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Rotational variation of the spectral slope of (21) Lutetia, the second asteroid target of ESA *Rosetta* mission

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ABSTRACT

The ESA *Rosetta* mission, launched in 2004 March, will flyby the second asteroid target (21) Lutetia in 2010 July. This asteroid is quite different from (2867) Steins, encountered by *Rosetta* in 2008 September. Lutetia is in fact a much larger asteroid, approximately 100 km of diameter, as compared to the 5 km of Steins and also its surface composition seems fairly different. A wide international ground-based observational campaign has been carried out and is still going on to obtain information on the object. In this context, we observed Lutetia four times spectroscopically in the visible region totally covering its rotational period. In this paper we have compared all our observations, in order to try to shed more light on its nature. Moreover, an analysis of the geometric configuration of Lutetia during the several observations has also been performed. Our paper points out small variations of reflectance over the surface, possibly due to a large crater. However, the nature of Lutetia remains still elusive, probably because it could be a transition object between X and C taxonomic classes, pointing out to the crucial values of the forthcoming flyby to clarify the situation. Therefore, all the information we have gathered and here discussed have been very useful also to better define the observational strategy of the asteroid by *Rosetta*.

Key words: techniques: spectroscopic – minor planets, asteroids: individual: (21) Lutetia.

1 INTRODUCTION

After the successful encounter with the asteroid (2867) Steins on 2008 September 5, the ESA *Rosetta* mission will flyby the second asteroid target, (21) Lutetia, on 2010 July 10, before the encounter with the main target of the mission, the comet 67P/Churyumov–Gerasimenko in 2014. Lutetia will be encountered at a distance of 3000 km with a relative speed of 15 km s^{-1}. The asteroid has already been observed by *Rosetta* on 2007 January 2 and 3 from a distance of about 1.6 au, and a light curve of the object has been obtained (Faury et al. 2009). Lutetia has been observed far and wide in the last few years, but, in spite of the many things that we know now about it, still its nature has to be defined.

A high albedo seems confirmed; several absorption bands have been found: around 0.43, 0.51 and 3 μm and some similarities with carbonaceous chondrites and enstatite chondrites have been indicated. The taxonomy varies among C, M, X and Xc. Barucci et al. (1987) and Tholen (1989) classified Lutetia as an M-type asteroid because of the high *IRAS* albedo (0.221 ± 0.020). Howell, Merenyi & Lebofsky (1994) and Burbine & Binzel (2002) found an infrared spectrum unusually flat compared to other M asteroids. Rivkin et al. (2000) find the 3-μm absorption band typical of the presence of aqueous altered material [they find that more than 75 per cent of large ($D > 65$ km) M-types are hydrated]. Bus & Binzel (2002) from Small Main-Belt Asteroid Spectroscopic Survey II (SMASSII) data classify Lutetia as a Xk type. Birlan et al. (2004) obtained an almost flat featureless infrared spectrum similar to carbonaceous chondrite spectra, implying a more primitive composition. Busarev, Dorofeeva & Makalkin (2004) found the presence of features around 0.43 μm probably associated to hydrated silicates. Lazzarin et al. (2004) found a feature around 0.43 μm and around 0.51 μm that they attributed to hydrated silicates and/or carbon rich compounds and a spectral behaviour similar to the average C-type asteroids. Mueller, Harris & Delbo (2005) with thermal infrared observations find an albedo = 0.208 ± 0.025. Barucci et al. (2005) find a good match between their visible spectrum plus the near-infrared (NIR) spectrum of Lutetia from Birlan et al. (2004) with the CV3

