21 LUTETIA AS A POSSIBLE BINARY SYSTEM AFTER PHOTOMETRIC, FREQUENCY AND SPECTRAL INVESTIGATIONS

V. V. Busarev(1), V. V. Prokof'eva(2) and V. V. Bochkov(2)

(1) *Sternberg Astronomical Institute (SAI), Moscow University, Universitetskij pr., 13, Moscow, 119992 Russia,* busarev@sai.msu.ru;
(2) *Research Institute Crimean Astrophysical Observatory, p/o Nauchnyi, Crimea, 334413 Ukraine,* prok@crao.crimea.ua

ABSTRACT

We have analyzed spectra (0.4-0.9 μm) of 21 Lutetia, a target of the ROSETTA space mission, and discovered periodic splitting of them on three nights (4/5, 5/6 and 7/8) in November 2004. The effect was confirmed by us on 3/4 March 2006 at a twice aspect angle. We suggested that the asteroid is a close binary system. Extraction of its component reflectance spectra showed considerable variations in their shapes corresponding to C-S-type bodies. It may point to changes in matter content from carbonaceous-chondritic to silicate-metallic materials. This contradicts classification of Lutetia as an M-type asteroid.

The frequency and colorimetric analysis of Lutetia's *BVR*-data obtained in August-November 2000 and November 2004 led us also to conclusions that 21 Lutetia is a close binary system consisting of a pair of similar in size bodies orbiting with the period of ~17^h around a common center of masses. Also, the components probably are in rotation with periods of ~3-4 hours. From the conception it follows that previously determined period of Lutetia's rotation ($8.^h172$) may be actually a half of the supposed period of revolution of its components.

1. SPECTROPHOTOMETRIC AND PHOTOMETRIC DATA

Spectrophotometric (0.37 - 0.74 μm) and photometric (*B, V, R*) observations of 21 Lutetia were carried out in the Crimean Astrophysical Observatory with a 0.5-m meniscus telescope MTM-500 by Bochkov. The system included a digital television facility equipped with an LI804 superisocon television camera tube with an electron–optical preamplifier stage. The analog signal was digitized and summarized on a personal computer. Usually, the information from several hundreds of television pictures was summarized.

A slitless spectrograph with two exchangeable transparent gratings which provided a resolution capability of 40 or 30 Å was used for the spectrophotometric observations [1]. The observations were continued for 14 nights from August 31 to November 20, 2000. For the whole observation period it was obtained 186 original spectra of 21 Lutetia. Its phase angle changed from 2.7° to 23°; the magnitude in the *V*-band, from $9^m.27$ to 11.02; and the aspect angle, from 62° to 68°. A solar analog star, HD10307 [2], was also observed for calculation of the approximate asteroid reflectance spectra. The extra-atmospheric synthetic magnitudes *B, V* and *R* of the asteroid were calculated from the averaged spectra taken out of the atmosphere. The resulting values were recalculated for a unit distance from the Sun and the Earth to the asteroid and for zero phase angle.

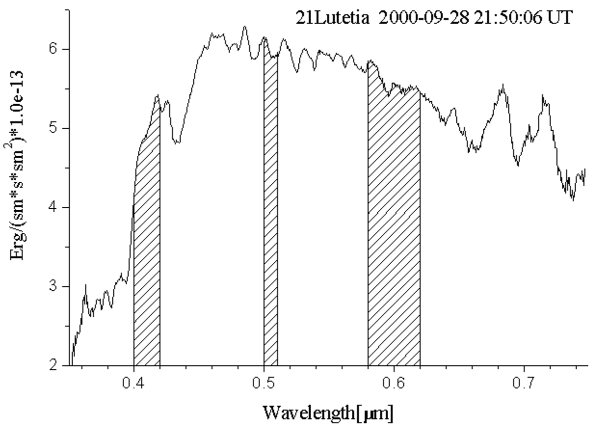


Fig. 1. Positions of three artificial photometric bands in the out-atmosphere spectrum of Lutetia obtained on 28 September 2000 in $21^h\ 50^m\ 06^s$ UT.

