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# A new stage in remote sensing of atmosphereless bodies of the solar system

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The proposed new spectral-frequency method is based on the registration of a number of integral spectra of a celestial body observed as a dot object. The method includes calculation of the reflectance spectra of investigated body, identification of some spectral features in the spectra and estimation of sizes of corresponding spectral details on the surface of the body. It was successfully applied to study the surfaces of asteroids (21) Lutetia and (4) Vesta, targets of the Rozetta and Dawn space missions. After identification of an absorption band of phyllosilicates (of a serpentine group) at 0.44 $\mu$m in rows of reflectance spectra of both asteroids, a lot of phyllosilicate formations were found on their surfaces corresponding to the absorption feature. In total, at the level of 4–5 signal to noise ratio, 8 and 16 different sizes of them were found on the surfaces of Lutetia and Vesta, respectively. Additional frequency analysis of colorimetric data obtained from the spectral data of (4) Vesta allowed establishing a bluish color of a known largest crater at the South Pole of the asteroid.

As applied to investigations of asteroids, the spectral-frequency method gives us a possibility of obtaining fundamentally new information about the minor planets and their evolution.

*Keywords*: Asteroids; Reflectance spectra; Frequency method; Spots on asteroids

## 1 Introduction

The quantity of numbered small objects in the solar system has considerably increased in recent years and is more than 300 000. However, only orbital elements and magnitudes are known for the majority of the bodies. The use of large telescopes for investigations of physical and chemical characteristics of many minor planets is impossible because the observational time on the instruments is highly restricted. Therefore, methods are necessary which make possible the investigation of such objects with small and average-size telescopes.

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## 2 The spectral-frequency method and its applications

The spectral-frequency method (SFM) of investigation of celestial atmosphereless bodies observed as dot objects is based on rows of their observational data obtained by the spectrophotometric method (Busarev *et al.*, 2007). It is known to be based on the property of a cold atmosphereless body to reflect incident solar radiation which can be measured on the detector. Due to a strong roughness of the surface of solid celestial bodies (down to the microlevel where the size of roughnesses is comparable to the optical wavelength), the term "reflection of a body" implies that the solar light reflected by the surface of a body includes mirror-reflected and scattered components. The scattered component is of interest and includes the radiation scattered by both the surface (determined by the scattering indicatrix) and also the internal volume of the material. This is a component of the radiation reflected by a celestial body, which is described as diffusive and gives information (codified in the reflectance spectra of the body) on the chemical-mineralogical content of its matter. If the surface of a body has a spot-like structure or some relief details which have different composition or scattering indicatrices, then the rotation of the body will modulate the radiation flux (spectral or integral) reflected towards the observer. During one complete revolution of a celestial body about its axis of rotation, the observer can register all the changes in the radiation field of the body as variations of its brightness curve. It gives information on details of the body surface. By determining frequencies, we can estimate the characteristic size of inhomogeneities (which are less than the diameter of the body!). It should be stressed that in SFM, instead of the brightness curve of an observed body, we take a row of its reflectance spectra obtained at close phase angles (or in a narrow interval of them). Thus, we try to separate influences of scattering indicatrix and content of the surface details to body integral brightness variations, to pick out the second.

A specificity of SFM is also the identification of some allocated spectral features in the reflectance spectra of an investigated body (e. g., an absorption band or slope of the spectral continuum in some spectral range). Corresponding values characterizing a found absorption band (the equivalent width) or slope of spectral continuum in the specific spectral range (the synthetic color-index) are calculated for each of the reflectance spectra. Then the row of obtained values receives a frequency analysis. The calculations are simultaneously carried out by three independent methods, by Lafler-Kinman (1965), Jurkevich (1971) and Deeming (1975). The calculation program allows us to find all periods less than the rotational period of the body hidden in changes of values of the row. A search of the periods is performed by means of "whitening" the polynomial approximating of the row of values from oscillations with determined period (and also its harmonics and conjugate periods) in the order of consecutively decreasing amplitudes. The procedure may be carried out up to the level of noise in the row of observational data. We suppose that half of each found period corresponds to a specific size of a spectral detail on the surface of investigated body. Investigation of (21) Lutetia (M-type, a target of the Rosetta space mission) and (4) Vesta (V-type, a target of the Dawn space mission), asteroids of magmatic types (Tholen, 1989; Gaffey *et al.*, 1989), by means of SFM lets us obtain the following results.

