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Asteroids 10 Hygiea, 135 Hertha, and 196 Philomela: Heterogeneity of the Material from the Reflectance Spectra

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Abstract—The reflectance spectra of asteroids 10 Hygiea (C-type), 135 Hertha (M-type), and 196 Philomela (S-type) are obtained in a range of 0.40–0.91 μm with different time intervals. In this paper, the technique of the spectral measurements of asteroids is analyzed and the reflectance spectra of Hygiea, Hertha, and Philomela are interpreted. The main physical and chemical factors and processes influencing the spectral characteristics of asteroids are considered. It is determined that the spectra of Hertha and Hygiea contain variations exceeding the measurement errors several times at different relative rotation phases, whereas spectral variations of Philomela caused by its rotation hardly exceed the error limits. Most probably, these variations are caused by local manifestations of the impact metamorphism of the material of asteroids in serious impact events. Results show that, to determine the prevailing spectral type and the corresponding mineralogy of each asteroid, one should estimate and take into account the changes in its spectral characteristics for a time interval comparable to the rotation period.

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INTRODUCTION

As we know from numerous optical laboratory studies of solids, the albedo, or reflectivity of a solid body in the visible range, is the averaged characteristic of its physical and chemical properties. The albedo variations of asteroids can be induced by several causes, the main of which are the changes in the element composition of the material and/or its oxidation degree, as well as the physical state or structure of the material (the mean density, porosity, or granulometric composition). In the late 1970s, the results of approximately 20-year studies of asteroids with the ground-based optical telescopes, equipped with rather precision registering electronic instruments, showed that polarimetric and colorimetric parameters of these bodies change within the limits of measurement errors regardless of the observed side. This led to the conclusion on the photometric homogeneity of the surfaces of asteroids; specifically, the absence of noticeable albedo variations was suggested (Burns and Tedesco, 1979; Degewij et al., 1979). It was even hypothesized that the homogeneity of the upper layer of the crushed material (regolith) of asteroids can be explained by impact processes, which should mix and uniformly distribute the surface material (Housen et al., 1979). However, Akimov et al. (1983) were the first to show that variations in the reflectance of asteroids caused by their rotation exceed the measurement errors. Comparison of the measured light curves of several best-studied asteroids with their model curves calculated for different shape parameters of their bodies allowed the conclusion that their photometric heterogeneities may reach 0^{m},17 and are mainly determined by albedo heterogeneities (Akimov et al., 1983). These authors note that there is no contradiction with the polarimetric and colorimetric characteristics of asteroids obtained earlier. According to the works of the noted specialists (Bowell et al., 1979; Morrison and Zellner, 1979), if the range of albedo variations is assumed to be 100%, the ranges of variations in the polarimetric and colorimetric characteristics of asteroids are relatively small—not more than 1.5 and less than 30%, respectively.

The spectral dependence of the albedo is the reflectance spectrum (in absolute units) of a solid body obtained at a zero phase angle. However, such dependence can be easily measured only in a laboratory, whereas the main volume of the observational data on solid celestial bodies is obtained under phase angles differing from zero (they are sometimes varying or different). In this case, to describe the spectral properties of a solid celestial body, the normalized reflectance spectrum or the spectrum of the brightness coefficient (factor) is used. This simplified relative characteristic can be expressed as

$$\rho(\alpha, \lambda) = k\big(p_\lambda F(\alpha, \lambda)\big)/\big(p_{\lambda 0} F(\alpha, \lambda_0)\big), \qquad (1)$$

where p_λ is the monochromatic geometrical albedo accounting for the integral physical and chemical properties of the observed hemisphere of the celestial body (or, being more precise (by definition), its projection to the picture plane of the observer); $F(\alpha, \lambda)$ is the phase function ($F(\alpha, \lambda) = 1$, when $\alpha = 0$), λ is the current value of the wavelength; λ_0 is the fixed wavelength, at which the normalizing value of the brightness coefficient $\rho_0(\alpha, \lambda_0) = p_{\lambda 0}F(\alpha, \lambda_0)$ is chosen (usually, the value corresponding to the middle of the V photometric band $\lambda_0 = 0.55$ μm, is chosen); and k is a constant factor. It is worth stressing that $\rho(\alpha, \lambda)$ is a function of the geometric albedo and the phase function of the celestial body at different wavelengths, and it is independent of the changes in the shape of the body due to its rotation. Moreover, relation (1) is valid, if the observed object is a point source of radiation, and its spectrum is registered simultaneously in the whole spectral range. In the ground-based optical studies, practically all of the asteroids are point sources (their angular sizes are less than several tenths of an arc second); therefore, the measurements yield their integral characteristics of the observed hemisphere.