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carbonaceous chondrite Vigarano. Prokof'eva, Bochkov & Busarev (2005) confirm the band around 0.43 μm. Birlan et al. (2006), with NIR observations, confirmed a similarity with the CV-CO meteorites. Barucci, Fulchignoni & Rossi (2007), with NIR observations, find again a composition compatible with a primitive body. Nedelcu et al. (2007), with NIR spectra (0.8–2.5) at Infrared Telescope Facility (IRTF) and photometric data from Pic du Midi, find no absorption features and a spectral variation with the rotation. A best fit is obtained with a carbonaceous chondrite spectrum for the neutral spectra of Lutetia and with enstatitic chondrite spectra for the redder spectra. Barucci et al. (2008), with IR observations with *Spitzer*, find analogy to carbonaceous chondrite meteorites, in particular to the CO-CV types. Shepard et al. (2008) found a radar albedo not consistent with a largely metallic object, but higher than the mean C-class asteroid, suggesting a higher near-surface bulk density than the typical C-class asteroid. DeMeo et al. (2009) with the new Bus-De Meo taxonomy, based on reflectance spectrum characteristics for 371 asteroids measured over the wavelength range 0.45–2.45 μm, classify Lutetia as a Xc type. Drummond et al. (2009), with adaptive optics at Keck, determined the asteroid's triaxial ellipsoid diameters to be 132 × 101 × 76 km, with uncertainties of 1 km for the equatorial dimensions, and 31 km for the shortest axis; determined that Lutetia's pole lies at 2000.0 coordinates of $\alpha = 48°$, $\delta = +9°$, or ecliptic coordinates of $\lambda = 49°$, $\beta = -8°$, with a formal uncertainty radius of 3°. Lazzarin et al. (2009), with New Technology Telescope (NTT) + ESO Multi-Mode Instrument (EMMI) at European Southern Observatory – La Silla find a behaviour similar to X-type asteroids and three absorption bands probably connected to pyroxenes. Vernazza et al. (2009), with laboratory irradiation experiment, suggest Lutetia as a possible parent body of enstatite chondrite meteorites. Weaver et al. (2009), with UV and visible observations with *Hubble Space Telescope*, confirm a diameter of 95 km and no companions >1 km. They find a far-UV albedo of about 10 per cent, too high for typical C-chondrite material (4 per cent). Carry et al. (2010) and Drummond et al. (2010) computed a new pole solution (ecliptic coordinates of [53°; −7°] ±5°) and rotational period ($P = 8.168\,270 \pm 0.000\,001$) that we will use in our analysis.

All these observations have not yet revealed the compositional nature of Lutetia. In this context, we observed the asteroid in the last few years during four observational campaigns in the visible region. We performed the first observations in 2003 May (Lazzarin et al. 2004), the second in 2004 May (Barucci et al. 2005), the third in 2004 December (Lazzarin et al. 2009) and the last in 2008 November (Perna et al. 2010). In this work, we have performed a comparison among the results obtained during the several observational runs in order to obtain a wider picture of the compositional nature of the asteroid.

2 DATA ANALYSIS AND DISCUSSION

For the comparison we have used: three spectra obtained in 2003 May at ESO (Chile) with the NTT equipped with EMMI spectrograph (Lazzarin et al. 2004), covering the rotational period of Lutetia; a spectrum from Barucci et al. (2005) observed at ESO (Chile) in 2004 May with the NTT+EMMI; a spectrum we obtained in 2004 December at ESO with the NTT+EMMI (Lazzarin et al. 2009); 13 visible spectra obtained in 2008 November at the Telescopio Nazionale Galileo (TNG) equipped with Low Resolution Spectrograph (LRS) covering the rotational period (Perna et al. 2010). More details about the data used are reported in Table 1.

Table 1. List and description of all the sets analysed in this paper. Here we report the telescope and spectrograph used to perform observations; the date and UT of the acquisition are reported together with the time corrected for the One-Way light-time; a short name is also specified to easily distinguish different sets on the paper.

Telescope	Instrument	Obs. date (UT)	Corr. (UT)	Set
ESO-NTT	EMMI	2003 May 06 (01:53)	01:41	set1
ESO-NTT	EMMI	2003 May 06 (04:48)	04:36	set1
ESO-NTT	EMMI	2003 May 06 (07:30)	07:18	set1
ESO-NTT	EMMI	2004 May 26 (10:30)	10:10	set2
ESO-NTT	EMMI	2004 Dec 07 (02:08)	01:56	set3
TNG	LRS	2008 Nov 27 (23:51)	23:39	set4
TNG	LRS	2008 Nov 28 (00:05)	(27) 23:53	set4
TNG	LRS	2008 Nov 28 (01:05)	00:49	set4
TNG	LRS	2008 Nov 28 (01:45)	01:33	set4
TNG	LRS	2008 Nov 28 (02:35)	02:23	set4
TNG	LRS	2008 Nov 28 (03:17)	03:05	set4
TNG	LRS	2008 Nov 28 (04:06)	03:54	set4
TNG	LRS	2008 Nov 28 (04:44)	04:32	set4
TNG	LRS	2008 Nov 29 (22:30)	22:18	set4
TNG	LRS	2008 Nov 29 (23:24)	23:12	set4
TNG	LRS	2008 Nov 29 (23:25)	23:13	set4
TNG	LRS	2008 Nov 30 (00:19)	00:07	set4
TNG	LRS	2008 Nov 30 (01:09)	00:57	set4

