanisms are less important and have only been shown valid in a very few instances.

On Lutetia, the impact mechanism has been proposed as being the dominant factor that created the lineaments on the surface. In a very detailed study of the surface, Thomas et al. (2012) mapped more than 400 lineaments on the entire visible surface from the OSIRIS camera. Given the preferred orientations of the lineaments, which are often oriented east–west, the authors proposed that the NPCC crater could be the source of most of the lineaments. Thomas et al. (2012) also acknowledge that some lineaments (e.g., mostly in the Narbonensis region) have a different orientation suggesting that not all the lineament orientations could be explained by the NPCC alone. Jutzi et al. (2013) have explored in more detail the hypothesis of impact for the creation of the lineaments by focusing on the NPCC (and its main crater of about 34 km diameter) with numerical simulation of surface deformation. The authors found that velocity field lines after 50 s are reasonably in agreement with the orientation of the lineaments on the surface, thus suggesting that the NPCC could indeed be the impact at the origin of most of the lineaments. These simulations are, in some cases, capable of explaining the various orientations of the lineaments seen by Thomas et al. (2012) with the NPCC impact being the sole source.

In this analysis, we explore the impact mechanism theory in order to complement the study of Thomas et al. (2012), and determine the origin of all the preferred orientations of the lineaments. This analysis is done from an observational point of view using the visible images of the OSIRIS camera. This work relies on the calculation of the pole solution of the lineaments to infer the location of the impact that may have created them. This is only valid if one assumes that the lineaments are created orthogonally from the location of the impact (i.e., or concentric around the impact crater), as opposed to created radially (e.g., Phobos and the crater Stickney). Moreover, although cross-cutting relationship were described in Thomas et al. (2012), a detailed analysis of these relationships in the context of the origin of the lineaments has not been done yet. This work aims at giving a relative age and stratigraphy of the different events that created the lineaments by the study of cross-cutting relationships.

2. Observations and mapping

2.1. Rosetta and OSIRIS observations

The Rosetta spacecraft flew by the asteroid Lutetia at a distance of 3168 km. Observations were taken continuously by the OSIRIS Narrow and Wide Angle Camera (i.e., NAC and WAC) for a period of 2 h (Sierks et al., 2011). These observations have different spatial resolutions, with a pixel scale of 59 m at closest approach (CA) for the NAC. Only images from the NAC are used to map the lineaments in this analysis, with a total of 45 images used. The phase angle varies very rapidly, from 0° 20 min prior to CA, to 80° at CA, and up to 139° for the last image used in this analysis 6 min after CA. The range of phase angles, higher than 30°, is appropriate for mapping geological features such as lineaments. The orange filter (649 nm) is used in this study as no absorption or emission features are expected in this domain. This filter is combined with a neutral filter to diminish the flux of small phase angle imaged before CA. A summary of the images used in this analysis is provided in Table 1. The images with the time of acquisition between 15.40.19 (UT) and 15.46.58 (UT) were the most helpful images for mapping the lineaments.

Analysis of morphological features on a surface is always sensitive to the lighting conditions, and could be subject to bias in their identifications. The images used to map the lineaments have been obtained through a limited period of time (i.e., less than two hours) during which the position of the Sun does not change significantly. At the same time, the spacecraft moves rapidly, dramatically changing the phase angle from 26° to 139° during the ten minutes around CA. However, the movement of the spacecraft is in the plane of the incoming light from the Sun to the surface, thus not changing the perspectives on the surface. As it can be seen in Fig. 1 with the direction of the shadows and in Fig. 2, numerous lineaments are found with directions that are perpendicular or parallel to the direction of the Sun. This is particularly true in the Achaia and Narbonensis regions where cross-cutting lineaments are observed. Thus, the mapping of the lineaments is believed to be robust, and mostly independent of bias from the illumination conditions.

2.2. The Small Body Mapping Tool (SBMT)

To analyze the lineaments and their orientations, the mapping is done using the Small Body Mapping Tool (SBMT) (Kahn et al., 2011).

Table 1
Summary of the images used and their parameters. Although a large number of images are available, the mapping is mostly done on a limited number of images (images 22 to 40). The additional images are used as check-up with different phase angles and resolutions. Images only with the filters F82 or F22, which are combinations of Neutral-Orange and Clear-Orange respectively (see Keller et al., 2007 for details on the filters), are used in this anaysis.

Name	Time of acquisition (UT)	Phase angle (degree)	Resolution (m/pixel)
(1)N20100710T142438992ID20F82	14.24.58	8.58	1354
		↕ 21 images with increasing phase and decreasing resolution	
(22)N20100710T154000819ID20F82	15.40.19	26.40	97
		↕ 12 images with increasing phase and decreasing resolution	
(35)N20100710T154441262ID20F22	15.45.00	80.48	59
		↕ 4 images with increasing phase and resolution	
(40)N20100710T154639204ID20F22	15.46.58	109.2	68
		↕ 4 images with increasing phase and resolution	
(45)N20100710T155039219ID20F22	15.50.58	138.77	118