Variations in the mean composition or the oxidation degree of the observed portion of the surface of asteroids can be found in their successive-in-time (or -in-rotation-phase) spectra of the diffuse reflection. Such variations appear as the changes in the slope and the shape of the continuum of the visible reflectance spectra of asteroids. The continuum characterizes the intensity and the width of the oxygen-metal absorption band centered at 0.2 μm; it is induced by the electron transfer of a charge in silicate compounds containing oxygen (Platonov, 1976; Burns, 1993; Loeffler et al, 1994). Due to the changes in the composition of the material, the absorption bands, characterizing the dominating minerals or their complexes, also appear (or disappear) in the successive reflectance spectra of asteroids. It is worth stressing that such mineralogical absorption bands are rather wide: from several hundred to one–two thousand angstroms. Because of this, such bands, if their relative intensity is sufficient (more than 3–5%), can be reliably identified in the reflectance spectra of asteroids against the background of the high-frequency noise component (see, e.g., Busarev et al., 2007). As we know, one of the most intense mineralogical absorption band in the near-infrared reflectance spectra of asteroids and other solid atmosphereless celestial bodies with silicate composition is the pyroxene-olivine band centered at 1 μm (Adams, 1975), which substantially influences the continuum shape of their reflectance spectra. One more absorption band, close to the one mentioned, is observed in the reflectance spectra of the hydrated or highly oxidized silicate material at 0.75–0.80 μm; it is appear due to the electron transfer of a charge $Fe^{2+} \longrightarrow Fe^{3+}$ (Burns et al., 1972; Platonov, 1976; Bakhtin, 1985; Burns, 1993). As our experience in the study of the terrestrial mineral samples containing iron forms of different valence shows, the intensity of the absorption band mentioned in the reflectance spectrum is also controlled by the total content of iron in the silicate material rather than only by portions of two- and three-valent iron (Busarev et al., 2004). Interestingly, this band may even mask the 1-μm diagnostic absorption band of terrestrial pyroxenes and olivines if the Fe_2O_3 content is increased (Adams, 1975). Because of a high content of hydrosilicates and their close phases in carbonaceous chondrites (Dodd, 1981; Jarosewich, 1990), the intense absorption band centered at 0.75–0.80 μm or at the close wavelengths imparts the characteristic concave shape to their reflectance spectra in the whole range from 0.5 to 1.0 μm (see Busarev and Taran, 2002, for example). The important additional indicator of hydrosilicates and highly oxidized iron oxides in the visible range is the absorption band at 0.44–0.45 μm discovered in the spectra of diffuse reflection of the crushed samples of terrestrial serpentines (Busarev et al., 2004). The equivalent width of this absorption band in the reflectance spectra of a set of serpentine samples turned out to correlate strongly with the Fe^{3+} content (Busarev et al., 2008). As indicators of the oxidized material, the absorption bands centered at 0.60 and 0.67 μm can be used; they were found in the reflectance spectra of oxidized Fe and Fe–Ni compounds and minerals of the spinel group, which are complex oxides of Fe, Mg, Al, and Cr (Hiroi et al., 1996). In the work mentioned, it was shown that these weak absorption bands frequently occur in the reflectance spectra of S-type asteroids.

THE OBSERVATIONAL DATA AND THEIR DISCUSSION

The spectra of asteroids 10 Hygiea, 135 Hertha, and 196 Philomela were acquired at different times from November 2004 to November 2008 with the 1.25-m telescope of the SAI (Sternberg Astronomical Institute) Crimean Observatory coupled with a charge-coupled device spectrograph operating in the range from 0.40 to 0.91 μm with a spectral resolution of about 8 Å. Each of the spectra of the asteroid was sequentially recorded by two portions (in the wavelength intervals 0.40–0.67 and 0.65–0.91 μm or vice versa) and took about half an hour. Besides the asteroids, the star standards, simultaneously being the solar analogs by their spectrophotometric parameters (16 Cyg B and HD 10307) (Hardorp, 1980; Cayrel de Strobel, 1996, Glushneva, et al., 2000), were also observed. They were used to determine the spectral transparency of the terrestrial atmosphere and to approximate the reflectance spectra of asteroids. The mean moments, the conditions of observations of the asteroids and the star standards, and the errors in the reflectance spectra are listed in the table. The reflectance spectra were approximated by the following formula (Busarev, 1999):

$$\rho(\varphi, \lambda) = kI_{\mathrm{a}}(\varphi, \lambda) f(\lambda)^{-\delta(M_{\mathrm{a}}(z) - M_{\mathrm{s}}(z))} \Big/ I_{\mathrm{s}}(\lambda), \qquad (2)$$

where $\rho(\varphi, \lambda)$ is the spectral distribution of the brightness coefficient (or factor) of the asteroid; $I_{\mathrm{a}}(\varphi, \lambda)$, and $I_{\mathrm{s}}(\lambda)$ are the spectral distributions of the intensity of the light flux from the asteroid and the star (solar analog), respectively; $f(\lambda)$ is the function of the spectral transparency of the atmosphere for the specified observatory determined for each of the observational

Time, coordinates, and conditions of the spectral observations of asteroids and solar-analog stars