The first detection of water-bound compounds on the surface of (21) Lutetia was

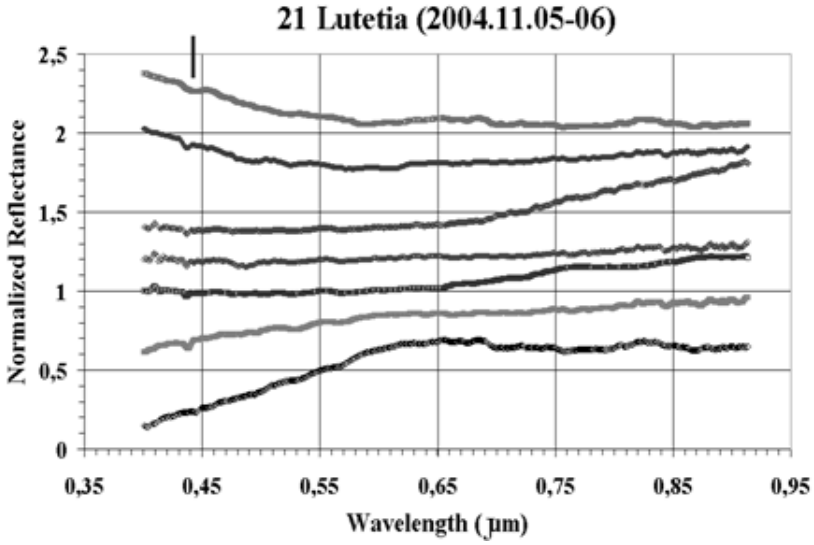



**Figure 1** Normalized to unity (at 0.55 $\mu$m) and shifted from each other reflectance spectra of Lutetia obtained at night of 5/6 November 2004. The spectra were registered successively with about 10-min intervals in 0.40–0.91 $\mu$m spectral range with a resolution of ∼7–8 Å. A short vertical line at the top curve shows the position of an absorption band of phyllosilicates at 0.44 $\mu$m.

made during IR-observation of the asteroid near 3.0 $\mu$m (Rivkin *et al.*, 2000). An absorption feature of phyllosilicates (of a serpentine group) with relative intensity up to ∼10% was identified at 0.44 $\mu$m in the reflectance spectra of (21) Lutetia (Busarev *et al.*, 2004a; Busarev *et al.*, 2004b). Examples of spectral changes in the reflectance spectra of Lutetia at night of 5/6 November 2004 are shown in Fig. 1 (16 Cyg B was used as a solar analog star). The spectra were obtained by V.V. Busarev with a spectrograph mounted on 1.25 m reflector of the Crimean Observatory of Sternberg Astronomical Institute.

Then about 50 spectra of Lutetia and the same number of spectra of solar analog HD10307 (G2V) and regional standards for a range of 0.37–0.74 $\mu$m with a resolution of 0.003–0.004 $\mu$m were registered. The observations were performed by V.V. Bochkov in the Crimean Astrophysical Observatory at the MTM-500 (0.5 m meniscal reflector) with a television system (Abramenko *et al.*, 2000; Bochkov *et al.*, 2003). From the reflectance spectra obtained at different rotation phases of the asteroid for September, October and November 2000 (in the range of ∼4–20° light phase angles), values of the equivalent width of the absorption band at 0.44 $\mu$m were calculated. Frequency analysis of the row of values of the equivalent width showed the presence of many significant frequencies, mainly from 15 to 20 c/d (c/d is the number of cycles per day). A supposition was made (Prokof'eva *et al.*, 2005) that it may be caused by a heterogeneous distribution of hydrated materials on the surface of Lutetia. Variations of the equivalent width of an absorption band at 0.44 $\mu$m in reflectance spectra of the asteroid during a night in October 2000 are shown in Fig. 2.

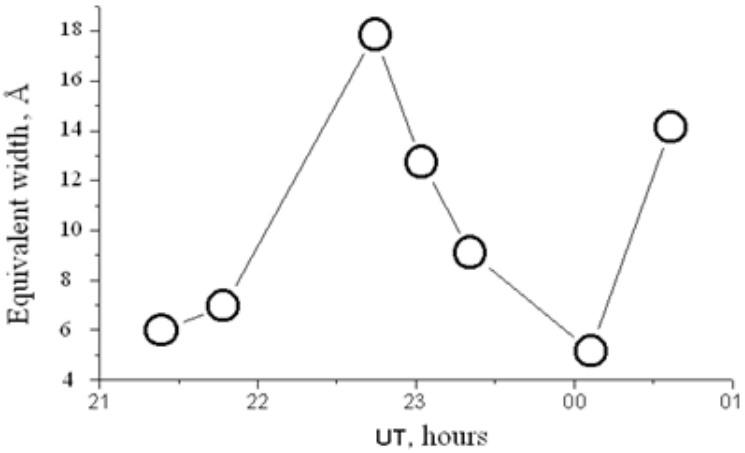



**Figure 2** The equivalent width of an absorption band near 0.43–0.44 $\mu$m in the reflectance spectra of (21) Lutetia during a half of the known asteroid rotational period ($8.172^h$) at night of 05/06 October 2000.

At slightly simplified suppositions (a spherical shape of the asteroid and equatorial distribution of investigated features), sizes of corresponding phyllosilicate formations on the asteroid surface were estimated from 3–5 to 70 km (with the most probable value between 30 and 40 km). In total, 8 sizes of phyllosilicate details were found on the surface of Lutetia at the level of 4–5 signal to noise ratio. Predominance of phyllosilicates on the observed hemisphere of Lutetia is seen from a concave shape of its reflectance spectra at some rotational phases of the asteroid (see Fig. 1, three top spectra) (Busarev, 2008) typical for chondrites.