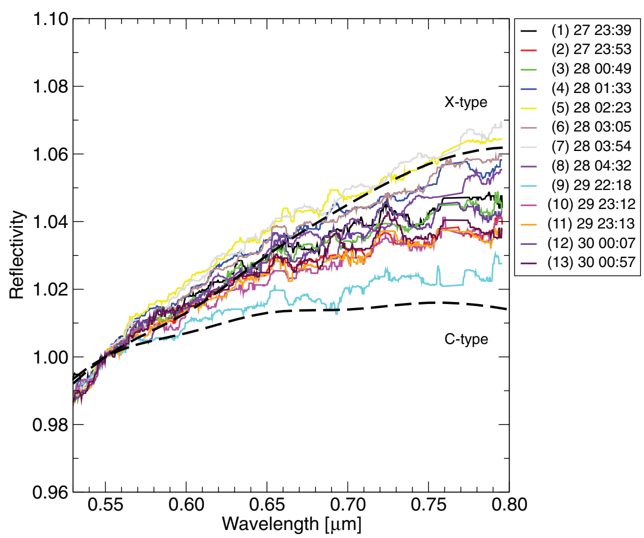

Figure 1. The 13 spectra (set4) by Perna et al. (2010), overfiltered to be able to superimpose them. The C and X Bus mean type (Bus 1999) are also reported.

In Fig. 1 we report the 13 spectra (hereafter set4) obtained on 2008 November 27 and 29 together with the average C-type and X-type of Bus taxonomy. A median filter has been applied to all spectra to remove noise as much as possible in order to better visualize the possible differences among the spectra. The spectra seem all similar and with small differences only for the slope, here computed from 0.55 to 0.80 μm, with a variation from 0.116 ± 0.012 to 0.310 ± 0.013 μm^{-1}. In particular, what we immediately note is that the 13 spectra span the whole region between the two average taxonomic types.

This could justify the different taxonomic classifications of Lutetia proposed till now by several authors.

In Fig. 2 we report for comparison all the sets and the average X-type and C-type.

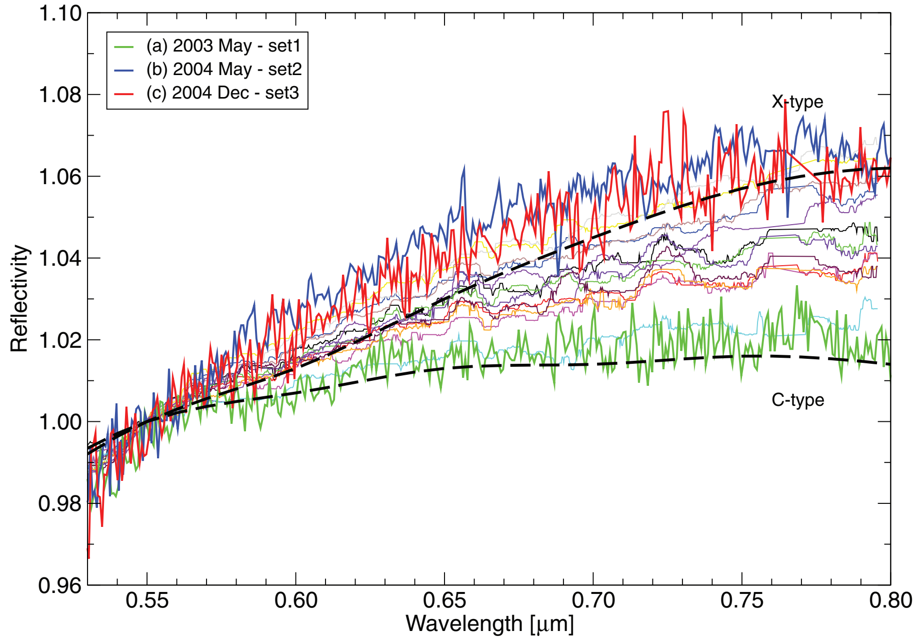

Figure 2. (1) to (13) as described in Fig. 1 legend: set4 – 2008 November (Perna et al. 2010); (a) set1 – 2003 May (Lazzarin et al. 2004); (b) set2 – 2004 May (Barucci et al. 2005); (c) set3 – 2004 December (Lazzarin et al. 2009). The C and X Bus mean type (Bus 1999) are also reported.