Object	Date	UT, h, min, s	α, h, min, s	δ, degree, arc min, arc s	Δ, AU	*r*, AU	φ, deg	*V*, magnitude	ω	*M*(*z*)	σ_1	σ_2	σ_3
16 Cyg B	2004 11 07	17 49 39	19 41 52	+50 31 00	–	–	–	6.2	–	1.223	–	–	–
135 Hertha (*1*)	2004 11 07	19 17 21	00 28 31	+05 54 41	1.237	2.115	16.3	11.2	0.000	1.298	0.036	0.017	0.081
135 Hertha (*2*)	2004 11 07	19 23 30	00 28 31	+05 54 41	1.237	2.115	16.3	11.2	0.012	1.301	0.048	0.017	0.081
135 Hertha (*3*)	2004 11 07	19 32 38	00 28 31	+05 54 40	1.237	2.115	16.3	11.2	0.030	1.306	0.021	0.008	0.060
135 Hertha (*4*)	2004 11 07	19 38 40	00 28 31	+05 54 40	1.237	2.115	16.3	11.2	0.042	1.311	0.057	0.012	0.056
16 Cyg B	2007 10 04	21 03 04	19 41 52	+50 31 00	–	–	–	6.2	–	1.394	–	–	–
10 Hygiea (*1*)	2007 10 04	22 42 11	00 27 01	+08 51 24	2.370	3.367	1.7	10.2	0.000	1.307	0.046	0.012	0.047
10 Hygiea (*2*)	2007 10 04	23 16 58	00 27 00	+08 51 17	2.370	3.367	1.7	10.2	0.021	1.390	0.094	0.019	0.072
16 Cyg B	2008 10 28	16 37 30	19 41 52	+50 31 00				6.2	–	1.123	–	–	–
196 Philomela	2008 10 28	23 47 28	02 39 26	+09 21 10	2.163	3.151	2.3	11.0	0.000	1.604	0.041	0.010	0.115
135 Hertha	2008 10 29	01 28 43	03 27 13	+22 29 25	1.308	2.269	8.4	11.2	0.451	1.689	0.060	0.010	0.059
16 Cyg B	2008 10 29	18 29 30	19 41 52	+50 31 00	–	–	–	6.2	–	1.425	–	–	–
135 Hertha	2008 10 30	00 56 04	03 26 14	+22 26 57	1.307	2.271	7.9	11.2	0.243	1.447	0.034	0.007	0.100
16 Cyg B	2008 10 30	18 35 30	19 41 52	+50 31 00	–	–	–	6.2	–	1.460	–	–	–
135 Hertha	2008 10 31	01 13 22	03 25 11	+22 24 16	1.306	2.273	7.4	11.1	0.135	1.562	0.043	0.012	0.065
135 Hertha	2008 10 31	01 55 43	03 25 09	+22 24 10	1.306	2.274	7.4	11.1	0.219	1.861	0.081	0.019	0.071
HD 10307	2008 11 25	23 25 00	01 41 47	+42 36 48	–	–	–	4.9	–	1.432	–	–	–
10 Hygiea (*1*)	2008 11 26	02 09 35	04 44 36	+25 14 24	2.516	3.494	2.6	10.4	0.340	1.628	0.024	0.006	0.100
10 Hygiea (*2*)	2008 11 26	03 11 02	04 44 34	+25 14 19	2.516	3.494	2.6	10.4	0.377	2.170	0.023	0.008	0.065
196 Philomela	2008 11 28	21 06 36	02 16 22	+08 35 53	2.279	3.156	9.7	11.5	0.887	1.344	0.030	0.007	0.062
HD 10307	2008 11 28	22 25 30	01 41 47	+42 36 48	–	–	–	4.9	–	1.268			
196 Philomela	2008 12 01	20 34 48	02 14 47	+08 35 56	2.304	3.157	10.5	11.5	0.457	1.304	0.058	0.026	0.120
HD 10307	2008 12 01	22 59 15	01 41 47	+42 36 48	–	–	–	4.9	–	1.422			
10 Hygiea	2008 12 02	02 13 08	04 39 24	+25 01 25	2.507	3.492	0.9	10.3	0.556	1.937	0.080	0.018	0.049

Note: UT is universal time; α and δ are right ascension and declination, respectively; Δ and *r* is the geocentric and heliocentric distances, respectively; φ is the phase angle; *V* is the visible magnitude; ω is the relative rotation phase; *M*(*z*) is the air mass; and the errors in the reflectance spectra of the asteroids σ_1, σ_2, and σ_3 are the standard deviations in 0.44–0.45, 0.59–0.60, and 0.84–0.85 μm, respectively the numbers in brackets next to the names of some asteroids indicate the order numbers of their spectra obtained on the same date.