To estimate variations in intensity of an absorption band centered at 0.43 μm in the asteroid reflectance spectrum [3-4] characteristic of hydrated silicates [5] we calculated the equivalent width of the absorption band [6] according to the formula (1):

$$W = \sum_{i=1}^{N} (1 - r(\lambda_i))\Delta\lambda , \qquad (1)$$

where W is the equivalent width, $\Delta\lambda$ is the spectral step, $r(\lambda_i)$ are the residual intensities in the spectrum, and N is the number of points in the band. Additionally, to describe an overall shape of Lutetia's blue-visible reflectance spectrum with asteroid rotation we selected artificial bands 0.40-42 μm (1), 0.50-51 μm (2) and 0.58-0.62 μm (3) (Fig. 1) and calculated the synthetic color indexes as Δm_{1-2}, and Δm_{1-3}.

Photometric observations of Lutetia in November 2004 were performed with the same telescope and television facility, but a technique of simultaneous registration of light fluxes in *B*-, *V*- and *R*-bands was used. About 1000 measurements of the asteroid brightness in the bands were made on 3-11 November 2004. For the period, the phase angle of Lutetia changed from 1.6° to 4.9°; and the aspect angle, from 42.85° to 43.18°. The data were taken out of the atmosphere and reduced to a unit distance from the Sun and the Earth to the asteroid and to zero phase angle.

2. FREQUENCY ANALYSIS

Numerous photometric observations showed previously irregular variations in Lutetia's brightness with amplitudes ranging from $0.^{m}1$ to $0.^{m}25$ [7-11].

To elucidate a nature of Lutetia's brightness changes with rotation we analyzed the synthetic (after observations of August-November 2000) and usual (after observations of November 2004) values of *V* and color indexes *B–V* and *V–R* by four methods of frequency analysis (the Breger, Lafler–Kinman, Jurkewich, and Deeming ones) [12]. From the first set of data the frequency analysis of the synthetic values *V*(1, 0) (52 measurements) confirmed a known rotational period of Lutetia $0.^{d}3405$ ($8.^{h}172$) [11] and showed a two-humped light curve with a maximal amplitude of $0.^{m}25$. However, the synthetic color indexes *B–V* (51 measurements) and *V–R* (50 measurements) revealed no noticeable variations with the period [6].

A more precise frequency analysis of a considerably larger second set of *BVR*-data of 2004 year confirmed also absence of the known rotational period of Lutetia in the *B–V* and *V–R* color indexes. Averaging the data over five measurements provided accuracies $\pm 0.^{m}008$ in the values of asteroid brightness and $\pm 0.^{m}005$ in the values of the asteroid color indexes. At the same time, it was found presence of other periods in the *V*–data at a high confidence level of 7-10σ (the accuracy of the estimated value is taken as 1σ). Whitening the most pronounced frequencies in the row of *V*–data allowed to refine periods corresponding to the frequencies as $P_1 = 0.^{d}70$ ($16.^{h}8$)$\pm 0.^{d}01$ and $P_2 = 3.^{d}25 \pm 0.^{d}05$. Both periods yielded a two-hump convolutions with *V*-data at amplitudes $0.^{m}10$ (P_1) and $0.^{m}12$ (P_2). Similar curves were obtained with the periods for *B–V* and *V–R* color indexes (Figs 2 and 3).