In Fig. 2, set1 shows a good match with the average C-type (the three spectra have been averaged as they are indistinguishable), set2 and set3 seem compatible with the average X-type of Bus taxonomy (Bus 1999). The comparison show that they all share the same region, that is, within the uncertainties, they are all included between the average X-type and C-type.

We have then calculated the spectral slopes of the four sets considering the wavelength range from 0.55 to 0.80 µm. In Fig. 3 we report the slopes as function of the time of observation along the rotational period of Lutetia of 8.168270 (Carry et al. 2010) for the 13 spectra of set4. For a better vision we report two rotational periods. The error bars are due to the noise of the non-filtered original spectra, which is of the order of about 5 per cent. Moreover the

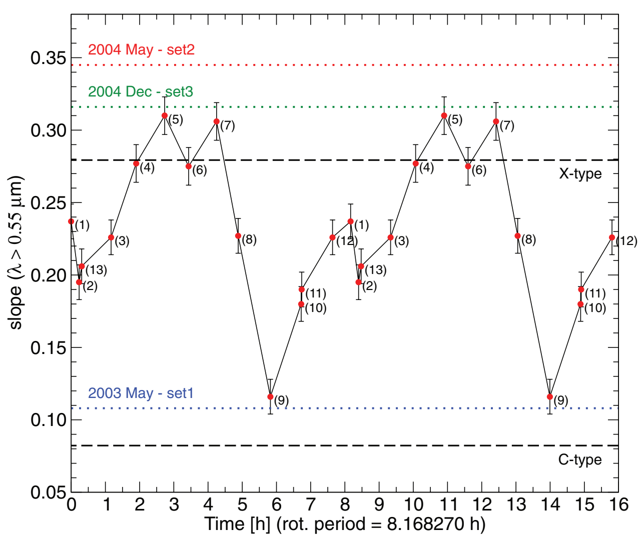

Figure 3. The spectral slope of set4 computed from 0.55 to 0.80 µm versus the rotational period. For simplicity, the zero time was attributed to the first observation. For a better vision we report two rotational periods.

slopes of the other sets and of the average C- and X-types are reported. We have used a shorter spectral range with respect to that present in Perna et al. (2010). This has been necessary in order to avoid the influence of absorption features present in only some of the 18 spectra compared. The spectral slopes of set4 here obtained are slightly different from those reported in Perna et al. (2010), but the general behaviour of the variation with the rotational phase in the two plots is quite similar and consistent.

We have then calculated the geometry of Lutetia as seen from the Earth during the different observations (set1, set2, set3, set4). To do this we have used the rotational period of $8.168\,270 \pm 0.000\,001$ h and the pole solution of $\lambda = 52^\circ, \beta = -6^\circ$ of Carry et al. (2010) and Drummond et al. (2010). Confident on the precision associated to the rotational period, one can compute the longitude of the sub-Earth point with a precision of $\pm 1\overset{\circ}{.}5$ in 4 yr. In Fig. 4 we see the hemisphere of Lutetia (considered as a sphere for simplicity) as seen from the Earth at the moment of the observations.

We have put a feature on the surface of the asteroid to better follow its rotation, but also to simulate the possible presence of a crater which could influence (reduce) the spectral slope [as previously suggested also by Carvano et al. (2008) for the North hemisphere]. The feature has been located in the central part of the 14th configuration of Lutetia (see Fig. 4), which corresponds to the spectrum of set4 (2008 November 29 UT = 22:18) with the lowest slope, the most similar to a C-type. Since the feature has been located far from the pole, its visibility varies with the rotation and so its influence on the spectral slopes.

The first three configurations correspond to the observations of set1 (2003 May), the 4th to set2 (2004 May), the 5th to set3 (2004 December) and from 6th to 18th to set4 (2008 November). The first three observations refer to Lutetia North Pole, while the others refer to Lutetia South Pole. The distinction between the North and the South Pole is due to the solution used ($\lambda = 52^\circ, \beta = -6^\circ$).