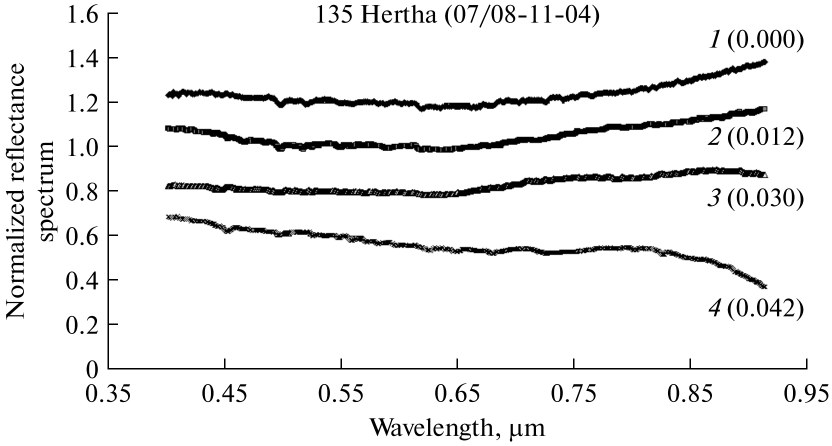

Fig. 1. The normalized (to the value at a wavelength of 0.55 μm) reflectance spectra of asteroid 135 Hertha obtained on November 7–8, 2004. Spectra *1–4* are shown in chronological order (bottom up) and shifted relative to each other for convenience. The relative phase of the asteroid's rotation is given in brackets. The rotation phase of the very first spectrum is assumed to be zero.

nights; $\delta(M_a(z) - M_s(z))$ is the air-mass difference depending on the zenith distances z of the asteroid and the star analog at the moments of their observation; and k is a factor. We see from Eq. (1) that $\rho(\varphi, \lambda)$ and $I_a(\varphi, \lambda)$ depend on both a wavelength λ and a phase angle of the asteroid φ. It is worth noting that, at $\varphi \approx 0°$, the spectral distribution of the brightness coefficient of the observed hemisphere of the asteroid transforms to the spectral distribution of its geometrical albedo $p(\lambda)$.

From the calculated reflectance spectra of the asteroids, their relative mean-root-square errors (the standard deviations from the continuum line) in a range of 0.44–0.85 μm were determined. They amount to less than 1–2% in the middle of the specified range and increases to approximately 5–7% at its ends (see table). Then, the calculated reflectance spectra of the asteroids were smoothed with the "running-average" method and normalized to the value at a wavelength of 0.55 μm. In some cases, after such smoothing, the spectra near 0.40–0.44 and 0.85–0.91 μm were additionally extrapolated with a polynomial to eliminate the residual noise component in the reflectance spectra of the asteroids beyond a range of 0.44–0.85 μm. The normalized reflectance spectra of the asteroids are shown in Figs. 1–5. The corresponding values of the relative rotation phase of the asteroids are specified in the plots near the labeling of the spectra (in brackets) and in the table. For each of the asteroids, the zero phase was assumed to be the rotation phase (RPh) corresponding to the first of the obtained spectra. The data in the table and in the plots are arranged chronologically. Now, we describe the reflectance spectra of each of the asteroids in detail.

The M-type asteroid 135 Hertha (Tholen, 1989) has a rotation period $P = 8.40^h$ (Batrakov et al., 2000); its IRAS diameter (the diameter determined from the Infrared Astronomical Satellite observations) is 79.2 km, and its albedo is 0.14 (Tedesco et al., 2004). Variations in its reflectance spectra measured in the RPh interval 0.000–0.042 during the night of November 7–8, 2004, were relatively small (Fig. 1). However, their general concave shape is typical of hydrated silicate material or the material of carbonaceous-chondrite composition, which may compose the C–F-type asteroids, but this is not typical of the M-type asteroids, as the latter should contain metallic compounds and high-temperature minerals of the pyroxene and olivine type (Gaffey et al., 1989; 2002). At an RPh of 0.012–0.042, the reflectance of the asteroid gently decreased by approximately 20–40% in a range of 0.70–0.91 μm (Fig. 1, cures *2–4*), which is probably connected with the appearance of the absorption band at 1.0 μm caused by the growth of the mean content of pyroxene and olivine in the material of the observed hemisphere of the asteroid. A similar shape of the reflectance spectra was also demonstrated by Hertha in October 29–31, 2008, when the RPh values were different, and their range was wider. Observations of the asteroid in the period mentioned showed that the shape of its spectra was more noticeably changed (Fig. 2): on October 31, it was concave (RPh = 0.135) and concave-convex, probably due to the appearance of the pyroxene-olivine absorption band at 1.0 μm (RPh = 0.219); on October 20, it was slightly convex, which is typical of M- or S-type asteroids (RPh = 0.243); and on October 29, it was again concave (RPh = 0.451). It is worth noting that, on October 29 and 31, the absorption band at 0.44–0.45 μm and the weak combined absorption band of olivine and pyroxene at 0.50 μm (Fig. 2) were registered more clearly in the reflectance spectra. The first one is connected with the presence of Fe^{3+} in the asteroid material, and the second one is induced by the forbidden-by-spin electron transition in Fe^{2+} in the crystalline fields of these minerals (Platonov, 1976; Bahktin, 1985). Thus, Hertha's reflectance spectra obtained at different rotation

