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The Surface Structure of the M-Type Asteroid 21 Lutetia: Spectral and Frequency Analysis

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Abstract—A preliminary study of the surface of the asteroid 21 Lutetia with ground-based methods is of significant importance, because this object is included into the *Rosetta* space mission schedule. From August 31 to November 20, 2000, about 50 spectra of Lutetia and the same number of spectra of the solar analog HD10307 (G2V) and regional standards were obtained with a resolution of 4 and 3 nm at the MTM-500 telescope television system of the Crimean astrophysical observatory. From these data, the synthetic magnitudes of the asteroid in the BRV color system have been obtained, the reflected light fluxes have been determined in absolute units, and its reflectance spectra have been calculated for a range of 370–740 nm. In addition, from the asteroid reflectance spectra obtained at different rotation phases, the values of the equivalent width of the most intensive absorption band centered at 430–440 nm and attributed to hydrosilicates of the serpentine type have been calculated. A frequency analysis of the values $V(1, 0)$ confirmed the rotation period of Lutetia $0.^{d}3405$ ($8.^{h}172$) and showed a two-humped light curve with a maximal amplitude of $0.^{m}25$. The color indices $B–V$ and $V–R$ showed no noticeable variations with this period. A frequency analysis of the equivalent widths of the absorption band of hydrosilicates near 430–440 nm points to the presence of many significant frequencies, mainly from 15 to 20 c/d (c/d is the number of cycles per day), which can be caused by a heterogeneous distribution of hydrated material on the surface of Lutetia. The sizes of these heterogeneities (or spots) on the asteroid surface have been estimated at 3–5 to 70 km with the most frequent value between 30 and 40 km.

INTRODUCTION

On March 2, 2004, the *Rosetta* spacecraft was launched to comet 67P/Churyumov–Gerasimenko from the Kourou space center in French Guiana (http://rosetta.esa.int/science-e/www/area/index.cfm?fareaid=13). The nucleus and the material of the comet will be studied in order to solve the problem of the origin of comets. On its way, the spacecraft is to approach two asteroids: 2867 Steins (September 5, 2008), found by Chernykh in 1969, and a large asteroid called Lutetia (July 10, 2010), discovered by Goldschmidt on November 15, 1852. These asteroids will be examined from a close distance in order to study their global characteristics, dynamic parameters, morphology, and surface composition. It is noteworthy that the instruments and the mission schedule have been being carefully prepared for more than 15 years. Due to its peculiar characteristics, the asteroid 21 Lutetia is one of the most attractive objects for examination within the framework of the *Rosetta* mission. Because of this, preliminary investigations of this asteroid with ground-based astronomical methods are of great interest.

According to the spectral classification by Tholen (1989), the asteroid 21 Lutetia belongs to the spectral class M, its albedo is about 0.22, and its diameter is 96–100 km (Tedesko *et al.*, 1989). It is orbiting along an ellipse with eccentricity $e = 0.163$. The orbit inclination is $i = 3.1°$, which allows the asteroid to be assigned to the plane component of the main asteroid belt (MAB). The semimajor axis of its orbit is 2.4369 AU, which is evidence that the asteroid is in the inner part of the MAB, closer to its center (Bell *et al.*, 1989). The location of the asteroid in the MAB and its spectral type indicate that it passed through the stage of magmatic melting, probably at temperatures from 1000 to 2000°C. The data concerning the determination of the pole coordinates and the semiaxis ratio of the ellipsoid of revolution for the asteroid are discussed by Michalowski (1996) and Lagerkvist *et al.* (1995). Michalowski derived the values a/b = 1.26 and b/c = 1.15, while, in his earlier paper (Michalowski, 1993), he reported b/c = 2.7. The evident uncertainty in the estimate requires further examination.

For an aspect angle of 90° and a zero phase angle, the absolute magnitude of the asteroid 21 Lutetia is $V = 7.^{m}37$ (Michalowski, 1996; Tedesko *et al.*, 1989). Frequent photometric observations showed irregular variations in the asteroid brightness with amplitudes ranging from $0.^{m}1$ to $0.^{m}25$ (Lupishko *et al.*, 1987; Lupishko and Velichko, 1987; Michalowski, 1993; Dotto *et al.*, 1992). The data reported by different authors also show insignificant variations in the period; the most reliable estimate of it is $8.^{h}172$ (Michalowski, 1996).

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The spectral observations of Lutetia performed by Busarev with 1.25-m and 0.6-m telescopes at the Crimean laboratory of the Sternberg Astronomical Institute (Busarev, 2002) and by Bochkov at a 0.5-m telescope of the Crimean Astrophysical Observatory (Bochkov *et al.*, 2003) revealed a noticeable absorption band centered at 430–440 nm in the reflectance spectra of the asteroid. A joint analysis of the reflectance spectra obtained in these studies confirmed the M spectral class of the asteroid (Busarev *et al.*, 2004a). The rather high albedo of the asteroid (0.22) leads to the natural suggestion that its surface material mainly contains high-temperature minerals (of pyroxene and olivine types) with an admixture of metallic iron (Gaffey *et al.*, 1989). However, laboratory examinations of the reflectance spectra of terrestrial hydrosilicate powders show that the 430–440-nm absorption band with a relative intensity of up to 10% and the noticeable depression in the 600–800-nm range observed in the reflectance spectra of this asteroid can be typical of serpentines or a mixture of serpentines with chlorites (Busarev *et al.*, 2004b). This allows us to conclude that serpentized hydrosilicates may also be present on Lutetia's surface. A study of Lutetia's spectrum in the infrared range (1.2–3.5 μm) made by Rivkin *et al.* (2000) showed, at a rather high significance level, that it contains an absorption band at 3 μm, which definitely indicates the presence of aqueous compounds on the asteroid surface. Unfortunately, this band is beyond the spectral range of 0.8–2.5 μm considered by Birlan *et al.* (2003).