The latitude on the surface of the object is reported on the basis of the pole solution used. The division of Lutetia in dark and light grey is a longitude separation useful to better follow the rotation of

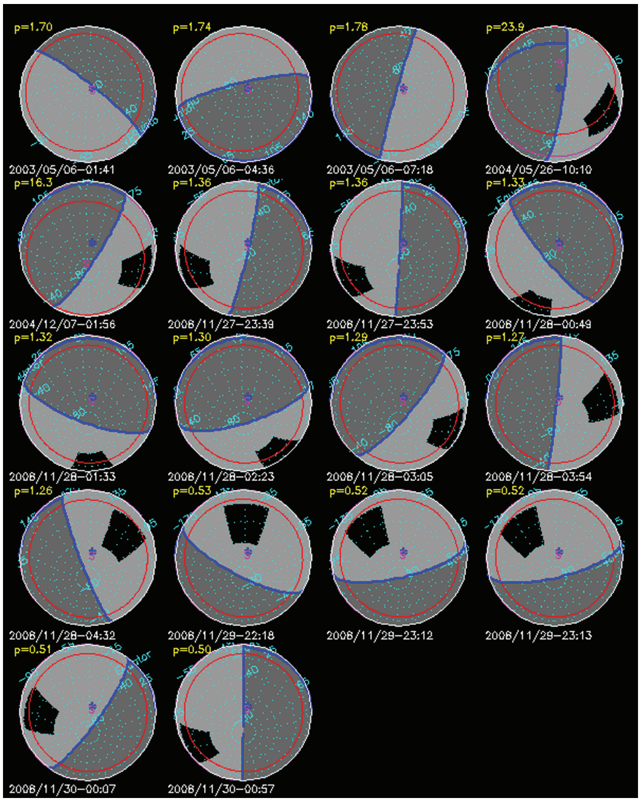

Figure 4. Geometry of Lutetia during the observations. The first three configurations refer to observations performed by Lazzarin et al. (2004) (set1). After that we report the positions relative to observations performed respectively by Barucci et al. (2005) (set2), Lazzarin et al. (2009) (set3) and Perna et al. (2010) (set4). First three positions are related to observations of Lutetia North Pole; last 15 positions refer to Lutetia South Pole.

the asteroid especially for the configurations where the feature is not present. For every position also the phase angle (*p*), the subsolar point (*S*, in pink), the terminator (violet arc), and the sub-Earth point (light blue asterisk) are reported. The subsolar and the sub-Earth point are mostly close together, since the observations of Lutetia were usually made very close to the opposition. For the same reason the terminator is very close to the asteroid border and it is almost never visible.

From Fig. 4 we can note the following.

(1) The spectra of set1 of 2003 May (the C-type) are all very similar. In fact, we are observing over one single pole, 11°.1 from what we define the North Pole, with a phase angle of only 1°.7–1°.8, so we can expect no spectral variations.

(2) The spectrum of set2, 2004 May (X-type), is 42°.2 from the South Pole and the phase angle is about 23°.9.

(3) The spectrum of set3, 2004 December (X-type), is 18°.9 from the South Pole and corresponds to a phase angle of 16°.3.

(4) In the observations of set4, 2008 November (those that span from the average C to the average X-type), the sub-Earth latitude is in the range 17°.2–17°.7 from the South Pole, similar to that of set3. The highest phase angle is of only 1°.36.

(5) Similar configurations show similar spectra: the 15th and 16th configuration (belonging to set4), with a very close observational time, and so, with a similar geometry, show a very similar spectral slope.

(6) The same situation occurs between the 7th and 18th configuration (both within set4 positions), even if they are separated by about 49 h, supporting the accuracy of the spectra observed.

(7) According to the period used and confidence on the error given, the 5th (set3) and the 11th position (set4) show a quite similar geometry, where the hypothetical feature is less visible, and they both correspond to a X-type, high slope, spectrum.

(8) Also 9th and 10th configurations, in which the feature is not much evident, correspond to a X-type spectrum.

(9) The 14th configuration, where we defined the hypothetical feature, corresponds to a spectrum similar to the average C-type.

(10) All the other configurations correspond to intermediate spectra between C- and X-types, with the exception of the 12th configuration, corresponding to a X-type spectral slope, even if the hypothetical feature is quite visible.

(11) Note that the 13th and 15th configurations correspond to spectra different from the 14th configuration, even though the geometries are quite similar.