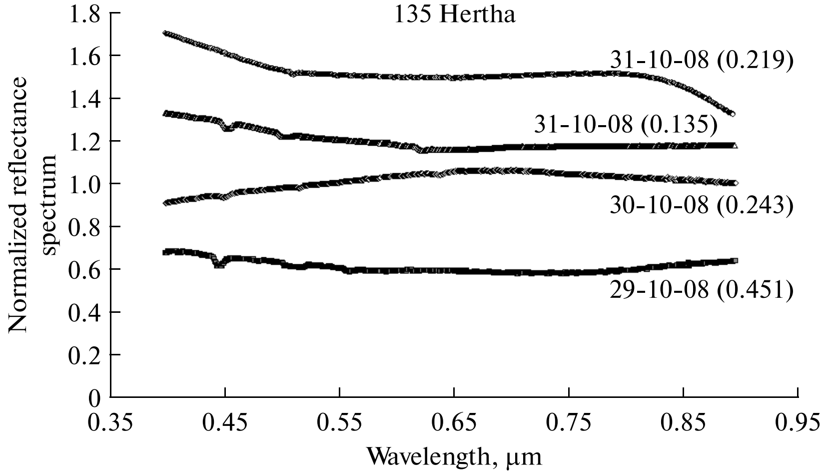

Fig. 2. The normalized (to the value at a wavelength of 0.55 μm) reflectance spectra of asteroid 135 Hertha obtained on October 29–31, 2008. The spectra are shifted relative to each other for convenience.

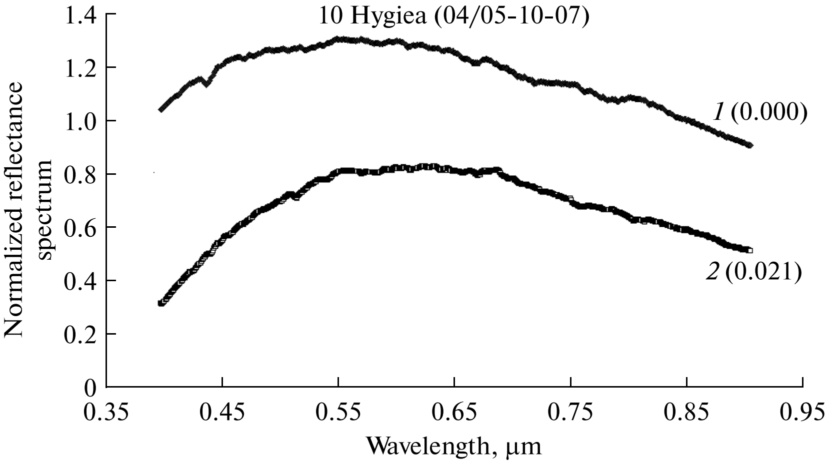

Fig. 3. Normalized (to the value at a wavelength of 0.55 μm) reflectance spectra of asteroid 10 Hygiea obtained on October 4–5, 2007. The spectra *1–4* are shifted relative to each other for convenience. The relative phase of the asteroid's rotation is given in brackets. The rotation phase of the very first spectrum is assumed to be zero.

phases testify to the changeability of its observed spectral type (from C–F to M–S) and, consequently, to the substantial heterogeneity of the composition of its surface material.

The C-type asteroid 10 Hygiea (Tholen, 1989) has a rotation period $P = 27.62^h$ (Batrakov et al., 2000); its IRAS diameter is 407.1 km, and its albedo is 0.07 (Tedesco et al., 2004). Its two first spectra were measured at night on November 4–5, 2007 (Fig. 3) with a small time interval (about half an hour). The spectra differ slightly, within the limits of measurement errors (see table), which could be expected for a rather slowly rotating asteroid. However, the shape of these reflectance spectra (see Fig. 3) does not agree with the determined spectral type of Hygiea, type C, to which the low-temperature mineralogy is assigned (Gaffey et al., 1989; 2002). This shape most likely resembles the reflectance spectrum of the high-temperature mineral—olivine (Platonov, 1976)—typical of S-type asteroids (Gaffey et al., 1989). At the other values of RPh, the spectra of Hygiea were also registered with a small time difference (about an hour) on November 25–26, 2008 (the two upper curves in Fig. 4). Though some differences (~10%–20%) are observed in them in a range of 0.65–0.91 μm, they generally agree with the spectral type C. In these reflectance spectra, there is a