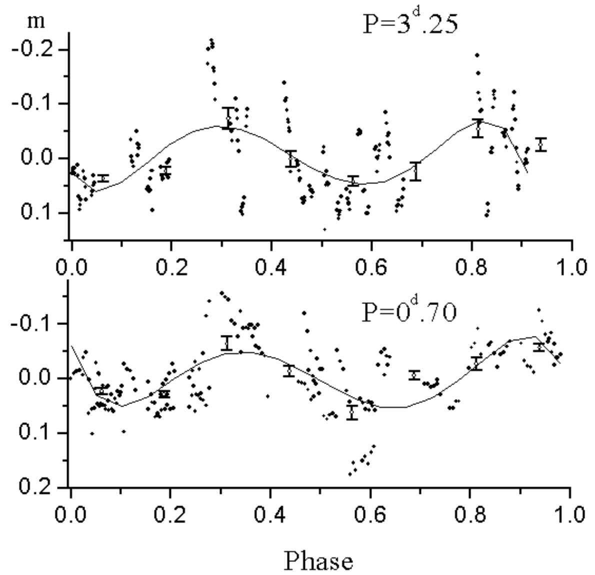


Fig. 2. Light-curves (convolutions) of Lutetia's *V*-values drawn with obtained periods $3.^{d}25$ (the top curve) and $0.^{d}70$ (the bottom curve). Zero-phase is JD2453313^{d}.4232. Points with vertical bars indicate the average brightness in centers of eight phase regions and their accuracy (the curve is a polynomial of 5th degree).

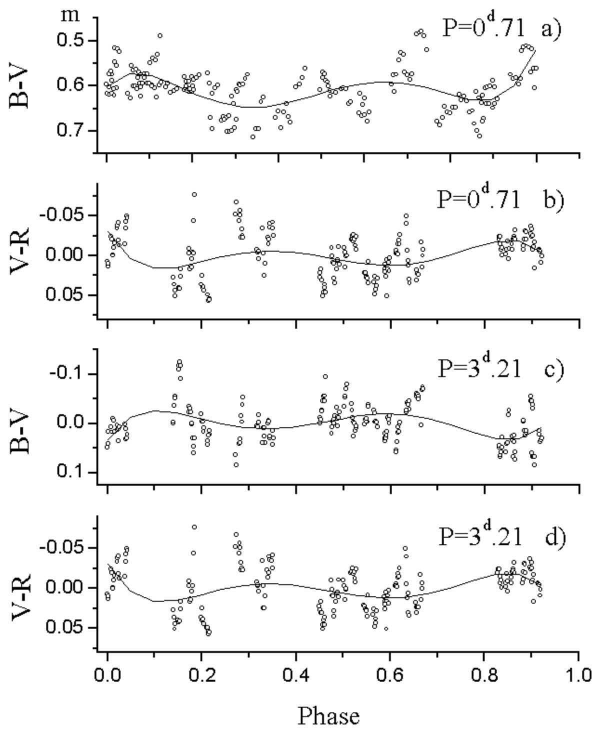


Fig. 3 (a, b, c, d). Phase diagrams (convolutions) of color indexes *B-V* and *V-R* drawn with periods found in the process of whitening. Values of the periods are shown in the pictures.

The *B-V* color indexes of 21 Lutetia (of 2004 year) were also analyzed in the high-frequency range. Two conjugated periods 8.17 c/d (2^h.94) and 9.17 c/d (2^h.62) were found. A 2^h.94-period convolution of the *B-V* color indexes is shown in Fig. 4. It has one maximum, and its amplitude is 0^m.05. Whitening low frequencies in the data led to ratio of its amplitude to its accuracy equal about 7. This indicates a high confidence level of the period existence.

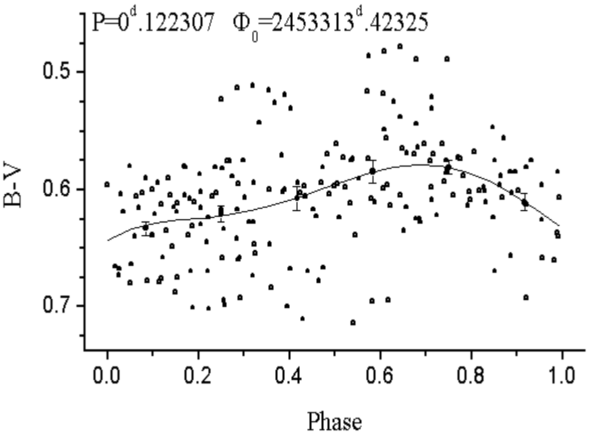


Fig. 4. Phase diagrams (convolutions) of color indexes *B-V* drawn with period P=0.^{d}12231 (2.^{h}94). Zero-phase is JD2453313^d.42325. The approximate curve is a polynomial of 5th degree.

It is interesting that frequencies greater of 5.5 c/d were not found in analyzed *V-R* color indexes. After three times of whitening in the low frequency range, only a 0^m.02-amplitude period of 1^h.8 was found at a low confidence level.