The purpose of the present paper is to consider and discuss the results of our spectral observations of the asteroid 21 Lutetia performed from August to November 2000. We made the frequency analysis of the variations in the equivalent width of the 430–440-nm absorption band in the reflectance spectra of the asteroid during its rotation, examined the color characteristics of the solar light scattered by the asteroid, and estimated the sizes of the surface details composed of hydrosilicates.

THE SPECTRA: ACQUISITION AND PROCESSING

Spectrophotometric observations of the asteroid 21 Lutetia were carried out at the Research Institute of the Crimean Astrophysical Observatory with a 0.5-m meniscus telescope MTM-500. 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. We used a slitless spectrograph with two exchangeable transparent gratings with 150 and 200 grooves per millimeter, which provided a resolution capability of 4 and 3 nm, respectively. The high-resolution observations were performed during one night only, namely, on October 1, 2000.

The observations were carried out for 14 nights from August 31 to November 20, 2000. The ecliptic longitude and latitude of the asteroid changed during the observations from 9.6° to 0.6° and from –5°.5 to –3°.8, respectively. More than half of the observations of the asteroid were made for an air mass ranging from 1.5 to 1.8; sometimes, it reached 2.6. For the whole observation period, the phase angle of the asteroid changed from 2.7° to 23°; the magnitude in the *V* band, from $9^m.27$ to $11^m.02$; and the aspect angle, from 62° to 68°. To calculate the aspect angle, the pole coordinates $\lambda = 240°$, $\beta = 37°$ 1950.0 given by Michalowski (1996) were used.

Table 1 presents the aspect data for the asteroid Lutetia for the mean moments of observations for each date in 2000. In the table, there are the distances from the asteroid to the Earth r and to the Sun Δ in astronomical units (the second and third columns), the phase φ and aspect A angles in degrees (the forth and fifth columns), the ecliptic coordinates λ and β for the 1950.0 epoch in degrees (the sixth and seventh columns), and the number of spectral records N obtained for the date considered (the eighth column).

All the spectra were preliminarily processed, i.e., the dark signal, sky background, and nonuniform field sensitivity of the instrument were taken into account. In addition, while smoothing with a rectangular window of a spectral-resolution width, the spectra were calibrated in wavelengths. The spectral data analyzed here were obtained by summarizing from two to seven (depending on the acquisition conditions) recorded spectra. For these averaged spectra, the relative root-mean-square error of the measured intensity varies from 1.4 to 0.6% in a wavelength range of 365–740 nm.

The wavelength scale was determined from the records of the spectrum of a planetary nebula. The accuracy of determining the zero mark of the wavelength scale was 1.2 nm for each spectrum. This value was found from the spectra of the solar analog HD10307 obtained over 20 nights. The same dispersion, equal to 1.2 nm, was obtained for the centers of the 430–440-nm absorption band in the reflectance spectra of Lutetia.

Each averaged spectrum of the asteroid was taken out of the atmosphere by the following formula:

$$R_a = \frac{i_a}{i_s} p_s^{X_s - X_a}, \quad (1)$$

where R_a is the reflectance of the asteroid; i_a and i_s are the intensities measured at a specified wavelength in the spectra of the asteroid and a standard star (a solar analog), respectively; p_s is the transparency coefficient of the atmosphere at the same wavelength; and X_a and X_s are the air masses at which the asteroid and the standard star were observed. For a given observation of the aster-

Table 1. The aspect data and conditions for the spectral observations of the asteroid 21 Lutetia at the Research Institute of the Crimean Astrophysical Observatory in 2000

Month and data of observations in 2000	r, AU	Δ, AU	φ, deg	A, deg	λ, deg (1950.0)	β, deg (1950.0)	N
08 31.98627	1.1334	2.0616	15.2	62	9.64	–5.53	4
09 01.92395	1.1292	2.0623	14.7	62	9.52	–5.56	6
09 28.95692	1.0875	2.0864	02.8	66	4.06	–5.70	7
09 29.97991	1.0892	2.0875	02.9	66	3.82	–5.68	6
10 01.81881	1.0931	2.0894	03.4	66	3.39	–5.65	18
10 05.95846	1.1048	2.0938	05.2	67	2.44	–5.57	29
10 22.87779	1.1935	2.1134	13.4	68	0.55	–5.03	7
10 25.84355	1.2153	2.1171	14.7	68	0.88	–4.91	25
10 29.83873	1.2473	2.1221	16.3	67	1.20	–4.75	10
10 31.82774	1.2643	2.1247	17.1	67	1.32	–4.67	4
11 01.87148	1.2735	2.1261	17.5	67	1.36	–4.62	17
11 17.79744	1.4340	2.1478	22.3	67	0.94	–3.95	11
11 19.80372	1.4565	2.1507	22.7	67	0.75	–3.86	15
11 20.79537	1.4678	2.1521	22.9	67	0.64	–3.82	16

oid, the spectral trend of the atmospheric transparency was determined from the observations of HD10307 made in the same night with the use of an artificial photometric standard.

Examples of the spectra of the asteroid Lutetia obtained in absolute energy units during one night are displayed in Fig. 1. The absorption band centered at λ = 430–440 nm is rather definitely identified in the spectra.