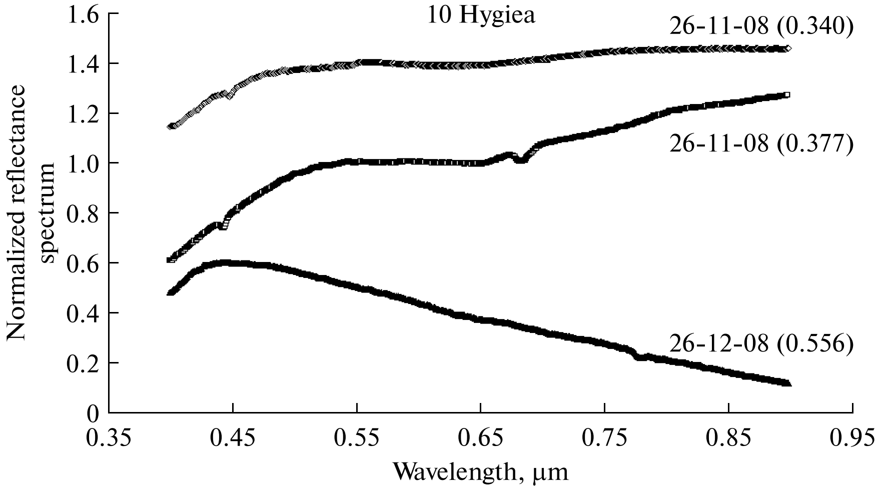

Fig. 4. The normalized (to the value at a wavelength of 0.55 μm) reflectance spectra of asteroid 10 Hygiea obtained on November 26–December 2, 2008. The spectra are shown in chronological order (bottom-up) and shifted relative to each other for convenience.

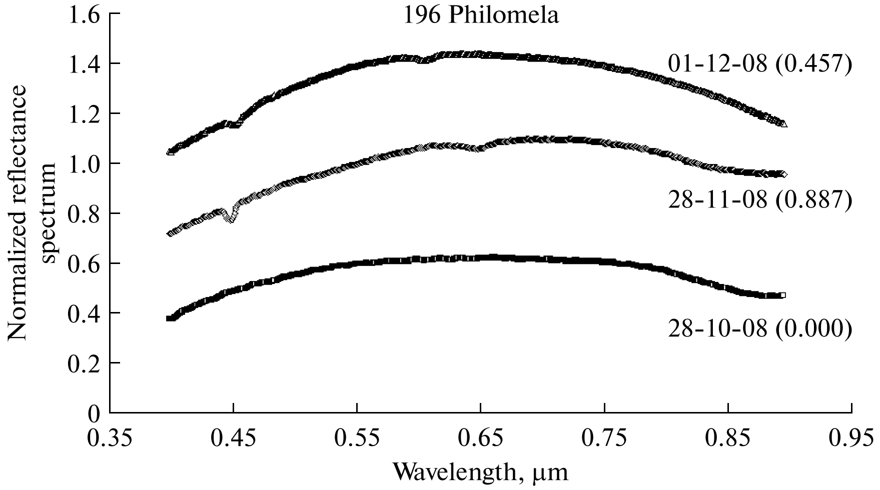

Fig. 5. Normalized (to the value at a wavelength of 0.55 μm) reflectance spectra of asteroid 196 Philomela obtained on October 28–December 2, 2008. The spectra are shown in chronological order (bottom-up) and shifted relative to each other for convenience. The relative phase of the asteroid's rotation is given in brackets. The rotation phase of the very first spectrum is assumed to be zero.

weak absorption band of Fe^{3+} at 0.44–0.45 μm, confirming the low-temperature mineralogy of the material. Hygiea's last reflectance spectrum, measured on December 1–2, 2008, at RPh of 0.556 (the lower curve of Fig. 4), characterizes the asteroid's side that is opposite to the side corresponding to the two spectra (in Fig. 3). The shape of this reflectance spectrum is rather unusual and differs noticeably from the spectra of Hygiea acquired at the other rotation phases. In the whole spectral range that we use, the slope of this spectrum is negative (Fig. 4). Such a shape is typical of the reflectance spectra of the B- and F-type asteroids, close to the C type (Tholen, 1989). Thus, the reflectance spectra of Hygiea obtained at its different rotation phases suggest the variability of its spectral type from C to B–F and even S.

Finally, three spectra of asteroid 196 Philomela were measured. It is an S-type asteroid (Tholen, 1989); its rotation period is $P = 8.34^h$ (Batrakov et al., 2000), the IRAS diameter is 136.4 km, and the albedo is 0.23 (Tedesco et al., 2004). The spectra were acquired on October 28–29, 2008, November 28–29, 2008, and December 1–2, 2008, at different rotation phases; but they are more or less uniformly distributed through the rotation period of the asteroid (table). By their shape, the reflectance spectra of Philomela correspond to the spectral class S and differ by ~6%–9% only at the boundaries of the used spectral range, which is within the limits of measurement errors (Fig. 5). Such results of the measurements testify to the high-temperature mineralogy (Galley et al., 1989) and relatively homogeneous composition of Philomela's surface material. The weak absorption bands at 0.44–0.45, 0.60, and 0.67 μm in the second and third (by time) spectra indicate the presence of small surface formations composed of oxidized and/or hydrated material on Philomela or to the admixture of this material in the main material of the asteroid.