Additionally, we performed the frequency analysis of 40 measurements of the equivalent width of a 0.43-μm absorption band of hydrated silicates in the first set of spectrophotometric data (of 2000 year). It was found eight significant periodic oscillations with frequencies from 6 to 31 c/d. The most pronounced frequencies turned out to be in the range from 11 to 14 c/d [6] and may characterize distribution of phyllosilicate spots on the asteroid surface.

The frequency analysis of the synthetic color indexes Δm_{1-3} and Δm_{1-2} calculated also on the first set of data of 2000 year gave periods P_{1-3}=0.^{d}718 and P_{1-2}= 0.^{d}717 corresponding to the most pronounced variations. The periods are close to each other and to 0.^{d}70-period found from the frequency analysis of *BVR*-data. Whitening frequencies corresponding to the periods from the Δm_{1-2}- and Δm_{1-3}-data allowed to refine oscillations with a shorter period of 0.^{d}1238 (2.^{h}97) in the both series of the synthetic color indexes. (Fig. 5). Convolutions of the synthetic color indexes Δm_{1-3} with periods of 0.^{d}718 and 0.^{d}12375 are presented in Fig. 5. Similar convolutions of the synthetic color indexes Δm_{1-2} with periods of 0.^{d}717 and 0.^{d}124 were obtained.

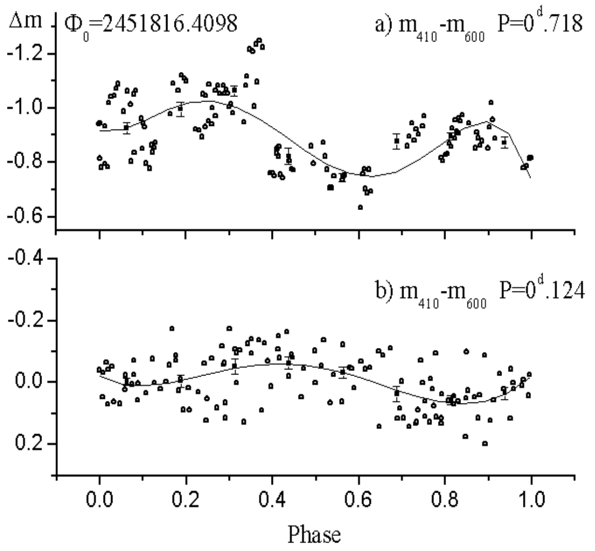


Fig. 5 (a, b). Convolutions of the synthetic color indexes Δm_{1-3}= m_{410}-m_{600} with periods of 0.^{d}718 (a) and 0.^{d}12375 (b) obtained in the process of whitening of the data.

At the same time, the frequency analysis of Δm_{1-2} and Δm_{1-3} synthetic color indexes not confirmed a period equal 3.^{d}20 found in the *BVR*-data.

SPECTRAL DATA

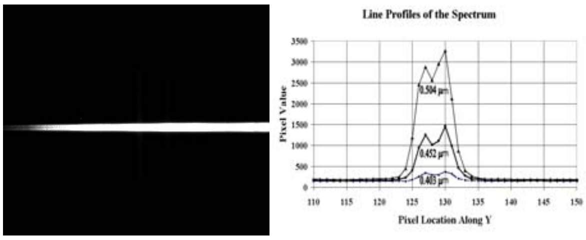
Spectral observations of 21 Lutetia were performed by Busarev on 31 August 2000 and 4-8 November 2004 with a spectrograph and ST-6 SBIG CCD mounted on the 1.25-m telescope of the SAI Crimean observatory. The data were reduced in a standard way. "Blue-visible" (0.40-0.68 μm) and "visible-red" (0.63-0.90 μm) parts of the spectra were observed separately at no more than a ten-minute interval. Relative statistical errors of the spectra do not exceed 1-2% within the 0.45-0.80 μm wavelength range and grow up to 8% and 3% at "blue" and "red" ends. A solar analog star, 16 Cyg B [13], was also observed for calculation of the approximate asteroid reflectance spectra. The original reflectance spectra with the spectral dispersion of about 8 Å/pix were smoothed with a 5-point running box average and normalized to unity at 0.55 μm. The weather conditions in November 2004 were not perfect but better on 5/6 November. The spectra obtained on 5/6 and 7/8 November at favorably small aspect (~43°) and phase (~3°) angles of the asteroid are shown in Figs. 6-10.