To calculate the equivalent width of the 430–440-nm absorption band from the reflectance spectra of the asteroid, the continuum line was drawn. The equivalent widths were calculated after the spectrum had been normalized with the following formula:

$$W = \sum_{i=1}^{N} (1 - r(\lambda_i))\Delta\lambda, \quad (2)$$

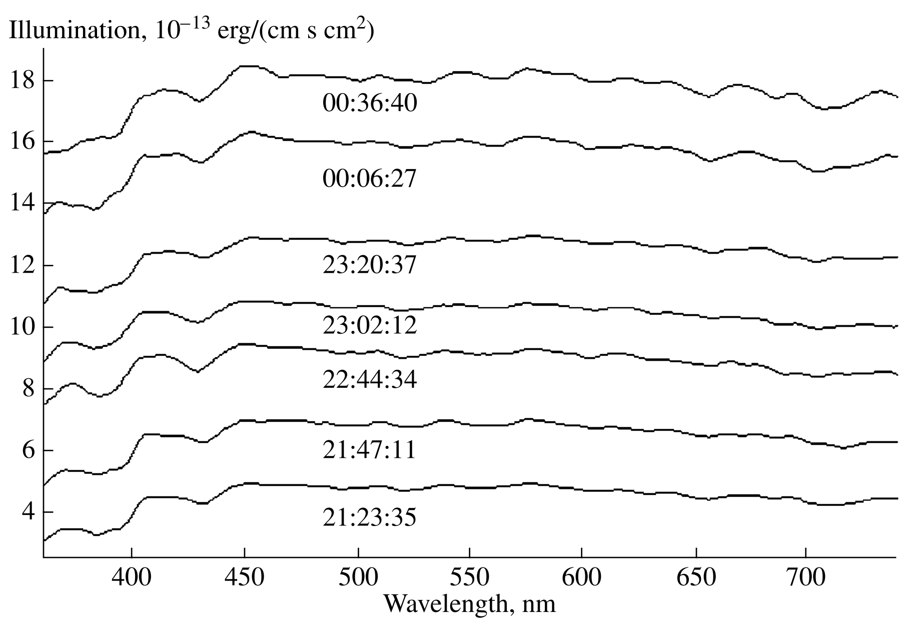

Fig. 1. The extra-atmospheric monochromatic illumination produced by the asteroid 21 Lutetia in its dependence on wavelength. The spectra are shifted upward along the Y axis by 2.0×10^{-13} relative each other. The moments of acquisition of the spectra are given in UT.

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 (Shestopalov, 1998). A random error in estimating the equivalent width turned out to be 0.13 nm, which was obtained from a set of 17 double equally precise values of the equivalent widths (Bol'shakov, 1965) for the same reflectance spectra of Lutetia taken twice out of the atmosphere with different spectra of the HD10307 standard.

In Fig. 2, the equivalent widths of this band are shown versus the observation time for the night of October 5, 2000. Their rather quick variations in time intervals of about an hour are worth noting. Further, only averaged spectra are analyzed. The synthetic values of V were determined and analyzed on the basis of 40 spectra obtained with a resolution of 4 nm and 12 spectra with a resolution of 3 nm. We used 51 and 50 spectra in the frequency analysis of the $B–V$ and $V–R$ colors, respectively. In the frequency analysis of the equivalent widths of the 430–440-nm absorption band, only 40 spectra with a resolution of 4 nm were used, in order to attain uniformity of the data.

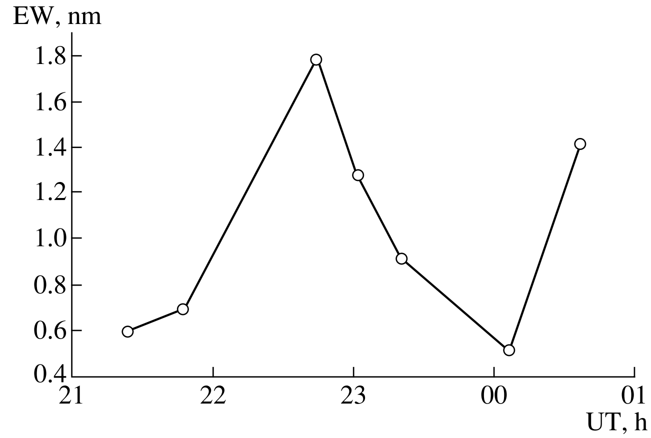

Fig. 2. The equivalent width of the 430–440-nm absorption band (EW, nm) in the reflectance spectrum of the asteroid 21 Lutetia during the night of October 5–6, 2000. The size of circles is equal to the root-mean-square error of 0.13 nm.

SYNTHETIC *V* MAGNITUDES AND *B–V* AND *V–R* COLOR INDICES

The extra-atmospheric synthetic magnitudes V of the asteroid 21 Lutetia 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 a zero phase angle. The two-parameter system of the magnitudes of minor planets was used. The calculations were performed with the parameters $H = 7.^{m}34$ and $G = 0.163$ (Tedesko, 1989) in the formulas published by Batrakov *et al.* (1997). The derived magnitudes $V(1, 0)$ allowed us to find the rotation period of the asteroid, which was observed from the Earth from August 31 to November 20, 2000.

Figures 3a and 3b present the periods determined with two methods (the Lafler–Kinman (a) and Jurkewich (b) methods) usually used to analyze series with gaps (Prokof'eva *et al.*, 1995). A sharp minimum in the upper plot clearly points to the most probable frequency $1/P = 2.9368$ c/d corresponding to the period $P = 0.^{d}3405 \pm 0.^{d}0001$ ($8.^{h}172$). In Fig. 3b, a wide maximum with the Jurkewich parameter $p \approx 100\%$ is associated with this period, confirming its high significance. The accuracy in determining this period is not high, and it is limited by the length of the observation set (115 days). The whitening of this observation series (see the plots in Figs. 3c and 3d) removed not only the frequency obtained above but also the neighboring extremums at the break frequencies.