It is worth noting that the substantial variation in the reflectance spectra of Hygiea and Hertha are registered in the period of the rather stable spectral transparency of the atmosphere. In the normalizing procedure of the reflectance spectra, the brightness variations connected with the irregular shape of the asteroids considered were eliminated. During observations of the asteroids, the light phase angles were small, and they change in relatively narrow limits (0.9°–2.6°, 2.3°–10.5°, and 7.4°–16.3° for Hygiea, Philomela, and Hertha, respectively). Consequently, the phase function could not influence their spectral reflectance much. Because of this, we can assert that the spectral differences found during the rotation of the asteroids are connected with the changes of the mean spectral reflectivity or the albedo of their observed hemisphere and, consequently, with the mean chemical and mineralogical composition of their material.

DISCUSSION

The most probable causes of the local heterogeneities of the material on asteroids are the consequences of their mutual collisions or falls of smaller bodies onto their surfaces. The frequency and energy of such impacts were very high in the past (~3–4 Ma), which was caused by the resonance and gravitational disturbances from growing Jupiter and large preplanetary bodies coming to the main belt of asteroids (Safronov, 1969; Safronov and Ziglina, 1991; O'Brien et al., 2007). However, smaller bodies may also fall onto asteroids now (see, for example Petit et al., 2001; Bottke et al., 2005). The most noticeable traces of the impact events on the surfaces of asteroids are impact craters and ejecta of the material which are well seen in the high-resolution images of asteroids taken during spacecraft encounters. As we know from the literature on studies of impact craters on the Earth (see, for example, Melosh, 1989; Grieve, 1991), at the impact of meteoritic bodies with the Earth's surface with velocities of about 1–10 km/s, the pressure in the epicenter may reach tens of gigapascals, and the temperature, several thousand degrees. The result of the influence of such pressures and temperatures on the silicate material is its complete melting and partial evaporation, at least in the crater's bottom. However, for asteroids, as studies of meteorites and the model calculations show, even at very strong impacts, the energy of which reaches the energy of the body destruction, no global heating to high temperatures occurs (Keil et al., 1997). In other words, on asteroids, at considerable pressures and temperatures in the epicenter of the impact explosion, the surface material is only partly melted and evaporated independently of the composition of the material of the colliding bodies. Even under such extreme conditions on the asteroid, formation of breccias (partly melted conglomerates of particles that are mostly different in both physical state and chemical and mineralogical composition), rather than continuous melts, is most probable (Dodd, 1981; Keil, 2000; Bischoff et al., 2006). From this, it follows that the impact metamorphism of the surface material of asteroids is rather heterogeneous and local.

Due to the occasional character of the impact processes, there are specific peculiarities in the evolution of each of the asteroids and the individual formations on its surface. Depending on the value and the direction of the velocity of the falling body, the bottom of the impact crater can be filled with both the material of the impactor and the material of the asteroid itself (Pierazzo and Melosh, 2000). This means that the fall of smaller bodies on the asteroids may result in the transfer or delivery of the material of the other type (since it was formed on the other parent body). Even if the impact crater or the material ejecta from it was mainly formed from the material of the asteroid, the substantial impact loadings and high temperatures may lead to the changes in the structure and the composition of the rocks and minerals (crushing, mixing, heating, partial melting, and removal of volatiles) (see, for example, Korzhinskii, 1957). As we know from numerous research of meteorites—fragments of asteroids—the surface material of the latter was subjected to the intense and multiple impact reprocessing containing a number of short-term, mainly reducing, processes, as they were accompanied by high pressures and temperatures on one hand and led to the formation of oxygen-depleted nonequilibrium melts or condensates on the other hand (Dodd, 1981; Scott et al., 1992; Ryan and Melosh, 1998; Keil, 2000, Wasserman and Melosh, 2001).

Moreover, it was recently found that the chemical reaction, which is characteristic of high-temperature and pressure mantle processes, took place at the condensation of the silicate-material vapors accompanying the impacts of solid bodies (Mao and Bell, 1977). The impulse-laser modeling of the impact melting, evaporation, and condensation of the iron-containing samples of augite and peridotite in the helium atmosphere showed that the processes are accompanied by the chemical disproportionation of bivalent iron when Fe^{2+} is transformed to Fe^0 and Fe^{3+} (Yakovlev et al., 2009). The composition of the successive layers of the condensate obtained in this experiment was determined; and its analysis suggested an unambiguous conclusion: when the concentration of Fe^{2+} decreases, not only the content of Fe^0 but also the content of Fe^{3+}

grows, and the latter increases several times faster. According to the interpretation proposed by the authors, the high density of the gas in the volume unit of the vapor, produced during impact, as if it “locks” the liberated oxygen in the “system”: for a certain duration, it is left in this volume, which increases the probability of its reaction with FeO and iron oxidation to the trivalent state. The same method was applied to examine the impact condensate on the fine-fraction particles of the lunar-regolith samples returned by the *Luna 16* spacecraft. The comparative study of its composition confirmed the effect of the disproportionation reaction of bivalent iron under the natural conditions on the atmosphereless celestial bodies: in the successive layers of the impact condensate, the ratios of the valent forms of iron averaged $Fe^0 : Fe^{2+} : Fe^{3+} = 1.2 : 1.9 : 0.7$ (Yakovlev et al., 2009; Gerasimov et al., 2002). This result is important in interpreting the observed spectral characteristics of solid atmosphereless celestial bodies.