The observations of Lutetia on 4-8 November 2004 became a sensation. It was discovered a subtle splitting of the asteroid spectra into two at about 1-2-hour interval. The effect was registered on three nights in November 2004 (4/5, 5/6 and 7/8) and confirmed on 4/5 March 2006 at a considerably bigger aspect angle

(~83°) in a longer interval of time. This means that images of two close objects instead of one were observed at the moments on the spectrograph slit. We suppose that no other instrumental, atmospheric or celestial factors could cause the periodic splitting of Lutetia's spectrum. We have made an assumption that the asteroid is a close binary system probably consisting of about similar in size components.

Examples of the most clear splitting of Lutetia's spectra on 5/6 and 7/8 November 2004 in the 0.40-0.68 μm and 0.63-0.90 μm regions and the line profiles of the spectra at several wavelengthes are shown in Fig. 6.

(a)



(b)

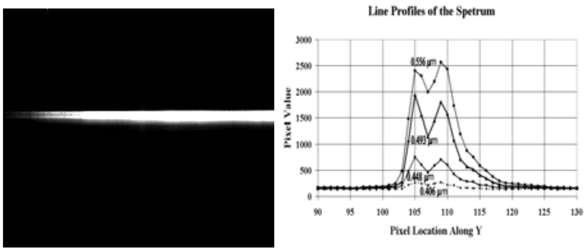


Fig. 6 (a, b). Examples of splitting of Lutetia's spectra obtained on 5/6 November 2004 and 7/8 November 2004: (a) the blue-visible spectrum of Lutetia obtained on 5/6 November 2004 (01:05:33 UT) and its line profiles along Y axis at 0.403, 0.452 and 0.504 μm; (b) the blue-visible spectrum of Lutetia obtained on 7/8 November 2004 (22:40:36 UT) and its line profiles along Y axis at 0.406, 0.448, 0.493 and 0.556 μm.

From seeing conditions on the nights (~2-3 arc seconds and, hence, the same width of a single spectrum) we estimated splitting of Lutetia's spectra as <1". From the line profiles (Fig. 6), the level of splitting is relatively far from the background and may correspond to a 3-4 times lesser arc distance between the asteroid components than the width of a single spectrum.

Table 1. Time (UT) of spectral observations (Figs 7-10).

N of spectrum	Date	Time (UT, hms)
21	5 November 2004	01 00 00
21-1	5 November 2004	01 05 33
21-2	5 November 2004	01 05 33
21-1-1	5 November 2004	01 05 33
21-1-2	5 November 2004	01 12 30
21-2-1	5 November 2004	01 05 33
21-2-2	5 November 2004	01 12 30
21-1-1	7 November 2004	22 21 38
21-1-2	7 November 2004	22 27 56
21-1-3	7 November 2004	22 34 36
21-1-4	7 November 2004	22 40 36
21-2-1	7 November 2004	22 21 38
21-2-2	7 November 2004	22 27 56
21-2-3	7 November 2004	22 34 36
21-2-4	7 November 2004	22 40 36

Note: The time corresponds to the middle of each exposition (300s).

We have preliminary designated a slightly brighter (and possibly bigger) component as 21-1 and a fainter (and possibly smaller) one as 21-2. From the forked spectra of Lutetia (Table 1) we extracted spectra of both components and calculated the reflectance spectra presented in Figs 7-10. As seen from the figs, shape of the reflectance spectra is changing quickly with time (and with rotation of the components) and is similar to bodies of C- or S-types at different moments. Interestingly, when the spectral splitting was not observed, Lutetia's integral reflectance spectrum was similar to that of an M-asteroid (curve 21, Fig. 7).