The light curve $V(1, 0)$ of the asteroid corresponding to the obtained period of its rotation $P = 0.^{d}34056$ has two maximums and two minimums (Fig. 4). The largest amplitude of the brightness variations is about $0.^{m}25$. The amplitude of the lower maximum is about $0.^{m}18$.

The synthetic values of the $B–V$ color index calculated from the spectra range from $0.^{m}63$ to $0.^{m}80$; their mean value of $0.^{m}715$ is rather close to the value $B–V = 0.^{m}73$ typical of the M spectral type. The $V–R$ color indices range from $0.^{m}02$ to $0.^{m}27$ with a mean value of $0.^{m}17$, while the value calculated from a typical spectrum of an M-type asteroid is $0.^{m}23$. This indicates a smaller spectral contrast between the visible and red spectral ranges for 21 Lutetia in comparison with the contrast typical of M-type asteroids. In other words, the spectrum of Lutetia is grayer on average, which confirms our previous conclusion concerning a depression or a weak absorption band present in the 600–740-nm wavelength range of the reflectance spectrum of the asteroid.

We analyzed the synthetic values of the color indices $B–V$ (51 measurements) and $V–R$ (50 measurements). At a low confidence level, the $V–R$ color indices yielded a one-hump curve with a frequency of the known rotation period with an amplitude of about 3σ (the accuracy of the estimated extremum value is taken as 1σ). The convolution of the color index $B–V$ with the fundamental period of the asteroid's rotation yields an even less significant curve with an amplitude of less than 2σ. At the same time, we found break frequencies of 2.83, 3.85, and 4.85 c/d, giving a convolution product with more significant amplitudes of about $0.^{m}06$. Probably, there are color spots on the asteroid surface. However, the available number of measurements of the color indices is not enough to estimate their size reliably. We came to the conclusion that the analysis of the color indices failed to reveal significant color variations with a frequency of 2.936857 c/d corresponding to the value of the known period of the asteroid's rotation.

Thus, the calculation and analysis of the synthetic values of $V(1, 0)$ allowed us to find the value of the

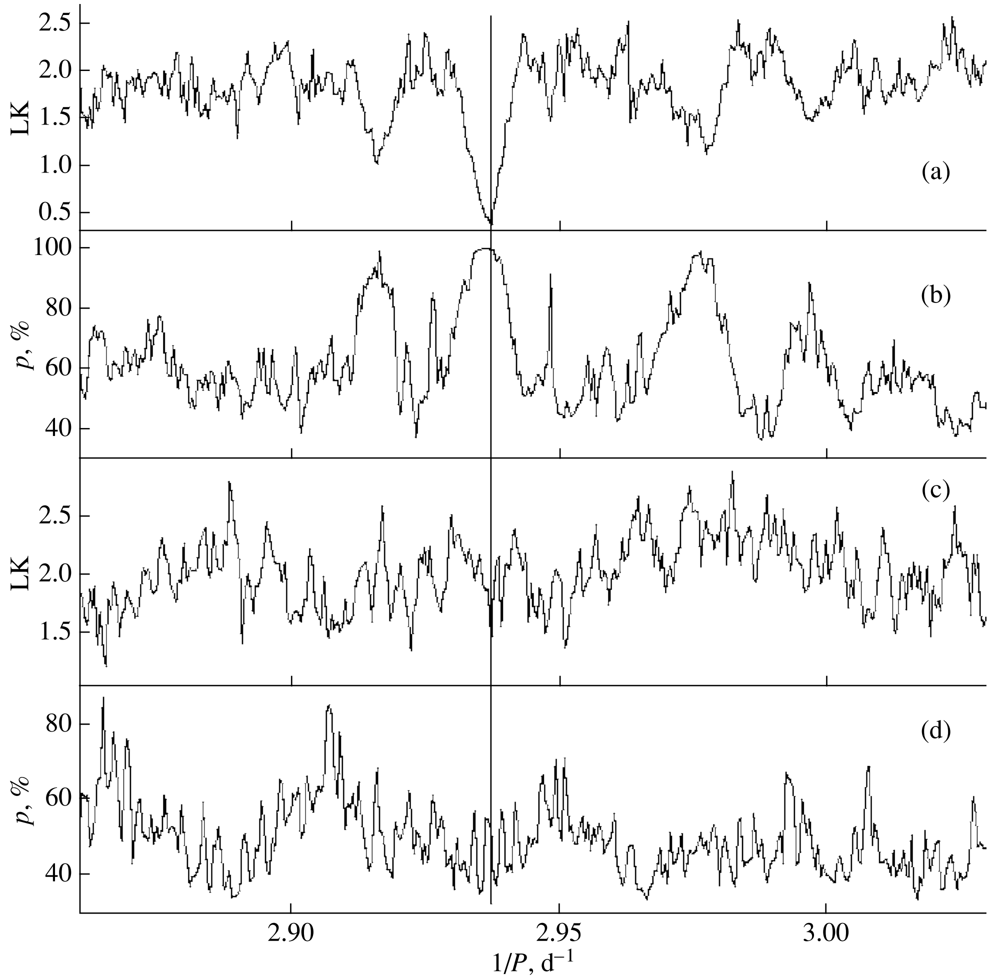

Fig. 3. Periodograms obtained from the analysis of 52 synthetic values $V(1, 0)$ with the Lafler–Kinman ((a) and (c)) and Jurkewich ((b) and (d)) methods. LK is the Lafler–Kinman parameter, and p is the probability of the existence of the period according to Jurkewich in percent. The two upper plots were constructed on the basis of the observational data $V(1, 0)$, and the two lower ones, from the data whitened for the period $P = 0.^d34056$.