It is obviously difficult to define the exact influence of a possible feature on the surface of Lutetia as many factors can contribute to the variation of the optical properties of its surface: real surface composition variations, maybe due to an impact crater that can uncover fresh material, different grain sizes, different quantity of regolith due to resurfacing effects, different shadowing during the observations, differences on the pole solutions found in literature, etc.

Although the nature of Lutetia is puzzling and still far to be completely understood, some considerations can be done on the basis of the whole sample of observational data presently available in the literature. A purely metallic composition, firstly supposed on the basis of the *IRAS* albedo, seems to be definitively rejected by the detection of the 3-μm water of hydration band [found by Rivkin et al. (1995) and Birlan et al. (2006)], and the measurement of a radar albedo which is considerably lower than that one of M-type asteroids (Magri et al. 1999).

Geometric albedo and radar measurements are compatible with a surface composition similar to both enstatite chondrites and carbonaceous chondrites. Nevertheless, the similarity with enstatite chondrites becomes doubtful when we consider the mid-IR spectrum of Lutetia (see Barucci et al. 2008 and Lazzarin et al. 2009), and we take into account that Lutetia exhibits aqueously altered materials, while aqueous alteration is a quite improbable process on enstatite chondrites (see e.g. Keil 1989).

Conversely, the agreement with carbonaceous chondrites seems to be more effectively supported by the geometric albedo (see Clark et al. 2009) when we take into account that asteroid albedoes are usually taken at zero phase angle, while meteorite albedoes are measured at larger phase angles depending on the experimental setup. Therefore, based on the phase curve published by Belskaya et al. (2010), for Lutetia an albedo of 0.2 at zero phase angle, corresponds to a value of 0.13–0.14 at phase angle 5° and 4°, respectively.

Also the V+NIR spectral behaviour of Lutetia is quite similar to several carbonaceous chondrite meteorites. Of course, the Lutetia spectra do not exhibit any feature at 1 μm, but in literature there are different carbonaceous chondrites with quite high albedo and no (or weak) feature around 1 μm.

Finally, polarimetric data strongly support a composition similar to carbonaceous chondrites; on the basis of the wide discussion presented by Belskaya et al. (2010), the closest meteoritic analogues of Lutetia surface composition seem to be particular types of CO, CV and CH chondrites.

The analysis of the observations here presented and discussed seems to suggest a composition for Lutetia intermediate between X- and C-types. C-type asteroids are characterized by low albedo (0.02–0.07) and are similar to carbonaceous chondrites, while X-type show typically a higher albedo (0.08–0.5) owing to the more abundance on their surface of metallic materials, but the comparison with meteorites is more uncertain. The two taxonomic classes are not in contrast and Lutetia could actually be a transition object between them. This is supported also by our previous results (Lazzarin et al. 2009) where the spectra of Lutetia show a good match with metal-rich carbonaceous meteorites such as CH chondrites. As previously reported, recently, also Bus and De Meo classify Lutetia as an Xc asteroid, supporting our findings.

3 CONCLUSIONS

In this work we compared visible spectra of Lutetia obtained during different observational runs in order to study possible slope variations of the spectra of the asteroid and to obtain a more general compositional picture. From previous results by different authors we know that it is bright (high albedo) and lacks deep NIR absorption bands, but shows UV-vis bands probably due to silicates. Its geometric albedo is too high for a C-class object, but it is not inconsistent with the possible presence on the asteroid of some carbonaceous material. In particular, we have seen that the spectral-albedo behaviour of Lutetia is well simulated by metal-rich carbonaceous meteorites such as CH chondrites (Lazzarin et al. 2009). Carvano et al. (2008), found a lower albedo on the Northern hemisphere and he attributed this to the possible presence of a big crater on that region. Nedelcu et al. (2007), in the same hemisphere, found spectral variations during the rotation of Lutetia. From our comparison, we obtain a slope variation in the southern region, that could again be explained by the presence of a crater that can lower the spectral slope because it uncovers material more similar to carbonaceous chondrites. This would make Lutetia an object with intermediate properties between C and X taxonomic classes, as recently classified also by Bus and De Meo in their new taxonomy. So, Lutetia continues to be a rather peculiar asteroid and, in spite of all the observations, it has not revealed completely its nature yet. However, all the information on the asteroid gathered up to now has been very useful for defining the observation strategy of Lutetia during the *Rosetta* flyby.

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