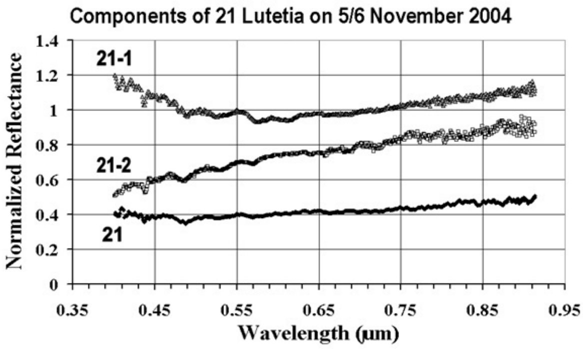


Fig. 7. Reflectance spectra of components of 21 Lutetia (21-1 – a brighter (bigger?) one; 21-2 – a fainter (smaller?) one on 5/6 November 2004. The spectra are normalized to unity at 0.55 μm and shifted on the vertical axis for clarity. Curve 21 is an integral reflectance spectrum of Lutetia when the splitting was not observed.

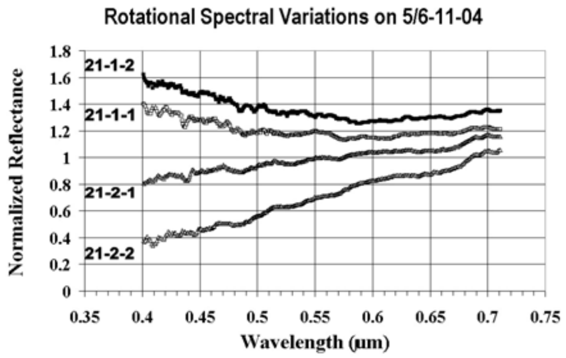


Fig. 8. Reflectance spectra of the components of 21 Lutetia in the blue-visible region obtained at the 10-minute intervals on 5/6 November 2004 (21-1-1and 21-1-2 – a brighter (bigger?) one; 21-2-1 and 21-2-2 – a fainter (smaller?) one.

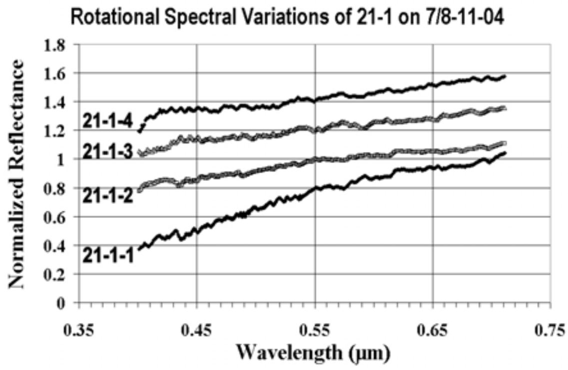


Fig. 9. Consecutive reflectance spectra of a brighter (bigger?) component of 21 Lutetia in the blue-visible region obtained at the 10-minute intervals on 7/8 November 2004.

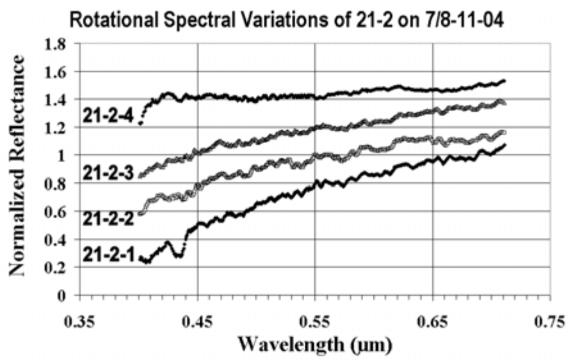


Fig. 10. Consecutive reflectance spectra of a fainter (smaller?) component of 21 Lutetia in the blue-visible region obtained at the 10-minute intervals on 7/8 November 2004.