known rotation period of the asteroid Lutetia ($8.^h172$), which indicates that the spectrophotometric observations and the technique for processing them are quite valid. The frequency analysis of the synthetic values of

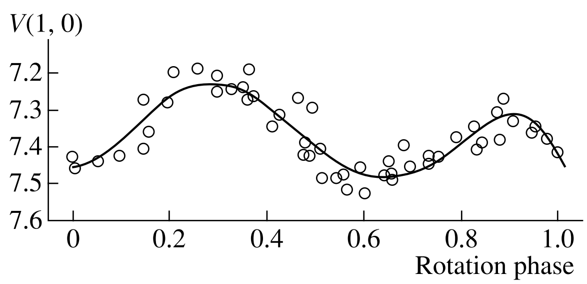

Fig. 4. The light curve constructed from the synthetic magnitudes $V(1, 0)$ with a period of the asteroid rotation $P = 0.^d34056$. The solid curve is a fifth-degree polynomial. The moment of the prime minimum at a phase of 0.65 is equal to JD $2451788.^d709$.

the color indices $B–V$ and $V–R$ failed to give the known rotation period of the asteroid, although one may suppose that there are color spots on the asteroid surface.

MEASUREMENTS OF THE EQUIVALENT WIDTH OF THE 430–440-nm ABSORPTION BAND: FREQUENCY ANALYSIS

The data presented in Fig. 2 show that the equivalent width of the 430–440-nm absorption band of hydrosilicates varied from 1.8 to 0.6 nm over an hour. One may suppose that the spectral intensity of the light flux reflected by the asteroid surface was strongly modulated in a wavelength range of about 410–450 nm, corresponding to the hydrosilicate absorption band.

For preliminary estimates of the variations in the equivalent width of the aforementioned absorption band with the period of the asteroid's rotation, several convolutions were constructed with the nearby periods. All of them showed four to six maximums. One of these

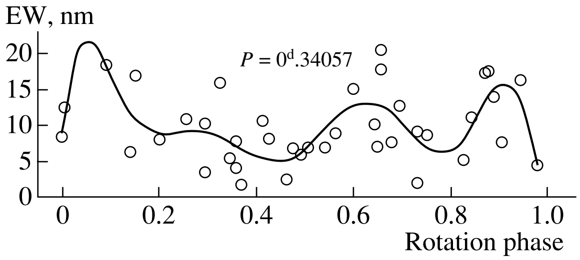

Fig. 5. The convolution of the equivalent width of the hydrosilicate absorption band (EW, nm) in the 430–440-nm wavelength range with the rotation period of the asteroid 21 Lutetia. The solid curve is a tenth-degree polynomial.

curves is displayed in Fig. 5 as an illustration. The approximation with a tenth-degree polynomial shows four maximums during the period of the asteroid's rotation. Obviously, there are at least four or more spots on the asteroid surface whose absorption in the 440-nm band is high and which correspond to the maximal values of the equivalent width of this band for the asteroid rotation period of $8.^h172$.

To estimate the size of these spots more accurately, we performed a more thorough frequency analysis of the data. Unfortunately, the resolution was limited by the time separation between the spectral data acquired. As was mentioned above, we analyzed the averaged reflectance spectra. The minimal time between their acquisitions was 18 minutes; it was much more in most cases. For our analysis, we chose the frequency range from 5 to 50 c/d, which corresponds to periods from $4^h.8$ to $0^h.5$. The last value is somewhat higher than the minimal interval between the moments of the spectrum acquisitions.

The analysis was fulfilled according to Breger's program for frequencies ranging from 5 to 50 c/d. The results are presented in three plots in Fig. 6. The most significant group of frequencies is between 10 and 16 c/d. The frequency groups of smaller powers are seen in the ranges 25–30 and 38–45 c/d. Note that the wide range of frequencies and limited number of sampling periods shown in Fig. 6 led to possible gaps in the frequencies. Due to this, while whitening the data for the most pronounced frequencies, we first refined the frequency by using three methods of frequency analysis simultaneously: the Lafler–Kinman, Jurkewich, and Deeming methods (Prokof'eva *et al.*, 1995). On the basis of the corrected period, the convolution was made, and the oscillation amplitude and its error were determined. We found eight significant frequencies in total, and their sequential subtraction yielded a data file