Coming back to the asteroids we have considered, let us discuss the possible influence of the impact processes on their material. C-type asteroids (to which Hygiea belongs) are believed to be the parent bodies of meteorites—carbonaceous chondrites, whereas S-type asteroids (to which Philomela belongs), the parent bodies of ordinary chondrites, because their reflectance spectra are similar (Gaffey et al., 1989). Laboratory studies of carbonaceous chondrites of the most-primitive groups (CI, CM, CO, and CV) showed that their material was not subjected to heating higher than 100–200 K as a rule, and it is enriched with the layered hydrosilicates containing bound water (see Dodd, 1981; Rubin, 1997; Huss et al., 2006, for example). Due to the impact events inducing local heating and melting, we can suppose that the material of carbonaceous-chondrite type dehydrates and their composition becomes similar to that of ordinary chondrites, which results in the corresponding transformation of the shape of reflectance spectra. Exactly such a behavior of the spectral characteristics of carbonaceous chondrites was demonstrated by crushed samples heated to different temperatures in the laboratory (Hiroi et al., 1993). It is necessary to note that, though the considered asteroid 135 Hertha belongs to the M type (Tholen, 1989), it can be partly covered with hydrosilicates. This follows from the presence of the diagnostic absorption band of H_2O/OH in its reflectance spectra at 3.0 μm (Rivkin et al., 2000), the weak absorption band of Fe^{3+} at 0.44–0.45 μm (according to our data, see Figs. 1 and 2), and from the relatively low IRAS albedo, 0.14 (Tedesco et al., 2004). As we have already noted, the shape of Hertha’s reflectance spectra changed from slightly convex (typical of M–S-type asteroids) to flat or concave (typical of C–F-type asteroids) (Fig. 2). The similar changes in the reflectance spectra were found in the other hydrated asteroid of the M type, 21 Lutetia, during its rotation (Busarev, 2008). As the studies of Lutetia fulfilled with the spectral-frequency method (Busarev et al., 2007) in the range of the Fe^{3+} absorption band at 0.44–0.45 μm showed, there are many local heterogeneities of hydrates and/or oxidized material on its surface, and their sizes mainly range from several kilometers to several tens of kilometers (Prokof’eva et al., 2005).

Thus, the main causes of the absorption bands of Fe^{3+} at 0.44–0.45 μm and Fe^{3+}–Fe^{2+} at 0.75–0.80 μm in the reflectance spectra of the asteroids are as follows: their “own” hydrated and/or highly oxidized compounds contained in their material (in particular, on the asteroids of primitive types), the delivery of such compounds during the falls of primitive bodies of carbonaceous-chondrite composition with a high content of hydrosilicates (especially on the asteroids of magmatic types) (Busarev, 1998, 2002), and the chemical reaction of disproportionation of bivalent iron during formation of the silicate-material condensate in the impact processes (Yakovlev et al., 2009). Different combinations of the listed causes cannot be excluded. Probably, if the hydrated and/or highly oxidized compounds are present on the surface of asteroids, the influence of the impact processes leads to the strengthening of the absorption bands of Fe^{3+} or Fe^{3+}–Fe^{2+} in their reflectance spectra. At the same time, we see from the mean ratios obtained for the disproportionation of Fe^{2+} in the impact processes (Yakovlev et al., 2009) that their predominantly reducing character remains. Because of this, it is natural to suppose that, if the asteroid’s surface is composed of ordinary-chondrite-type material, where such minerals as olivines and pyroxenes (more resistant than hydrosilicates to high temperatures and pressures) predominate, serious impact events result in no sharp changes in the composition of the material and/or in the degree of its oxidation and, consequently, in the spectral characteristics of the observed hemisphere of the asteroid. Probably, this is confirmed by the reflectance spectra of Philomela obtained in our study (Fig. 5).

It is worth stressing that the asteroids considered were observed at small phase angles of light under a stable atmospheric transparency. The absence of substantial errors in the observational data is confirmed by the same shapes of the reflectance spectra of asteroids at close values of the rotation phase. Because the spectral properties of each of the asteroids are determined by the mean chemical and mineralogical composition of the material of its observed hemisphere, they are influenced by existing local heterogeneities in the material composition. Probably, such heterogeneities in the surfaces of Hygiea and Hertha causing the spectral differences during rotation are the result of serious impact events. On the basis of the results and the cited published data, we assert that local heterogeneities in the surface-material composition connected with impact events are quite probable on primitive types of asteroids (C, G, B, and F) or in the hydrated asteroids of other types and less probable on high-temperature types of asteroids (M, S, E, and V), as their material is more resistant to high temperatures.

The results show that, to estimate the spectral type and the corresponding mineralogy of each of the asteroids, one should determine the ranges of the variations in its spectral characteristics through the time interval comparable with the rotation period and to take them into account if the differences are noticeable.

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