3. DISCUSSION AND CONCLUSIONS

We have paid a special attention to 21 Lutetia for unusual photometric and spectral properties. For the present, it is considered as an M-type asteroid according to well-known taxonomic classifications [14]. Relying on relatively high albedo (0.22) [15] and a shape of integral spectrum of the asteroid, we have concluded previously [4] about its M-type. From our data obtained in 2000, the synthetic *B–V* color indexes range from $0.^{m}63$ to $0.^{m}80$; their mean value of $0.^{m}715$ is rather close to the value $0.^{m}73$, typical of the M asteroid spectral type. At the same time, the synthetic *V–R* color indexes range from $0.^{m}02$ to $0.^{m}27$ with a mean value of $0.^{m}17$, while a value calculated from an average M-type asteroid spectrum [14] is $0.^{m}23$. This more low value agrees with our finds in Lutetia's reflectance spectra absorption bands characteristic of hydrated silicates of a serpentine-chlorite-type [4]. Frequency analysis allowed us to establish uneven distribution of the silicates on the asteroid surface. We estimated a typical size of hydrosilicate spots on the asteroid surface as 30–40 km (taking into account a known 96-100-km size of the asteroid [15]).

Binarity of 21 Lutetia was first suggested on the basis of the frequency analysis of its *BVR*-data of November 2004 [16]. According to the analysis, the most pronounced periods of variations in the *V*-, *B*-*V*- and *V*-*R*-values are $0.^{d}70$ (16.8^{h}) and $3^{d}.20$. We consider the first one as an orbital period of the asteroid components around the common center of masses whereas the second as a period of precession of the system. From these suppositions we came to a conclusion that the previously known period of $0.^{d}3405$ ($8.^{h}172$) was taken by mistake for a rotational period of Lutetia, and it is actually a half of the found orbital period of the asteroid components $0.^{d}70$ ($16.^{h}8$). As mentioned before, the $8.^{h}172$-period is not confirmed by our *B–V* and *V–R* color data. If we take into consideration the conception, a periodic 1-2-hour splitting of Lutetia's reflectance spectrum could be explained as a result of synchronous rotation of irregular in shape asteroid components with a period of 3-4 hours. This may happen when the line connecting centers of the bodies is perpendicular to the line of sight. Probably, the interpretation is confirmed by the found $0.^{d}1238$ ($2.^{h}97$) period of oscillations in the synthetic color indexes $\Delta m_{1\text{-}2}$ and $\Delta m_{1\text{-}3}$ characterizing changes in the asteroid reflectance spectrum and by a close $0.^{d}1223$ ($2.^{h}94$) period in the *B*-*V* color indexes. The discovered <1" splitting of the asteroid spectra may correspond to <1000-km distance between its components (at semi-major axis *a*= 2,4369 AU of Lutetia's orbit). However, we understand that the estimated distance was restricted by our seeing conditions. Actually, the distance may be several times lesser.

Further, from the obtained reflectance spectra of Lutetia's components (Figs. 7-10) we found that their shape changes quickly with rotation of the bodies and is similar to those of C-S type asteroids at different moments. It is possible that the components are conglomerates of materials with very different content (from hydrated silicates, the main component of carbonaceous chondrites, to igneous silicates and/or metals [17]).

In the framework of the current paradigm about nature of M- and S-type asteroids (e. g., [18]), 21 Lutetia may be a nucleus (or an internal part) of a differentiated parent body disrupted under strong collisions with other objects. For instance, those might have been bodies with a more primitive content ejected by Jupiter from its growth zone [19]. Such scenario could explain the co-existence of non-uniform materials in Lutetia's system. A non-monolithic internal structure of the asteroid also follows from the possible asteroid shock origin. In case of strong subsequent collision(s) the asteroid could have experienced fragmentation and separation into two or more parts presently observed.

Thus, we suggest that 21 Lutetia is a close binary system. Taking into account a similar intensity of its components' spectra (Fig. 6), the bodies may have approximately equal size (probably, ~60-70-km diameter basing on the radiometric diameter 96-100 km of the asteroid of [15]) and orbit around a common center of masses with a period of $\sim 17^h$. At the same time, the components are probably seen always in a visual contact under observations from the earth. For the reason, we could not observe more considerable changes in the integral brightness of the system than $0.^m25$, even in the case of mutual eclipses of the components. Probably, a periodic splitting Lutetia's reflectance spectrum points to the fact of physical separation of the components and their irregular shape changing the extent of the visual contact with their rotation. From our frequency analysis, the both components probably are in rotation with periods of ~3-4 hours. On the whole, the system may have a precession with the period of $\sim 3^d$.