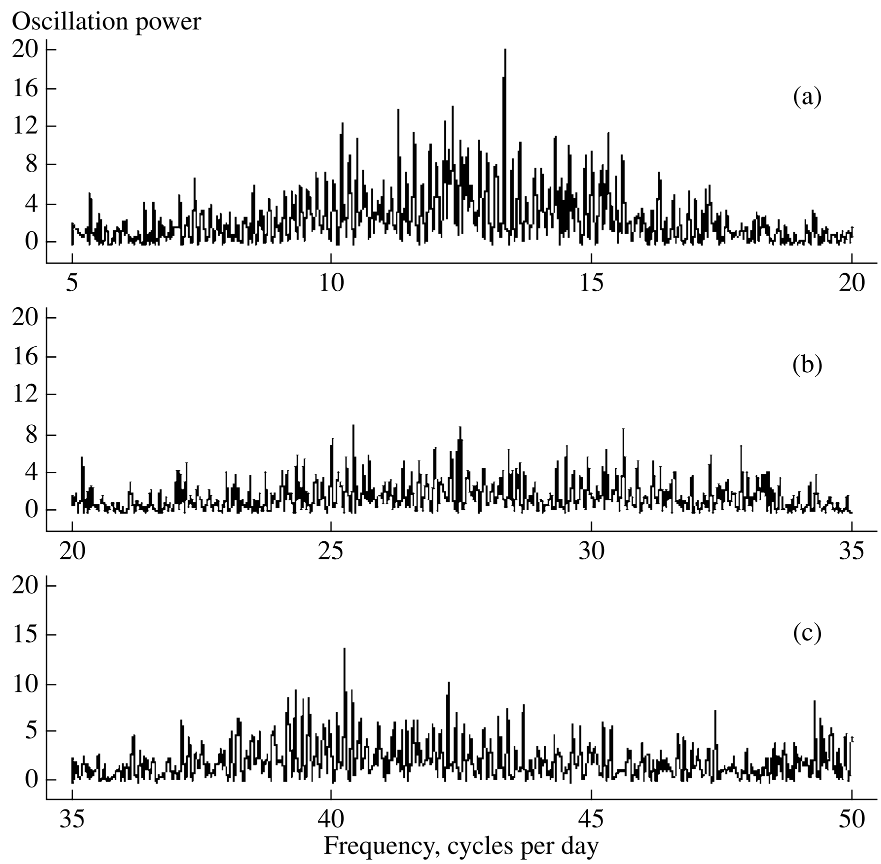

Fig. 6. The power spectrum constructed in the frequency range 5–50 c/d (c/d is the number of cycles per day) from the data of measurements of the equivalent width of the 440-nm absorption band.

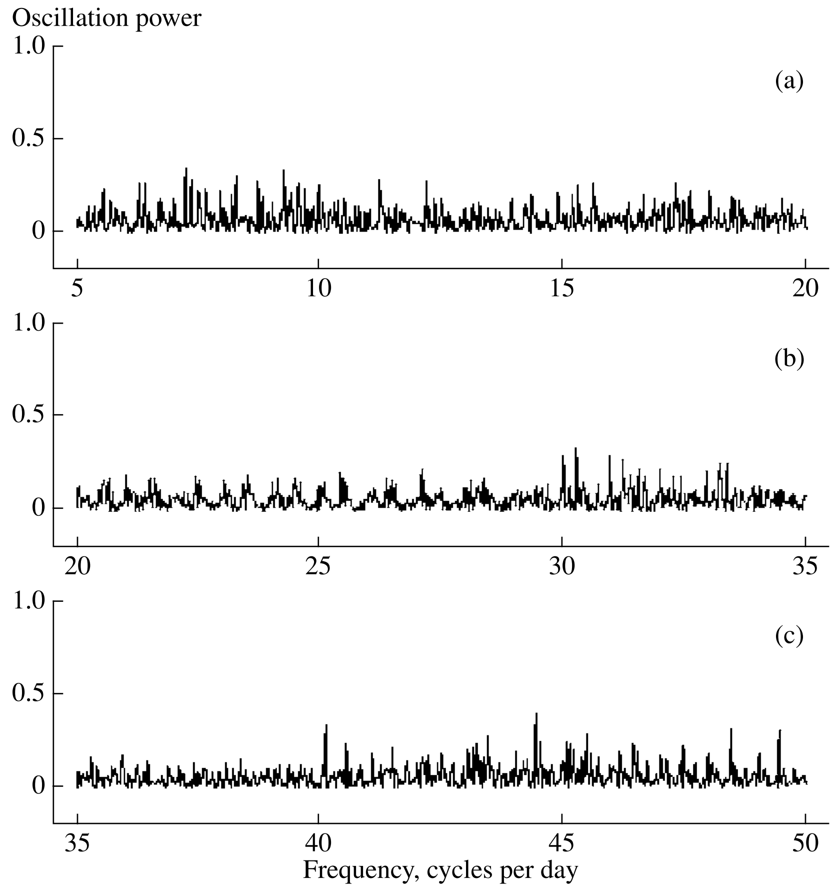

Fig. 7. The same spectrum as in Fig. 6, but based on the data whitened for eight significant frequencies obtained in our study.

containing practically only a noise signal. Its power spectrum is displayed in Fig. 7. Since the oscillation power decreased strongly, the plot scale was changed by a factor of 20 relative to that in the graphs of Fig. 6. The power of residual oscillations is less than 0.5, and, probably, it is impossible to extract any significant frequency from the remaining data.

The data convolutions obtained for the determined periods are given in the plots of Fig. 8 on a unified scale. The first four graphs are the results of the sequential whitening of the data for the obtained periodic oscillations. The fifth graph shows the last-found significant oscillation of the equivalent width of the hydrosilicate absorption band at 410–450 nm. A decrease in the oscillation amplitude and a simultaneous decrease in the data scattering around the curves are seen. Due to this, the accuracy in estimating the values in extremums increased in the course of the data whitening, and the fifth graph demonstrates the oscillation with a significant amplitude.

At the end of the whitening procedure, the accuracy in estimating the equivalent width of the absorption band in extremums reached 0.05 nm. This value corresponds to the above-mentioned mean accuracy of the data, namely, 0.13 Å, found from the analysis of the accuracy of the equivalent widths of the 410–450-nm absorption band determined from observations. This is also confirmed by the plot in Fig. 8e showing the minimal data dispersion around the curve.

Thus, Figs. 5–8 confirm the presence of several periodic oscillations of the equivalent width of the 440-nm absorption band. The data whitening for these oscillations decreased the data dispersion practically to the level of errors in estimating the equivalent width of this band.