For the first time, water-bound compounds were discovered on the surface of Vesta during its IR-observations at 3.0 $\mu$m (Hasegawa *et al.*, 2003). As in the case of (21) Lutetia, an absorption band of phyllosilicates (of a serpentine-type) was identified at 0.44 $\mu$m in the visible-range reflectance spectra of (4) Vesta (Prokof'eva-Mikhailovskaya *et al.*, 2008a). For the purpose, we used 691 records of the asteroid spectra registered on 2, 3, 4, and 7 February 2002 (asteroid light phase angle $\sim 22^\circ$) by Valerij Bochkov at the MTM-500 telescope with a television system. Then a row of reflectance spectra of Vesta and, further, a number of the equivalent width of the absorption band at 0.44 $\mu$m (91 values) were calculated. Frequency analysis of the row of values allows determining 16 sizes of phyllosilicate spots on the surface of the asteroid in the range of 7–800 km (50% of them in the range of 13–50 km) at the level of signal to noise ratio 4–5 (Prokof'eva-Mikhailovskaya *et al.*, 2008a). Features of largest sizes, 800 and 750 km, may be gathering of smaller spots near a known large crater at the South Pole of the asteroid. The prevalence of smaller-size spots allows us to suppose their relatively recent origin. Thus, our results confirm the presence of water compounds on the surface of Vesta (Hasegawa *et al.*, 2003). Interestingly, a maximum of distribution of the equivalent width of the absorption band of phyllosilicates seen in our data at 160–210° longitudes of the asteroid (Fig. 3) coincides with the coordinates pointed out by Hasegawa *et al.* (2003).

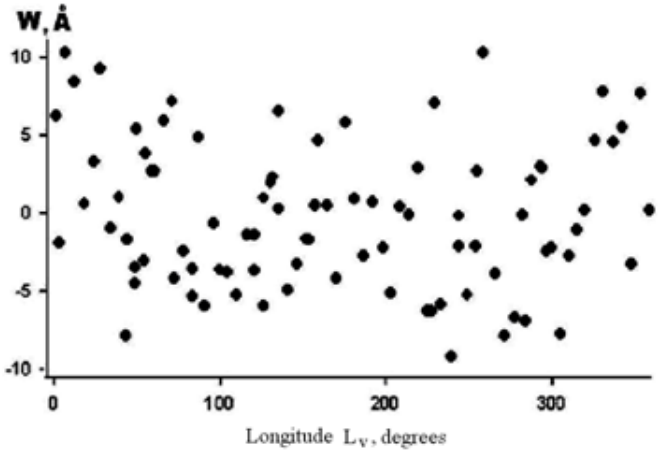



**Figure 3** Equivalent widths of an absorption band of phyllosilicates centered at 0.44 $\mu$m with latitude of asteroid (4) Vesta. Calculation of latitude values on Vesta were performed according to Cochran and Vilas (1998).

The presence of phyllosilicates on the magmatic type asteroids (21) Lutetia and (4) Vesta is not typical (e. g., Gaffey *et al.*, 1989). According to their high-temperature origin, the bodies could experience heating up to temperatures ∼1000–1500° C (Ghosh *et al.*, 2006). A spot-like character of phyllosilicate distributions on the surface of the asteroids suggests the transfer of these materials from primitive (hydrated) bodies in collisions with them.

Additionally, the sizes of B–V and V–R color spots on the surface of (4) Vesta were estimated with the SFM (Prokof'eva-Mikhailovskaya *et al.*, 2008b). The synthetic color indexes B–V and V–R were calculated from the asteroid spectra taken out of the terrestrial atmosphere. The changes with asteroid rotational period were eliminated from these data by the mentioned method of "whitening". After that, more short periods were successively determined. Thereby, we estimated 20 and 19 sizes of spots in the range of 9–660 km (supposing their equatorial position on the asteroid) corresponding to B–V (blue) and V–R (red) color indexes. As it turned out, the largest size of 660 km was found only in the blue spectral range. If the size of 660 km is diminished by a factor of 1.4 corresponding to the latitude of 45° of the asteroid, the value of 460 km is obtained. The size is equal to that of the largest crater actually found at the Hubble Space Telescope observations (Thomas *et al.*, 1997). The absence of this size in the red spectral range confirms the bluish color of the crater.

## 3 Conclusions

As is seen from the investigations of (21) Lutetia and (4) Vesta, application of SFM to the study of solid atmosphereless bodies makes it possible to obtain fundamentally new information. The method allows detection of details on the surface of the bodies

having specific spectral characteristics the sizes of which may be considerably less than those of the bodies. It is also important that the method may be used with small and average-size telescopes. For this reason, SFM facilitates significantly the research of a large quantity of small planets of the solar system. Thus, the obtained results may be considered as the beginning of a new stage of remote sensing of atmosphereless solid bodies of our planetary system.

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