We would recommend to investigate thoroughly Lutetia's system for instance with the Hubble Space Telescope since there is a possibility of existence in the system of smaller bodies having sizes lower of resolution of the earth-based telescopes. The smaller bodies may be hazardous to the ROSETTA spacecraft at the moment of its close approach to the asteroid in 2010 year.

4. REFERENCES

[1] Bochkov V.V., et al., Spectrophotometric observations of M-, S- and E- asteroids in the Sternberg Astronomical Institute and the Crimean Astrophysical Observatory, *ASTRON. ASTROPHYS. TRANS.*, Vol. 22, 621–624, 2003. [2] Busarev V.V., Spectrophotometry of atmosphereless celestial bodies of the solar system, *SOLAR SYS. RES.*, Vol. 33, 120-129, 1999. [3] Busarev V. V., Oxidized and hydrated silicates on M- and S- asteroids: spectral indications, *Lunar Planet. Sci. Conf. XXXII*, abstr. #1927, 2001. [4] Busarev V. V., et al., Characterizing 21 Lutetia with its reflectance spectra, in *The new ROSETTA targets* /L. Colangeli et al., eds., Kluwer Acad. Publishers, 79-83, 2004. [5] Busarev V. V., et al., Possible spectral signs of serpentines and chlorites in reflectance spectra of celestial solid bodies, *Vernadsky Inst. - Brown Univ. Microsimp. 40th.*, Moscow, abstr. #15, 2004. [6] Prokof'eva V. V., et al., The surface structure of the M-type asteroid 21 Lutetia: Spectral and frequency analysis, *SOLAR SYS. RES.*, Vol. 39, 410-420, 2005. [7] Lupishko D.F. and Velichko F.P., The direction of rotation of asteroids 21, 63, 216, and 349, *KINEMATIKA FIZ. NEBESNYKH TEL*, Vol. 3, No. 1, 57–65, 1987. [8] Lupishko D.F., et al., The pole coordinates and the phase dependence of brightness for asteroid 21 Lutetia, *KINEMATIKA FIZ. NEBESNYKH TEL*, Vol. 3, No. 5, 36–38, 1987. [9] Dotto E., et al., M-type asteroids: Rotational properties of 16 objects, *ASTRON. ASTROPHYS. SUPPL. SER.*, Vol. 95, 195-211, 1992. [10] Michalowski T., Poles, shapes, senses of rotation, and sidereal periods of asteroids, *ICARUS*, Vol. 106, 563–572, 1993. [11] Michalowski T., Pole and shape determination for 12 asteroids, *ICARUS*, Vol. 123, 456–462, 1996. [12] Prokof'eva, V.V., et al., Satellites of asteroids, *PHYS.-USP.*, Vol. 38, 623–649, 1995. [13] Hardorp J., The Sun among the Stars, *ASTRON.& ASTROPH.*, Vol. 91, 221-232, 1980. [14] Tolen D. J. and Barucci M. A., Asteroid taxonomy, in *Asteroids II* /R. P. Binzel et al., eds, Univ. of Arizona Press, Tucson, 298-315, 1989. [15] Tedesko E. F., et al., Three parameter asteroid taxonomy classification, in *Asteroids II* /R. P. Binzel et al., eds, Univ. of Arizona Press, Tucson, 1151-1161, 1989. [16] Prokof'eva V. V., et al., About possible binarity of asteroid 21 Lutetia by analysis of the simultaneous observations in the *BVR*-bands, *SOLAR SYS. RES.*, Vol. 40, 2006, in press. [17] Gaffey M. J., et al., Reflectance spectroscopy and asteroid surface mineralogy, in *Asteroids II* /R. P.Binzel et al., eds, Tucson: Univ. of Arizona Press, 98-127, 1989. [18] Bell J.F., et al., Asteroids: The big picture, in *Asteroids II* /R. P. Binzel, et al., eds, Tucson, Univ. of Arizona Press, 921-945, 1989. [19] Busarev V. V., Hydrated silicates on M-, S-, and E-type asteroids as possible traces of collisions with bodies from the Jupiter growth zone, *SOLAR SYS. RES.*, Vol. 36, 39-47, 2002.