HYDROSILICATE SPOTS ON THE SURFACE OF 21 LUTETIA: SIZE ESTIMATES

The frequencies obtained in our study are given in the first column of Table 2 in cycles per day. The period in days is also given (in the second column), as well as the amplitude of the equivalent width oscillations in nanometers and in σ units, determined as an accuracy of the curve extremums (in the third and forth columns), the ratio of the period of the asteroid rotation to the period found in this study P_{rot}/P (in the fifth column), and the spot size in degrees and kilometers (in the sixth and seventh columns, respectively) estimated for the case in when the spots are close to the equatorial region of the asteroid (the asteroid diameter is 100 km).

When estimating the size of a spot, we assumed that its size was approximately half the distance between the extremums in the corresponding data convolutions with the periods found.

It is worth noting that, due to the complexity of the spectrum given in Fig. 6, the procedure applied for searching the frequencies does not guarantee precise values of the periods and frequencies, because the break frequencies or harmonics could be found instead of the fundamental oscillations. This is also caused by the insufficient amount of data analyzed. Therefore, the frequencies listed in Table 2 should be considered as probable for the given asteroid and applicable only for estimating the sizes of hydrosilicate spots on its surface. In addition, it was supposed that the spot size is determined by the duration of the maximum of the curves shown in Fig. 8. This duration was assumed to be half of the period.

The estimates of the sizes of hydrosilicate spots on the asteroid surface presented in the sixth and seventh columns of Table 1 show that, typically, the spots are 30 to 40 km in size. Moreover, the maximal size of the spots, or, probably, of their cluster, is about 70 km. Smaller spots are about 12 km in size. As has been mentioned, the sizes were estimated under the assumption that the spots are in the equatorial region of the asteroid. In reality, they can be distributed across the whole surface. Then, their visible size can be two or three times less. In summary, we can conclude that there are hydrosilicate spots 3–5 to 70 km in size on the surface of the asteroid.

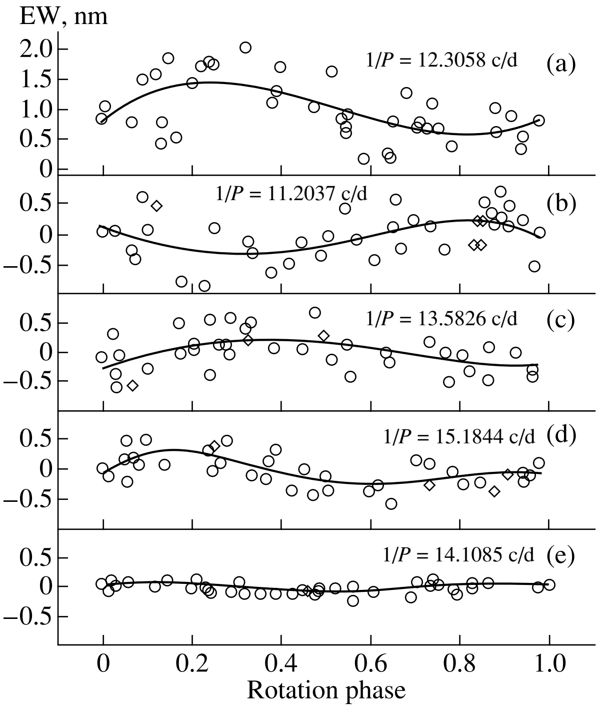

Fig. 8. The convolutions of the values of the equivalent width of the 440-nm band (EW, nm) with several periods from those obtained. The corresponding frequencies are indicated in the plots (c/d is the number of cycles per day). All the graphs are on the same scale in both axes. The solid curves are fourth-degree polynomials.

DISCUSSION AND CONCLUSIONS

Thus, the spectrophotometric observations carried out at the Research Institute of the Crimean Astrophysical Observatory in the autumn of 2000 allowed us to obtain 52 extra-atmospheric spectra of the asteroid 21 Lutetia in absolute energy units. The synthetic values $V(1, 0)$ calculated from these spectra yielded a light curve similar to that observed in 1983, when the asteroid had the same orbital position and a close aspect angle.

The frequency analysis of the synthetic color indices $B–V$ and $V–R$ did not reveal any significant changes with the period equal to that of the asteroid's rotation. However, since these values for 21 Lutetia were calculated with insufficient accuracy, a special set of observations of the asteroid in the BVR standard system is required to check the supposition concerning the color spots on its surface in the corresponding spectral range.

The frequency analysis of 40 measurements of the equivalent width of the 410–450-nm absorption band

Table 2. The frequencies, periods, and amplitudes of oscillations of the equivalent widths of the hydrosilicate absorption band at 440 nm, as well as the sizes of hydrosilicate spots estimated in degrees and kilometers

Frequency (1/P), c/d	Period (P), d	Amplitude, nm	Amplitude, σ	P_{rot}/P	Degrees	Size, km
12.3058	0.0813	0.9	7	4.1882	43	37
11.2037	0.0893	0.55	5	3.8130	47	41
13.5826	0.0736	0.5	5	4.6264	39	34
15.1844	0.0659	0.5	5	5.1669	35	30
6.2671	0.1596	0.35	4	2.1335	85	73
38.4057	0.0260	0.35	5	13.0962	14	12
30.9097	0.0324	0.24	4	10.5093	17	15
14.1085	0.0709	0.2	4	4.8025	37	33

allowed us to find eight significant periodic oscillations with frequencies from 6 to 31 c/d; the most pronounced frequencies are in the range from 11 to 14 c/d. The sizes of hydrosilicate spots on the asteroid surface are estimated at 3–5 to 70 km, and the most typical sizes are 30–40 km. The clusters of smaller hydrosilicate formations cannot be excluded.

Generally speaking, the discovery of a noticeable absorption band centered at 430–440 nm in the reflectance spectra of 21 Lutetia posed the problem of the origin of hydrated minerals on the surface of this asteroid, which probably passed through the magmatic melting stage at high temperatures. Earlier, from the results of infrared observations at 3 μm (Rivkin *et al.*, 1995, 2000), a number of M asteroids (about 35% of all observed) with spectral signs of water ice or bound water (hydroxyl) present in the silicate compounds on the surface were found. It is interesting to note that Rivkin *et al.* (1995, 2000) suggest considering such bodies to be an isolated class of objects, which, like asteroids of the C, P, and F types, are initially primitive and fell into the M type by mistake. One of the coauthors of the present paper suggested and developed the hypothesis that hydrosilicates could be brought to the asteroids of high-temperature types (M, S, and E) by fragments of silicate-icy bodies that arrived in the main asteroid belt (MAB) from the Jupiter Growth Zone (Busarev, 1998, 2000, 2001, 2002, 2003a, 2004; Busarev *et al.*, 2004a). This hypothesis is based on the theoretical results of Safronov (1979), Safronov and Ziglina (1991), and Ruskol and Safronov (1998), who showed that large silicate-icy bodies from the Jupiter region (Jupiter region bodies, JRBs) could be thrown away with a high velocity (up to several kilometers per second) by Jupiter's embryo when its mass reached several Earth masses. Quite possibly, in direct high-speed collisions of JRBs and asteroid parent bodies, the latter were removed from the MAB forever (Safronov and Ziglina, 1991). At the same time, strong gravitational disturbances of the orbits of the asteroid parent bodies remaining in the MAB (during their close approaches to JRBs) probably led to an increase in their mean relative velocity up to its current value (5 km/s) and to their mutual collisions and fragmentation. However, it is also possible that a significant portion of the JRB material, which is more friable and heterogeneous in composition as compared to asteroids, remained in the MAB in the form of fragments and dust, which could fall onto asteroids and neighboring planets for a long time (Busarev, 2003a, 2004). It is important to stress that the JRB material could be partially composed of already formed hydrosilicates, because the aquatic environment could have existed earlier in the interior of JRBs due to heating caused by the decay of the short-lived isotope ^{26}Al. This supposition can be based on the probability of the formation of a water ocean and hydrosilicates in the interior of large Kuiper bodies according to the analogous scenario (Busarev *et al.*, 2003b). A possible cause of the arrival of the ice component or already formed hydrosilicates on asteroids is a fall (at rather low rates providing for the preservation of hydrosilicates) of the material fragments and dust particles remaining in the MAB after the fragmentation of JRBs in their collisions with asteroid parent bodies (Busarev, 2003a, 2004). This collisional prehistory can result in a spotlike distribution of hydrosilicates over the surface of asteroids. This fact is now confirmed observationally in examinations of the modulation (integral or spectral) of the light flux reflected by the asteroid surface.

The rotating body of an asteroid with such surface features of its relief as craters or other forms with different scattering phase functions is known to modulate the light curves with frequencies that are high harmonics of its rotation frequency. If we find these frequencies, we can estimate the characteristic size of the surface heterogeneities of the asteroid surface. This kind of experience was gained in the photometric observations of the asteroid 1620 Geographos during its approach to the Earth in 1994 (Karachkina and Prokof'eva, 1997; Prokof'eva *et al.*, 1997). The frequency analysis revealed several periods of this kind; the periods obtained from the different maximums of the asteroid light curves differed slightly. According to those estimates, in the primary maximum, the largest details are about 1–1.2 km in size. In the secondary maximum, the details are smaller, namely, 150–250 m. Radar observations by Ostro *et al.* (1996) revealed a depression 1 km long and two craters of smaller size on the concave side of Geographos, corresponding to the primary brightness maximum. On the opposite convex side, corresponding to the secondary maximum, a crater 300 m across and 100-m depressions were found as well. Thus, the sizes of details on the surface of Geographos estimated from the data of the frequency analysis of photometric observations are almost fully confirmed by the sizes of depressions and craters recorded in radar observations.

Thus, the spectral observations of the asteroid 21 Lutetia, their processing, and the frequency analysis confirm the supposition put forward by Busarev concerning the delivery of hydrosilicates to the asteroid surface in its low-velocity collisions with more primitive bodies. In this case, hydrosilicates can be distributed over the asteroid surface as individual spots. If the crater-forming process that continued in subsequent impact events on the Lutetia surface is taken into account, two versions for the interpretation of such spots can be considered. Either hydrosilicates fill the largest craters on the asteroid surface or, on the contrary, hydrosilicate spots are the spaces between relatively young craters, which open the material of older age or different composition.

It is also interesting to compare our estimates of the crater sizes with the statistic data on the sizes of old and young craters on the Moon, Mars, and Mercury presented by Skobeleva (1987), who examined 11000 craters with crossing rims and diameters larger than 10 km. The statistical analysis showed that 70% of young craters are 10 to 30 km in diameter, 20–25% are 30–60 km across, and 7–8% are more than 60 km across. Among the old craters, approximately 20%, 35%, and 40–50% of craters have diameters of 10–30, 30–60, and more than 60 km, respectively. Comparing our estimates of the crater sizes on the asteroid 21 Lutetia to these statistical data, we can suggest that there are mostly young craters on the asteroid.

Nevertheless, for the moment, it is difficult to judge what structures the hydrosilicate spots found on 21 Lutetia correspond to. Closer examinations of Lutetia's surface with ground-based and space-borne methods, especially with the *Rosetta* spacecraft, should solve this problem.

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